East Asian Seminar on Economics,2025
March 27-28, 2025
National Bureau of Economic Research

Disruption Risk Evaluation on a Large-scale Production Network with Establishments and Products

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Background

Propagation of economic shocks through supply chains

- Earthquakes
  - Firm-level econometrics: Barrot et al. (2016), Carvalho et al. (2021), Boehm et al. (2019), Kashiwagi et al. (2021)
- COVID-19
  - Country-industry-level CGE: McKibbin et al. (2020), Guan et al. (2020)
  - Country-product-level econometrics: Hayakawa et al. (2021), Meier et al. (2020)
- Economic security and tariff wars
  - Country-industry-level CGE: Baqaee et al. (2024), Moll et al. (2023)
  - Country-product-level econometrics: Fajgelbaum et al. (2024)
  - Customs data: Matsuura et al. (2024)

Shortcomings of Existing Studies and Our Approach

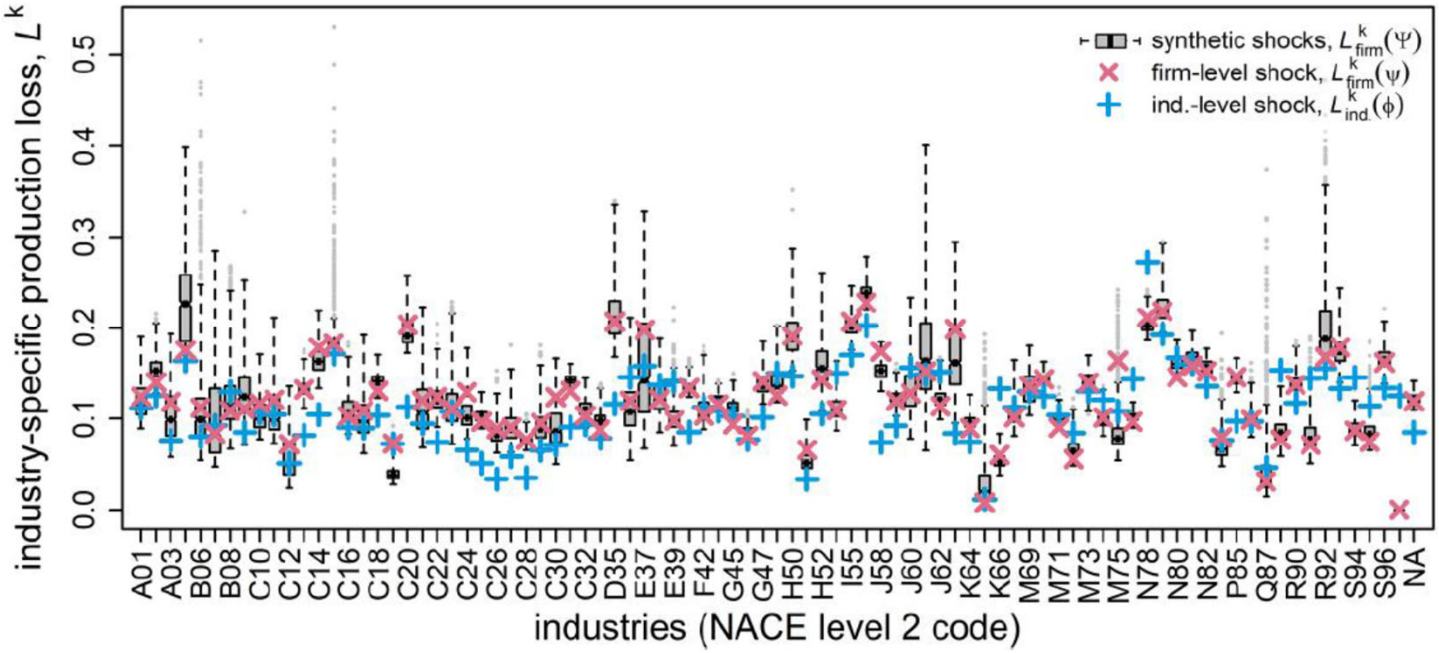
Econometric studies

- Cannot capture the whole network (e.g., feedbacks)

CGE analysis using IO Tables

- Ignores complexity of firm-level networks

➔ likely to undervalue propagation effects



Diem et al. (2024), *PNAS NEXUS.*

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Our approach

- Firm-level data of supply chains
- Agent-based model
  - Not CGE to avoid computational burdens

    ➔ limitations

Previous Studies by Inoue and Todo

Inoue & Todo (2019), *Nature Sustainability*.

- simulation using an **agent-based model** of Henriet et al. (2012) and **actual supply chains of 1M Japanese firms**
- estimate parameter values based on the Great East Japan earthquake
- examine the **role of supply chain structure** in propagation

Inoue & Todo (2020), *PLOS ONE*.

- predict the economic **effect of possible lockdown of Tokyo**, incorporating propagation through supply chains

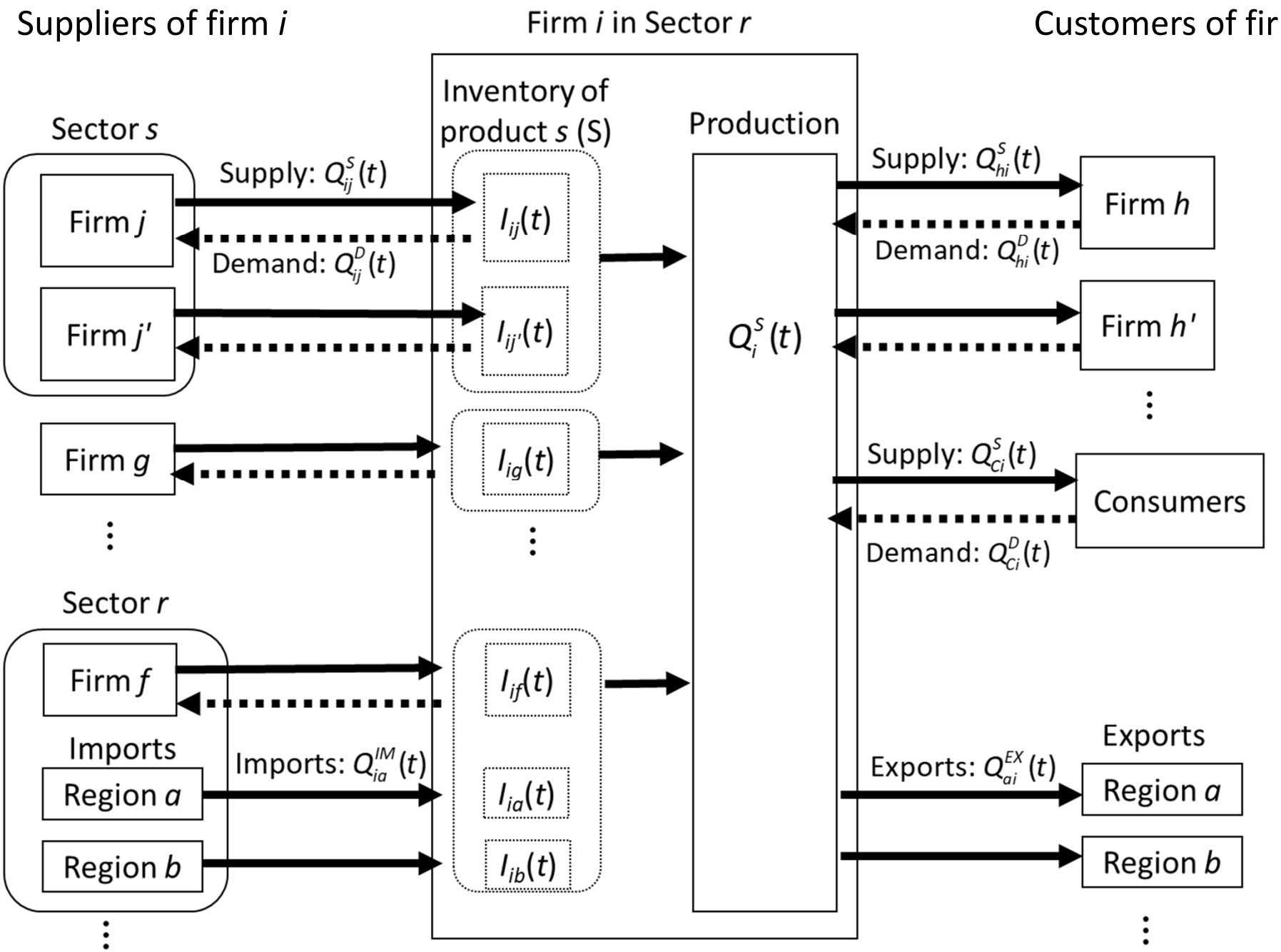
Inoue, Murase & Todo (2023), *Spatial Economic Analysis*.

- examine interactions between the economic effects of imposing and lifting **lockdown in multiple regions**
- examine the **role of inter-region supply chains** in the interactions

Inoue & Todo (2023), *PLOS ONE*.

- incorporate international trade by merging data on exports and imports at the firm level
- predict the effect of **disruption of exports/imports**

Agent-Based Model (ABM)



Assumptions of the Model

- **Leontief production function**
  - No substitution between different types of intermediate inputs
- **Each industry produces a specific good**

  (1460 industries as defined by the Japan Standard Industry Classifications)

  ➔ Possible substitution between suppliers in the same industry
- **Imported goods are defined by the industry of importers**
  - Because of lack of data on imported goods
- **Inventories of intermediate from each supplier**
  - Size of inventories determined by a Poisson distribution (average 9 days)
  - No inventory of intermediates from service firms

Assumptions of the Model

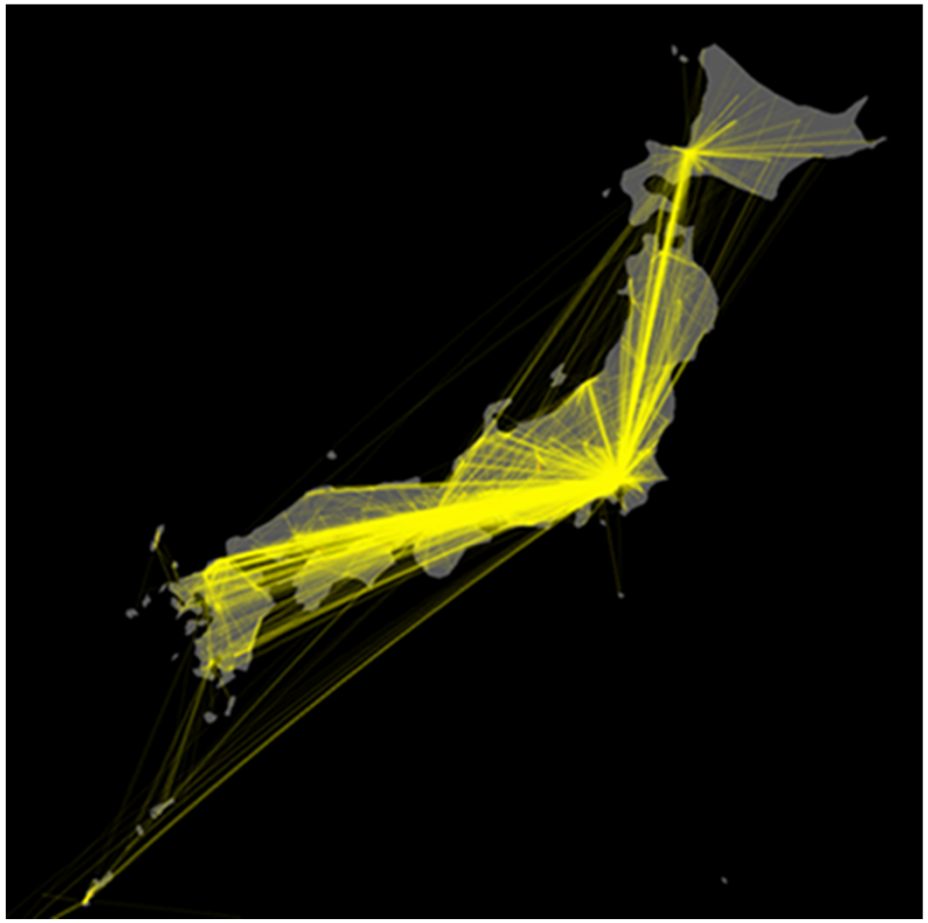
- **No price change**
  - Supply equals demand according to pre-determined rules for rationing products to customers and final consumers
- **No supply chain dynamics** (in the benchmark analysis)
  - No new link after an economic shock (when supply from a supplier decreases, the firm may increase purchases from another existing supplier in the same industry but cannot find a new supplier)

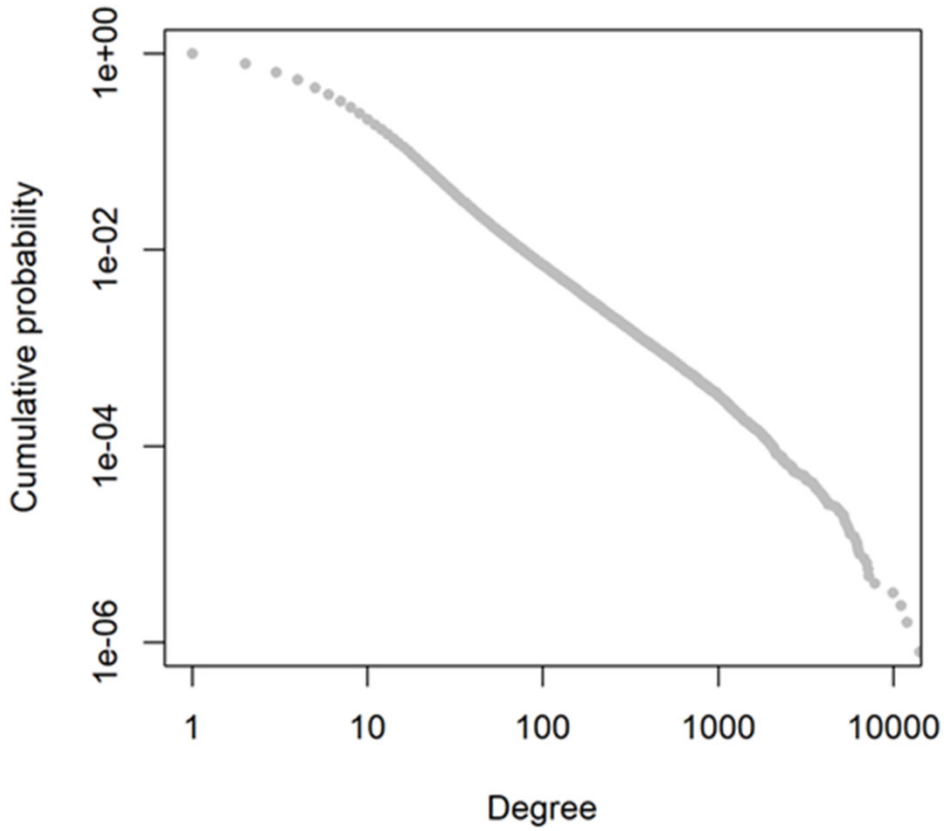
➔ We focus on short-term analyses.

Data

Tokyo Shoko Research (TSR) data

- About 1 million firms, 3.5 million supply chain links in 2020





Data

Basic Survey of Japanese Business Structure and Activities (BSJ)

- Annually collected by the government
- Target relatively large firms with more than 50 employees and initial capital of more than 30 million yen
- 37,000 firms
- Include imports from and exports to each "region"
  (China, other Asia, North America, Europe, Middle East, and Others)
  - Total exports and imports in BSJ = 83 and 48 trillion yen,
    Total exports and imports from trade statistics = 77 and 79 trillion yen

➔ Merge TSR and BSJ using firm ID numbers

Simulation

Calibration to estimate parameter values

using the case of the Great East Japan earthquake

Simulate propagation of shocks through supply chains

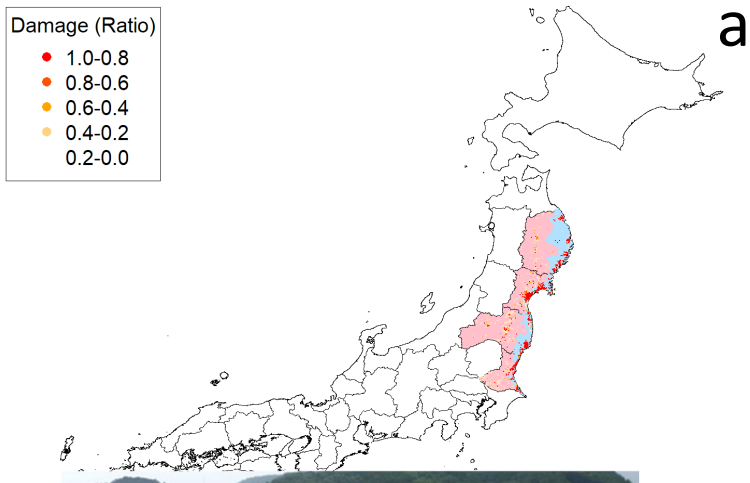
using the case of the Great East Japan earthquake

Simulation using different scenarios

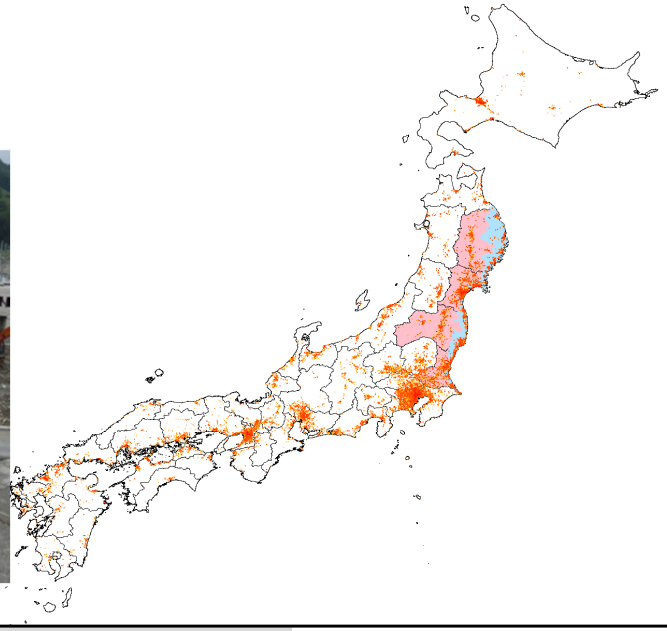
- Different degrees of input substitutions
- Hypothetical lockdowns in the COVID-19 pandemic
- Hypothetical disruption of imports

Economic shocks propagate and are magnified through supply chains

(A) Day 0



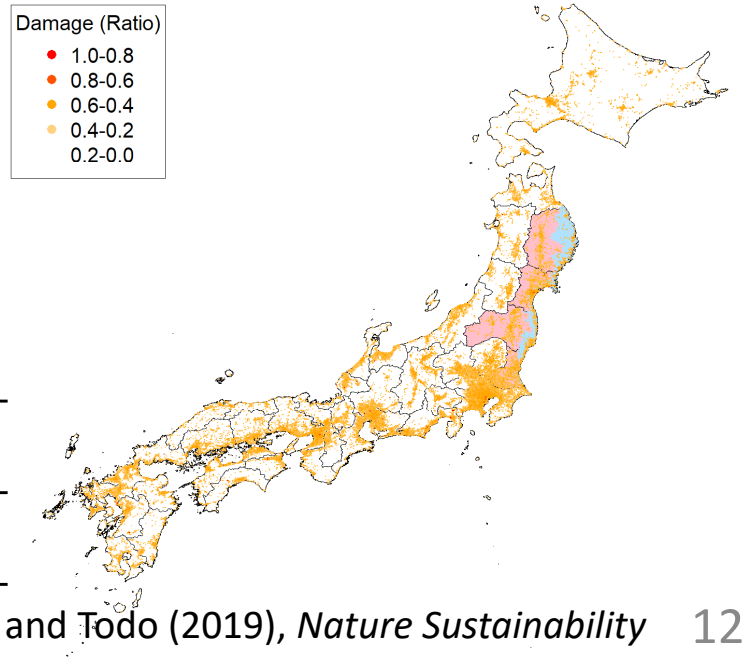
Day 20



Firms that reduce production after the Great East Japan earthquake in 2011

- by 80-100%
- by 60-80%
- by 40-60%

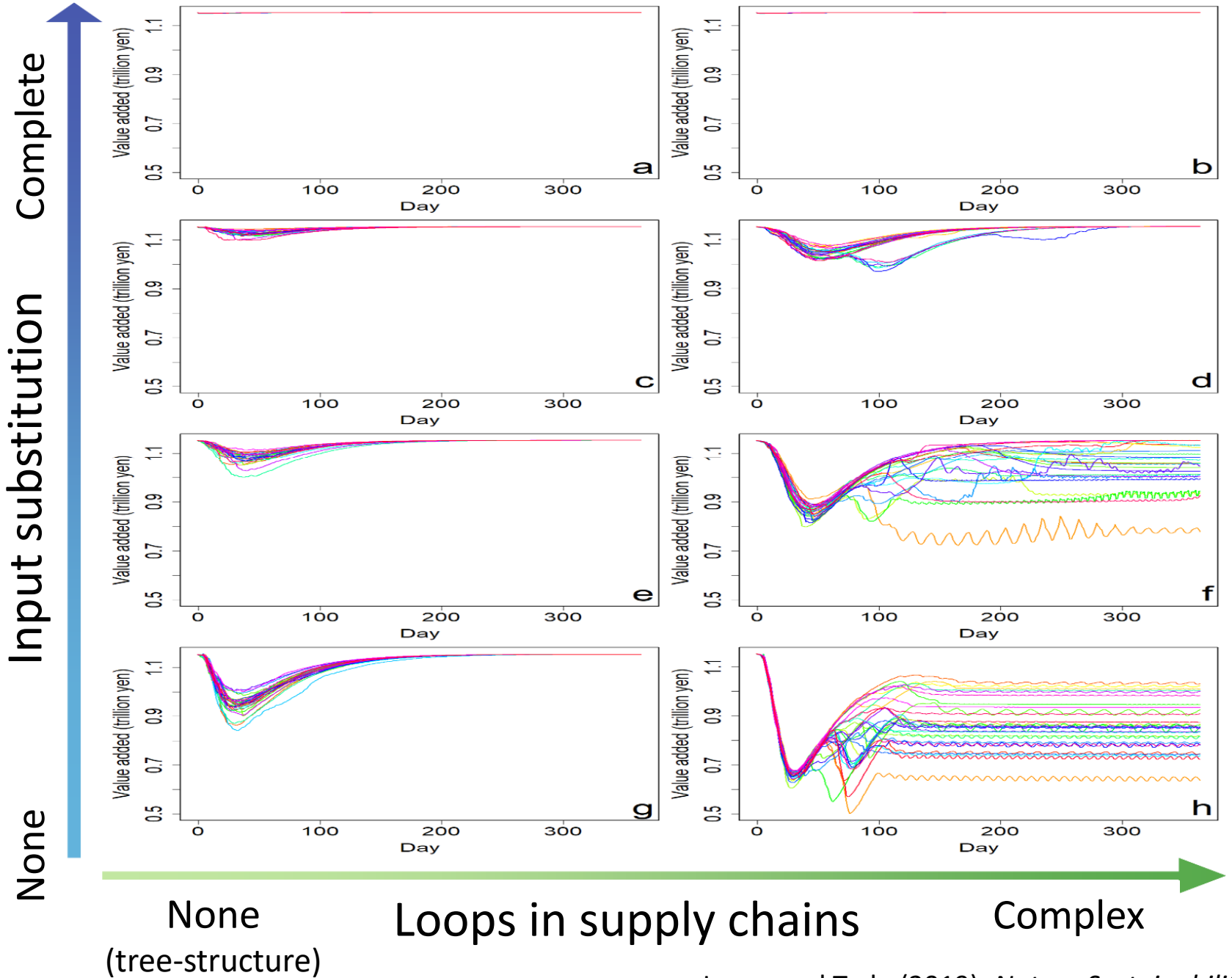
(D) Day 60



Production loss due to direct effect	100 billion yen
Production loss due to propagation	11 trillion yen

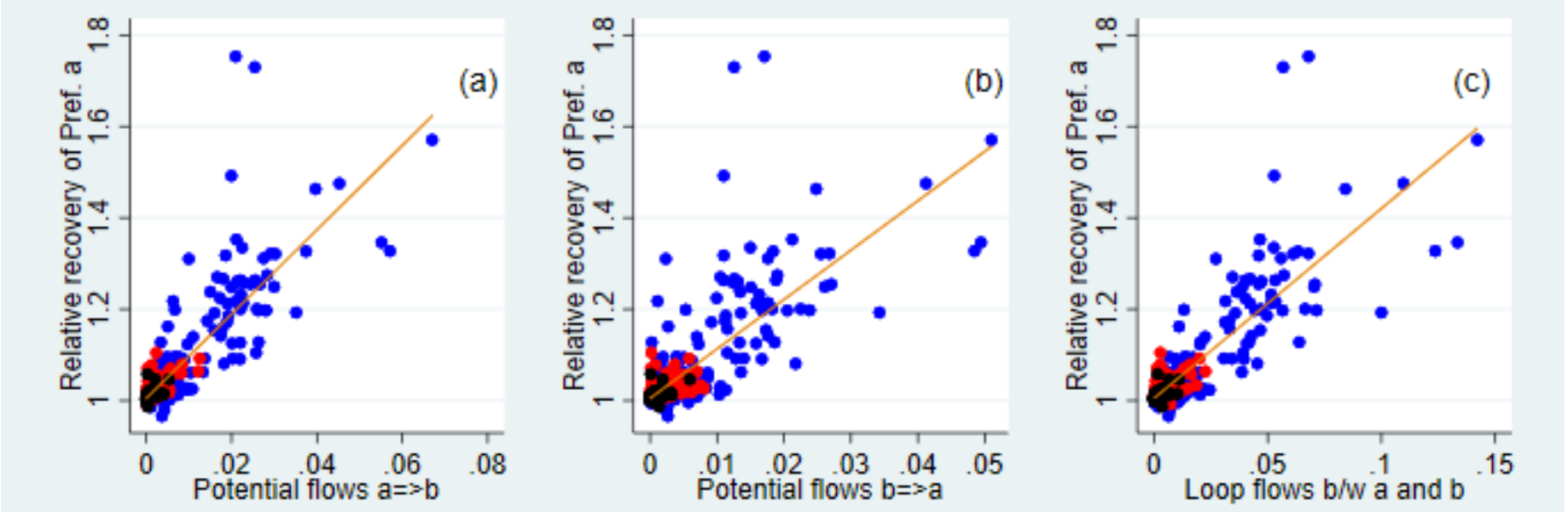
Inoue and Todo (2019), *Nature Sustainability*

The difficulty in input substitution and presence of loops magnify the propagation effect



Inoue and Todo (2019), *Nature Sustainability*.

Inter-region supply chains affect the effect of regional policy

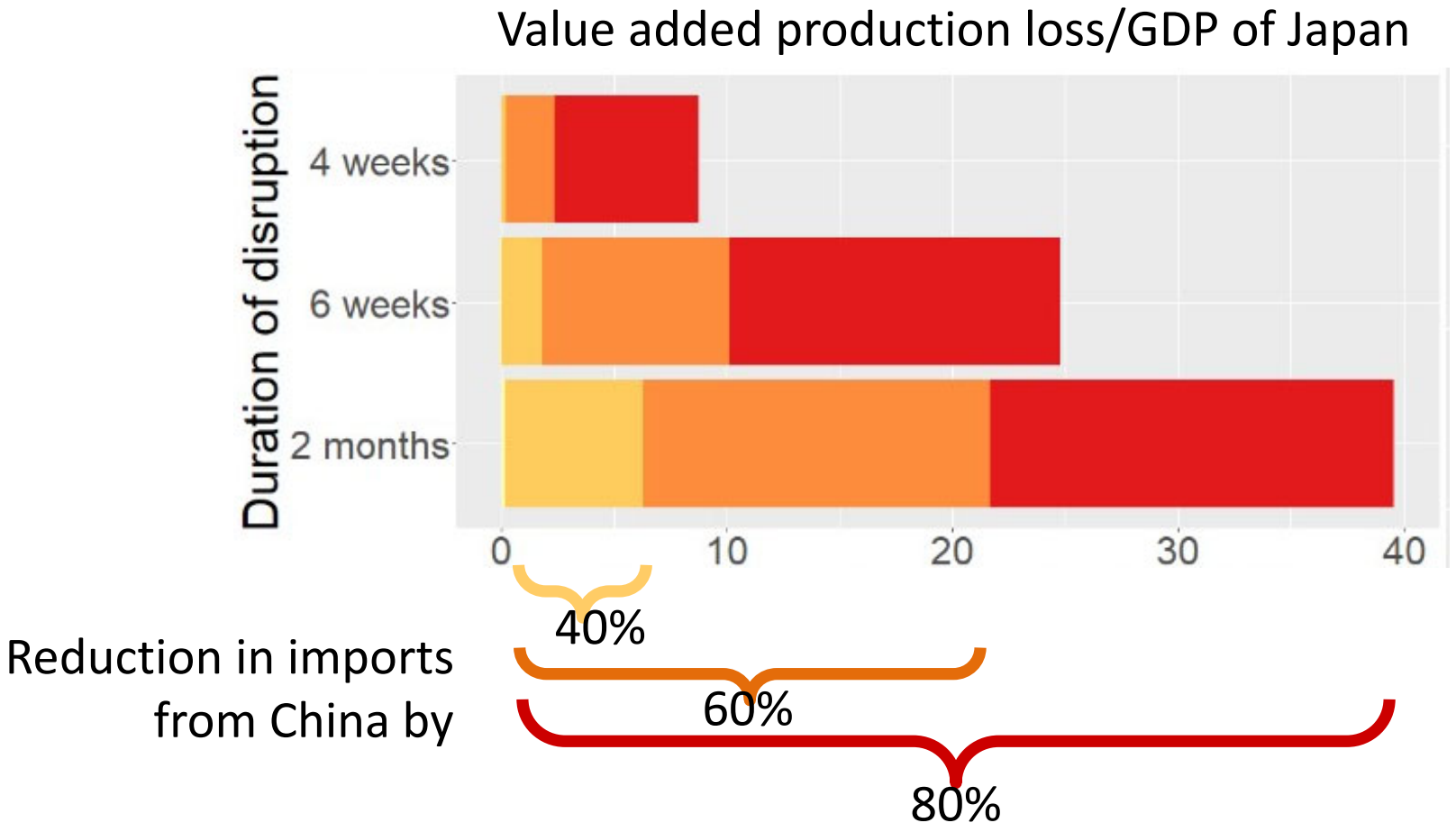


Relationships between production recovery when region *a* lifts lockdown together with *b* (relative to when *a* lifts alone) and measures of supply chains between *a* and *b*

Blue: Pref *b* is top 10 w.r.t. value added
Red: Middle 37
Black: Bottom 10

Inoue, Murase, and Todo (2021), *PLOS ONE*.

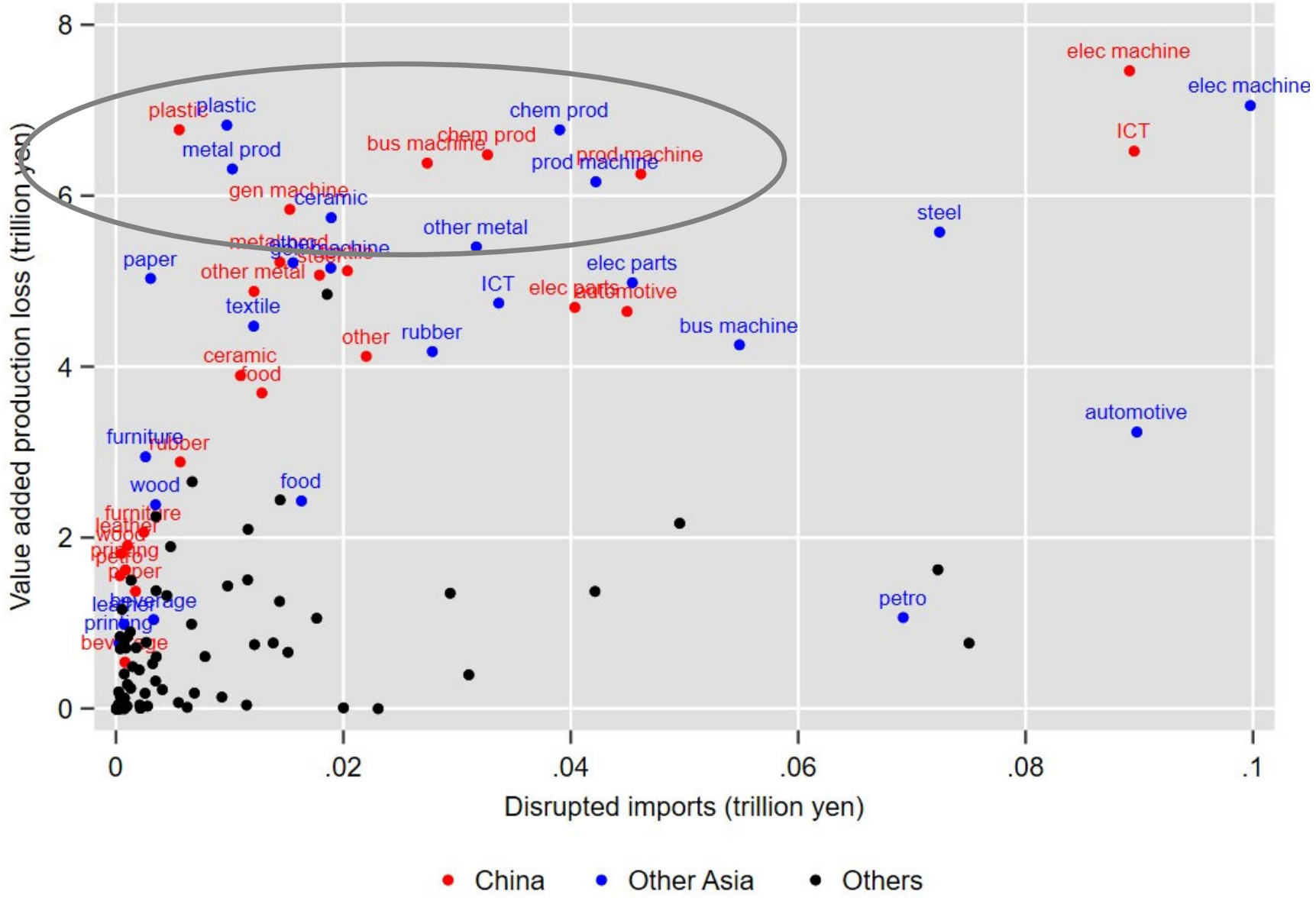
Disruption of imports from China may have a significant impact on the Japanese economy



The effect of import disruption is magnified through domestic supply chains.

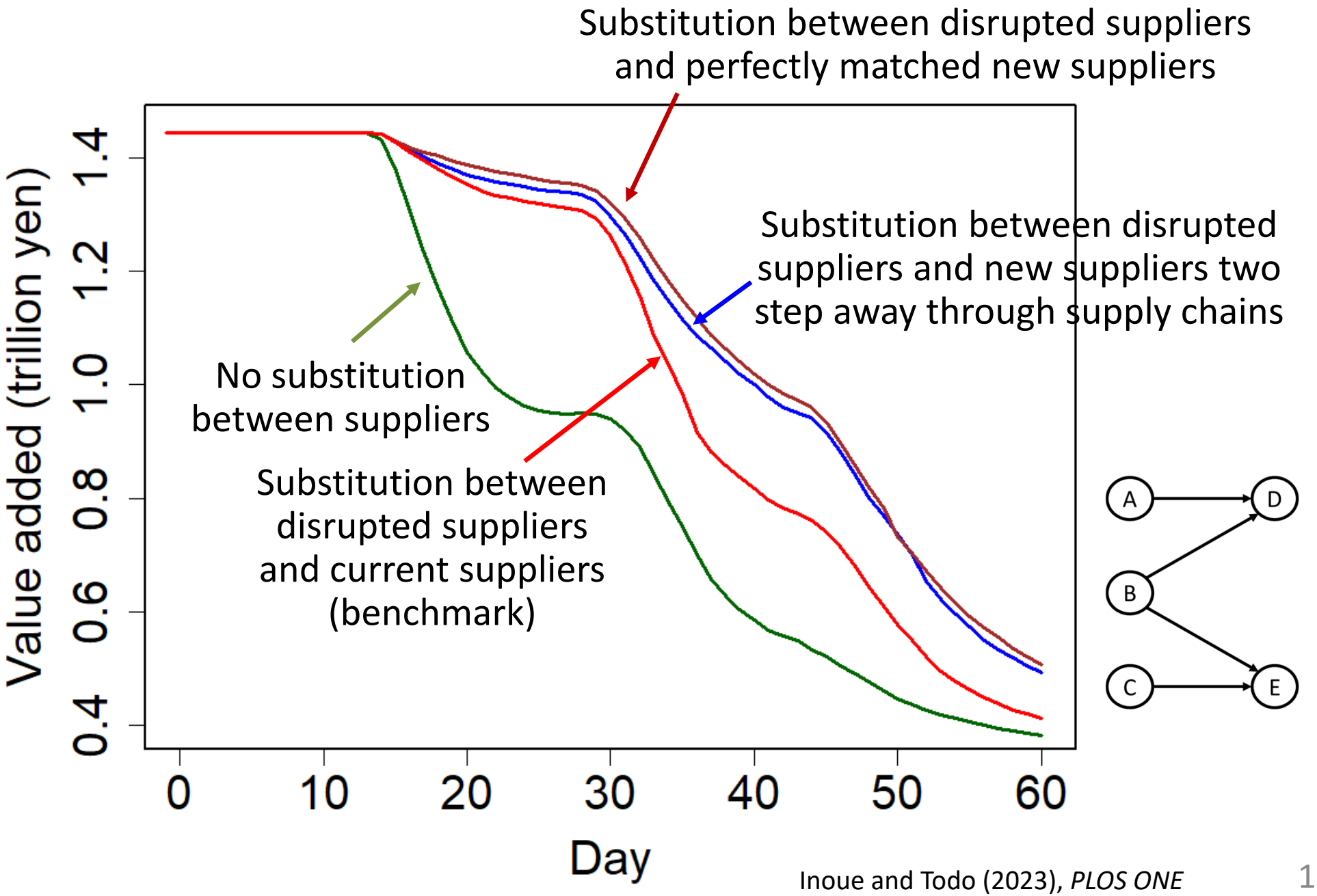
Inoue and Todo, 2023, *PLOS ONE*.

Import disruption of upstream products (e.g., metal, plastic, chemical, machinery) has a larger effect, relative to their import values



Inoue and Todo (2023), *PLOS ONE*

The difficulty of input substitution magnifies propagation



Inoue and Todo (2023), *PLOS ONE*

Shortcomings of Previous Studies by Inoue and Todo

- Data at the firm level, not establishment level
  ➔ Supply chains at the establishment level cannot be identified.
- Assuming firms in the same industry produces the same product
  ➔ Transactions at the product level cannot be identified

This Study

- Adding establishment-level data
  ➔ Estimate supply chains at the establishment level
- Adding data for products of each establishment
  ➔ Incorporate transactions at the product level
- Examine how these improvements affect propagation effects

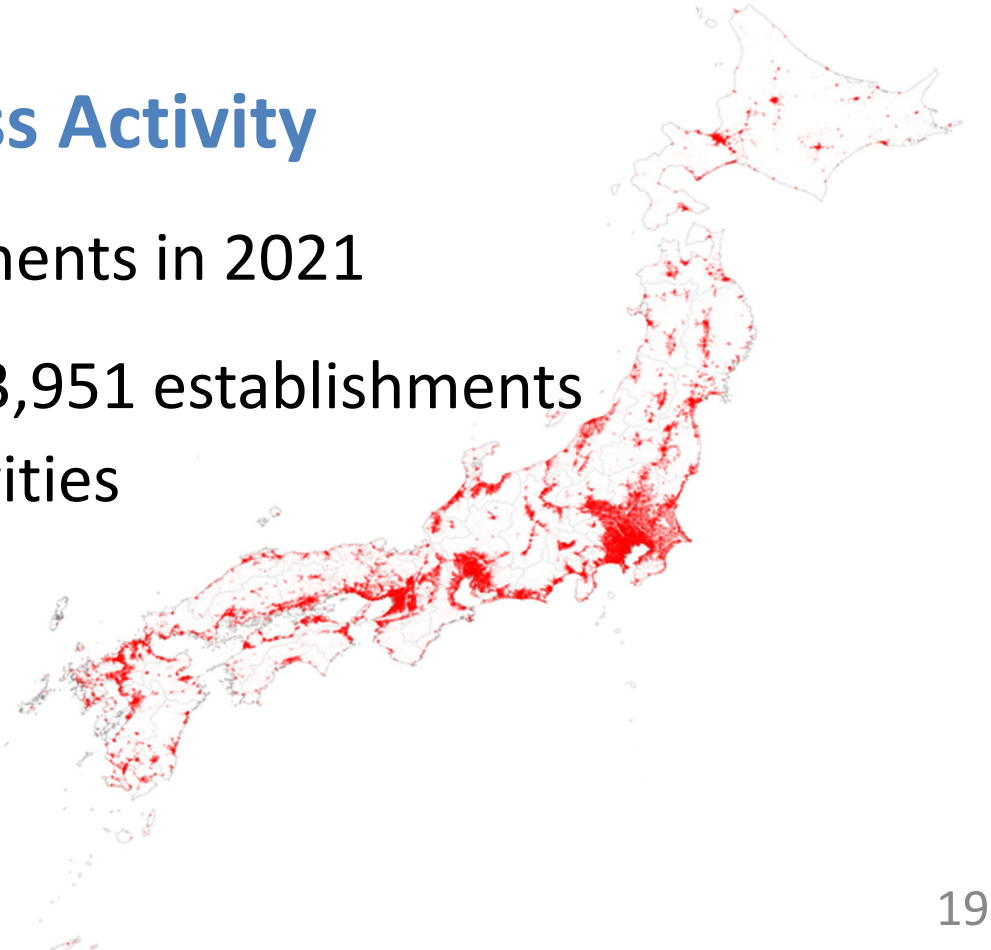
Data at the Establishment and Product Levels

Tokyo Shoko Research data (as in the previous studies)

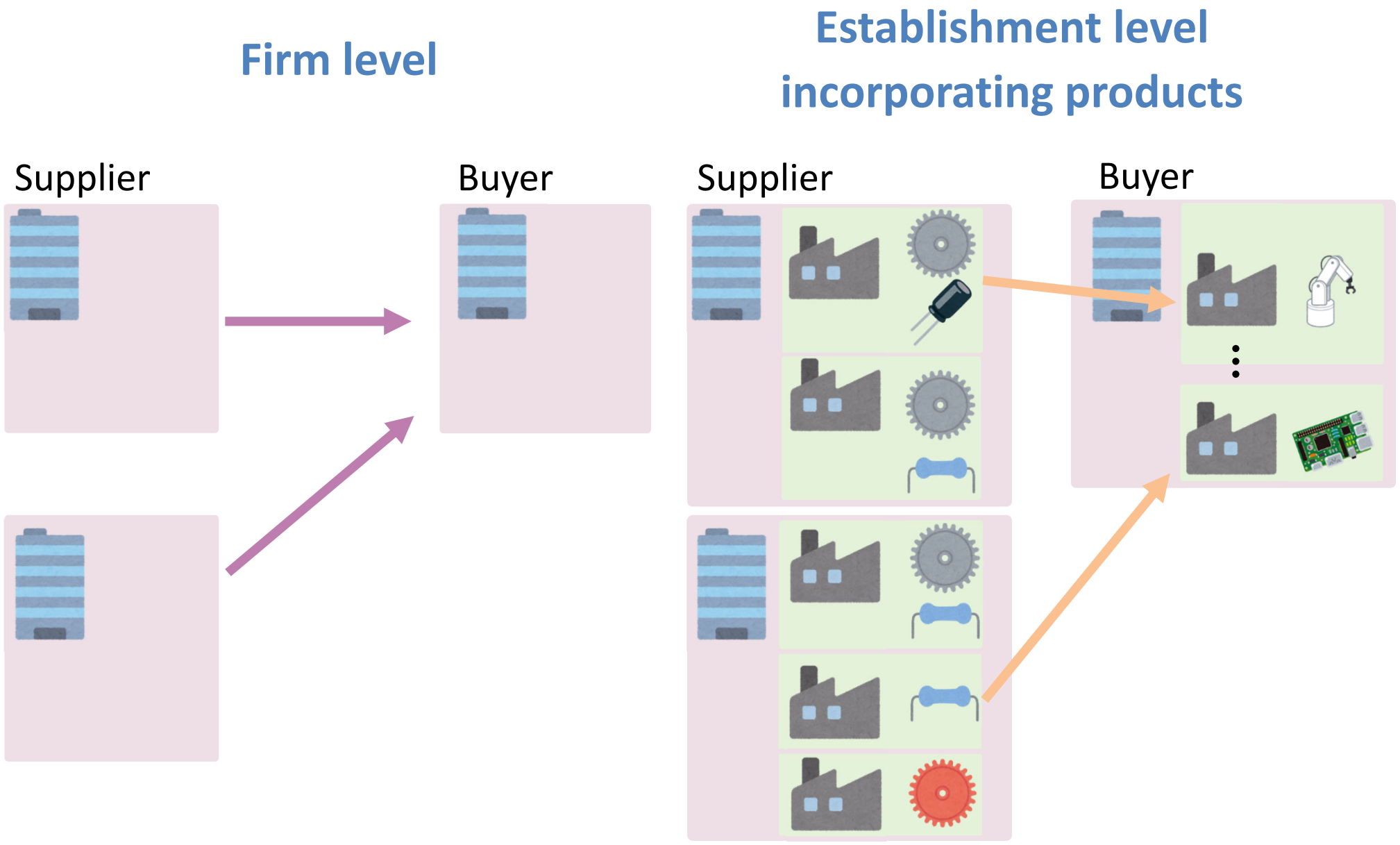
- 1.5 million firms and 5.9 million supply-chain ties in 2021

Economic Census for Business Activity

- Originally 5.2 million establishments in 2021
- Focus on 157,537 firms and 183,951 establishments engaged in manufacturing activities
- Product types: 17,295



Supply Chain at Various Levels

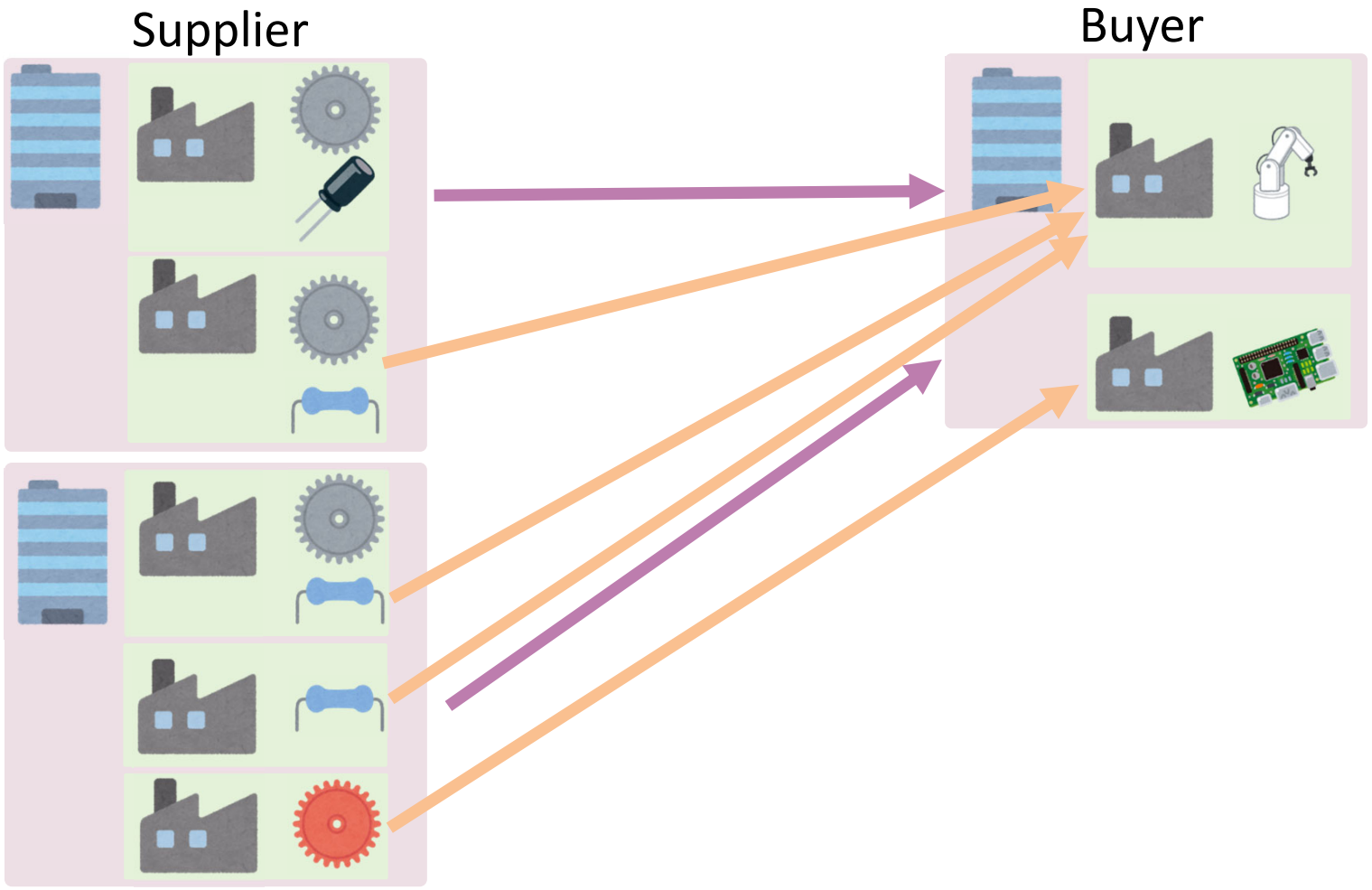


Estimate Establishment-Level Supply Chains Incorporating Products: 2-step Procedures

TSR data: Firm-level supply chains →

Economic Census: Products for each establishment

Establishment-level supply chains →



Step 1: Filtering by "Recipe"

Recipe: Identify major inputs to produce a good

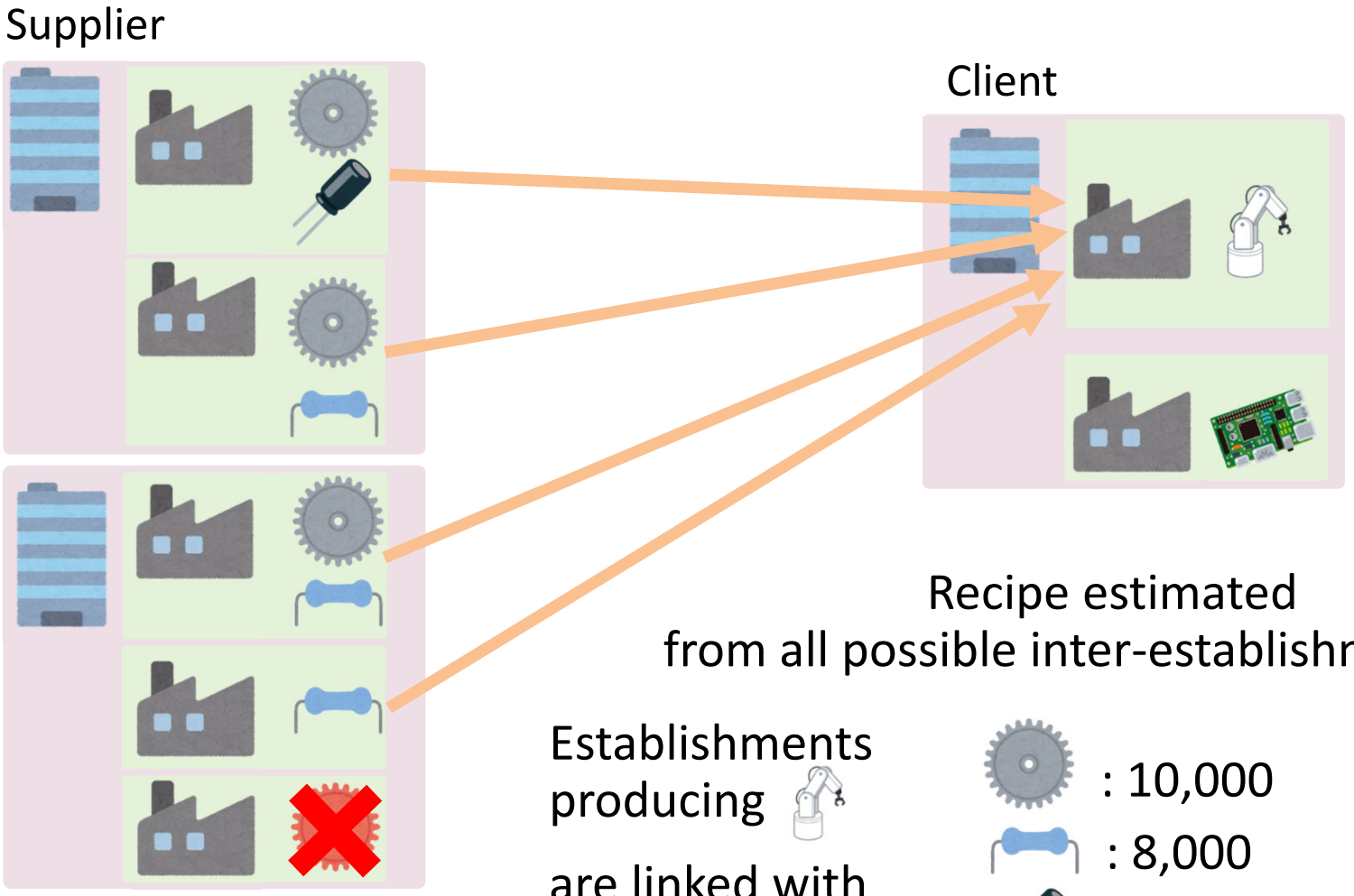
1. Consider all possible supply-chain relationships at the establishment level from firm-level network
2. For a particular output product Y, calculate the number of supplier establishments that produces a particular input product X
3. Identify X as an input of Y, if the number of links in which supplier establishments produce X < 0.5 * the maximum number of links in which supplier establishments produce input product X*

   For example:

   - Input X1 => Output Y1: 10,000 links in the whole network (maximum)
   - Input X2 => Output Y1: 60,000 > 0.5 * 10,000
   - Input X3 => Output Y1: 1,000 < 0.5 * 10,000

   ➔ Recipe: X1 and X2 are inputs of output Y1, but X3 is not.

Step 1: Filtering by "Recipe"



Recipe estimated
from all possible inter-establishment links

Establishments producing

are linked with establishments producing various inputs.

: 10,000

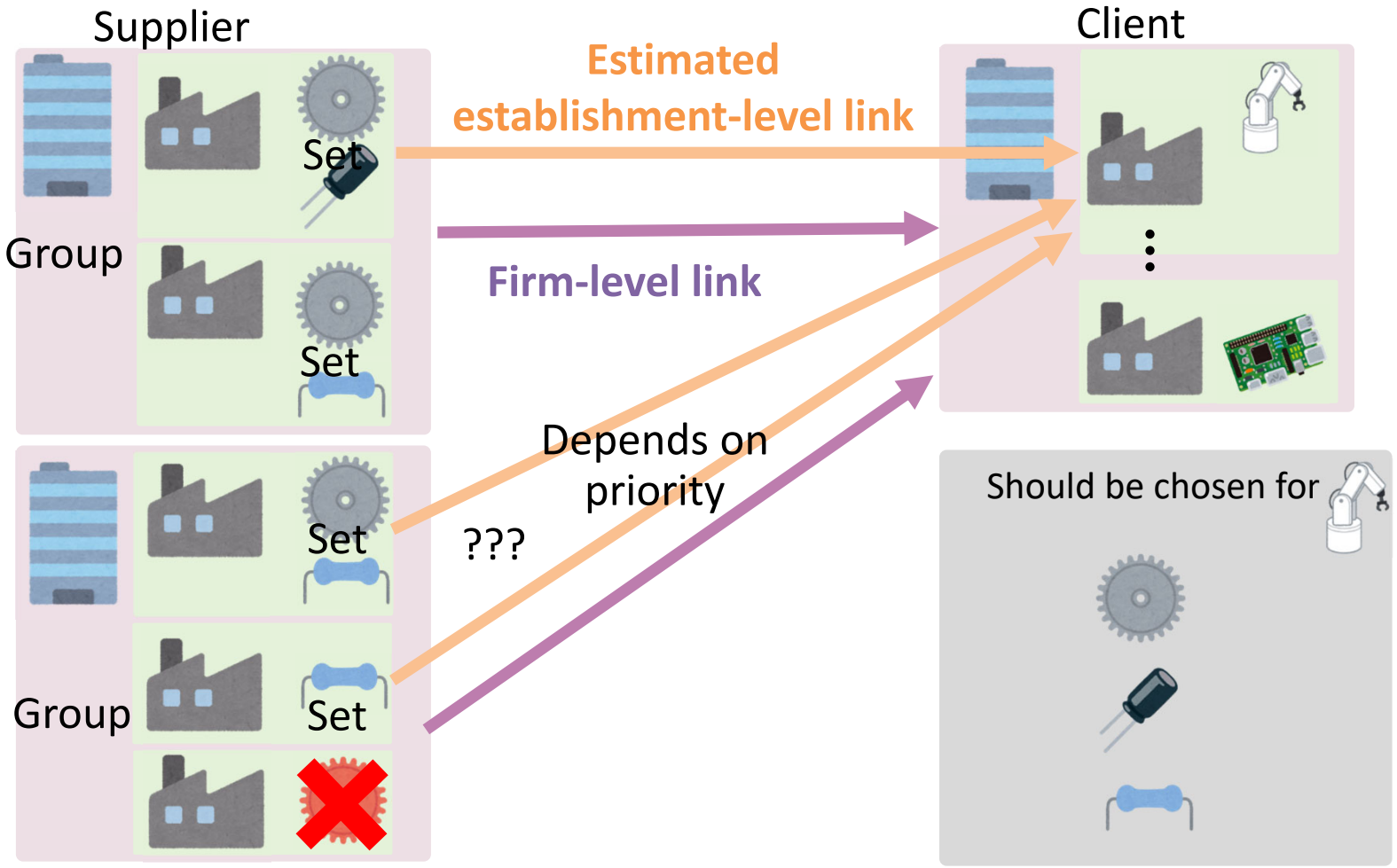
: 8,000

: 6,000

: 2,000 ➔ not an input of

Step 2: Solving for Set Cover Problem (Optimization)

- Select minimal combinations of supplier establishments for each establishment from the universal set identified by the recipe such that:
  - At least 1 inter-establishment link is chosen from each inter-firm link
  - Once an establishment is chosen as a supplier of an establishment, another establishment of the same firm is less prioritized.



Firm-level versus Establishment-level Network

Firm-level network

Firms: 157,537

Inter-firm links: 637,542

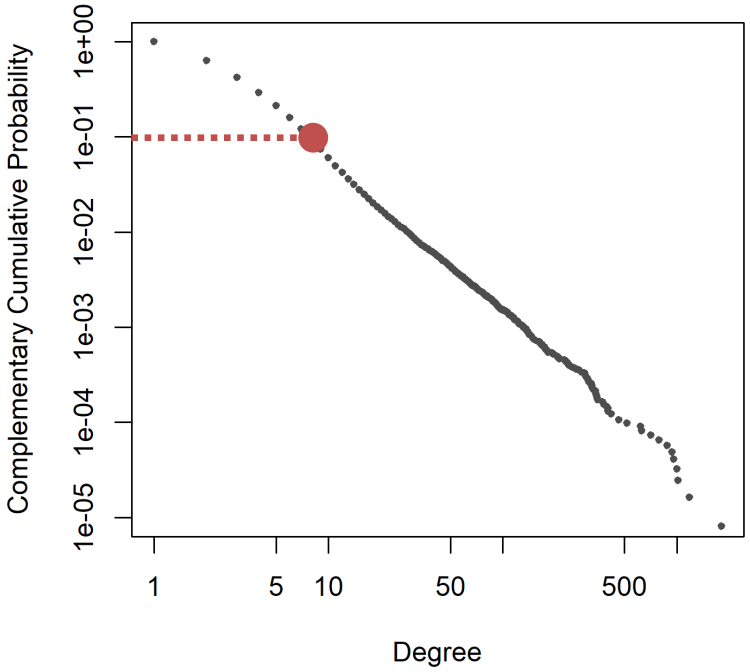
Establishment-level network

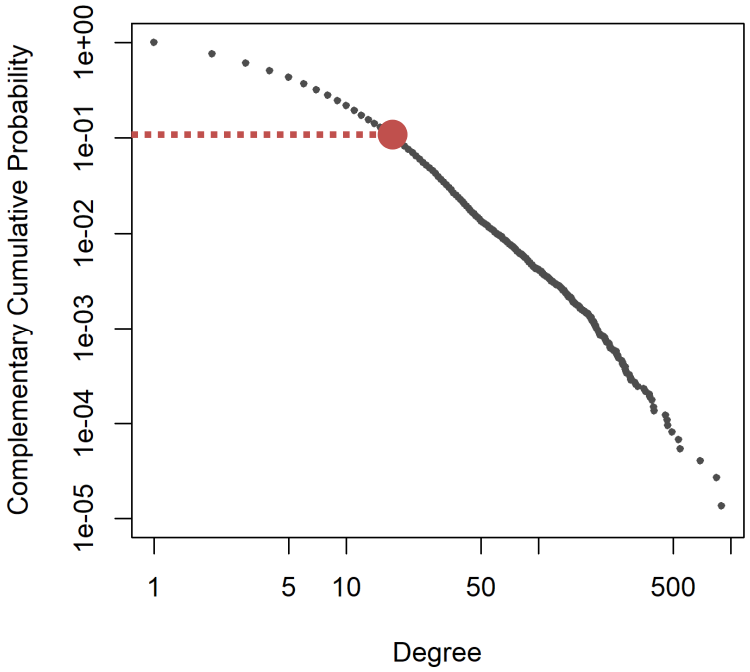
Firms: 157,537

Establishments: 183,951

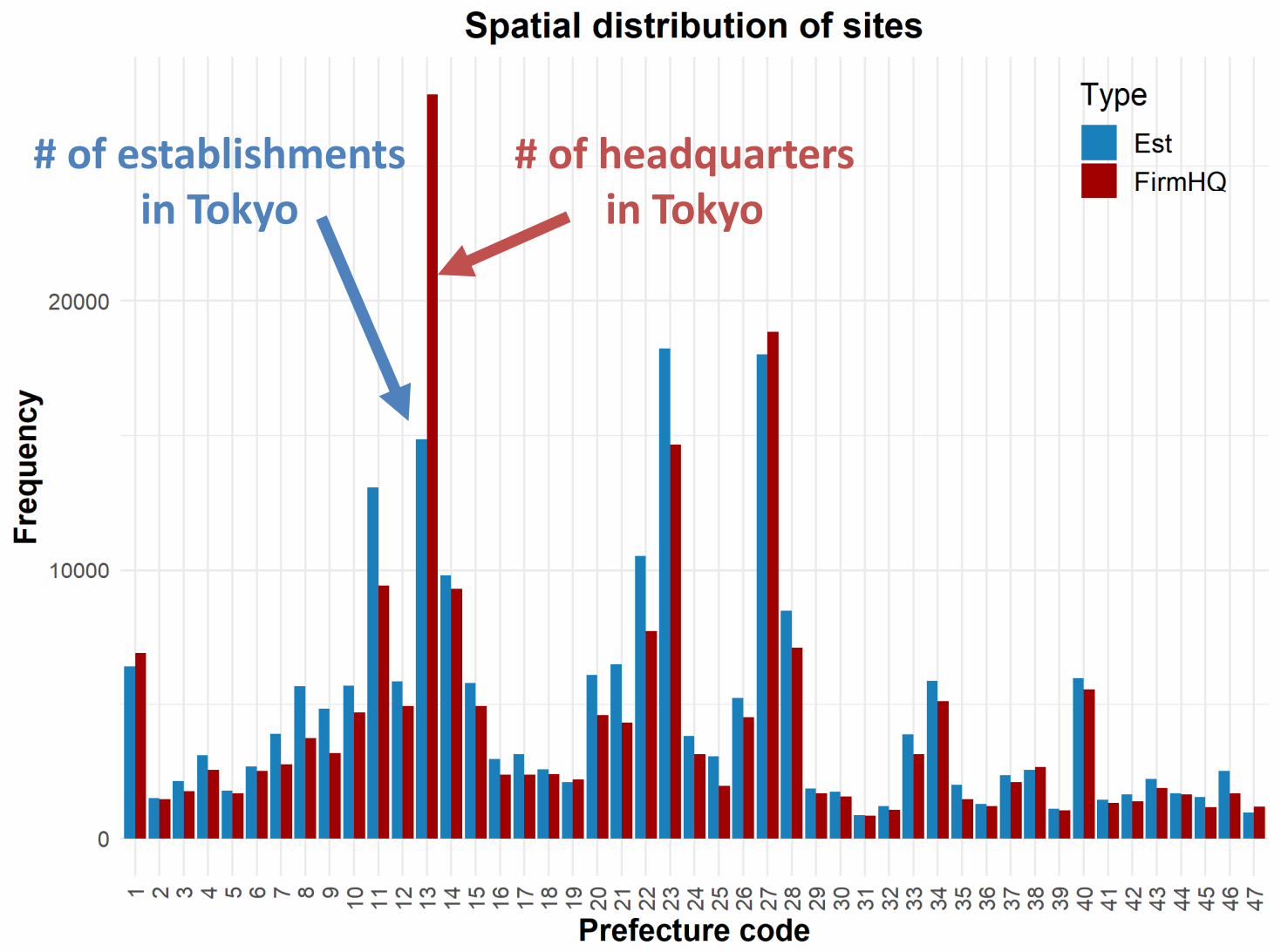
Inter-establishment links: 919,98

- Fewer than inter-est. links by 44%
- 90% of establishments have 17 links or fewer.
  90% have 7 links or fewer in firm network.
  ➔ Establishment network is denser.





Firm-level versus Establishment-level Network



Supply chain links of Tokyo are overvalued in the firm-level network than the actual establishment-level network

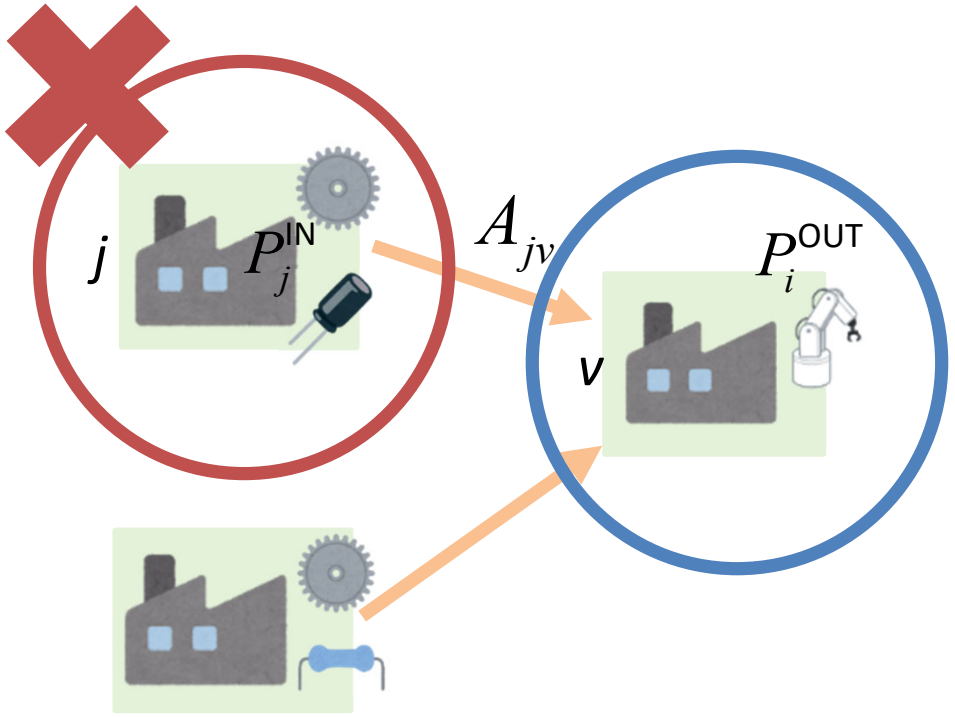
Simple Model of Probabilistic Diffusion of Shocks

In period 0, 1 establishment is randomly chosen and inactivated.

➔ In the next period, clients of the inactive est. are inactivated with a probability determined by the share of their inactive suppliers.

➔ Continue…

U_v: set of v's suppliers just inactivated in period t - 1



Probability of shock propagation to v in period t

Probability of shock propagation to v through product q in period t

$$\rho_v(t) = 1 - \Pi_{q \in \bigcup_{i \in U_v} P_i^{\text{out}}} (1 - p_{vqt})$$

Aggregate over outputs of est. v

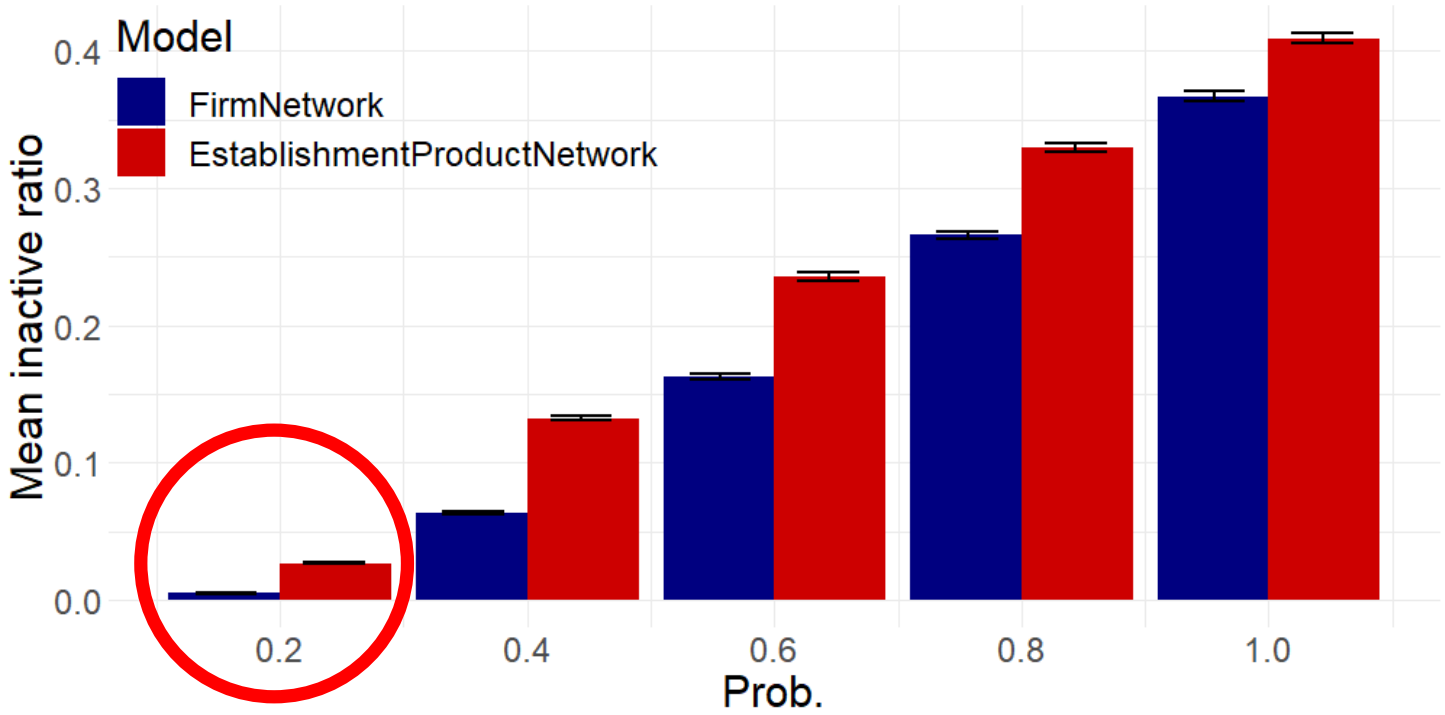
$$p_{vqt} = p \left(1 - \frac{\sum_j s_j(t) A_{jv} \mathbf{1}_{P^{\text{out}}_j}(q)}{\sum_j A_{jv} \mathbf{1}_{P^{\text{out}}_j}(q)} \right)$$

Benchmark prob.

Share of inactive suppliers of v producing product q in period t

$$\mathbf{1}_A(x) = \begin{cases} 1 & \text{if } x \in A \\ 0 & \text{if } x \notin A \end{cases}$$

Results: Firm versus Establishment Networks



Using firm network ➔ Undervalue propagation (for small *p*)

Establishment network

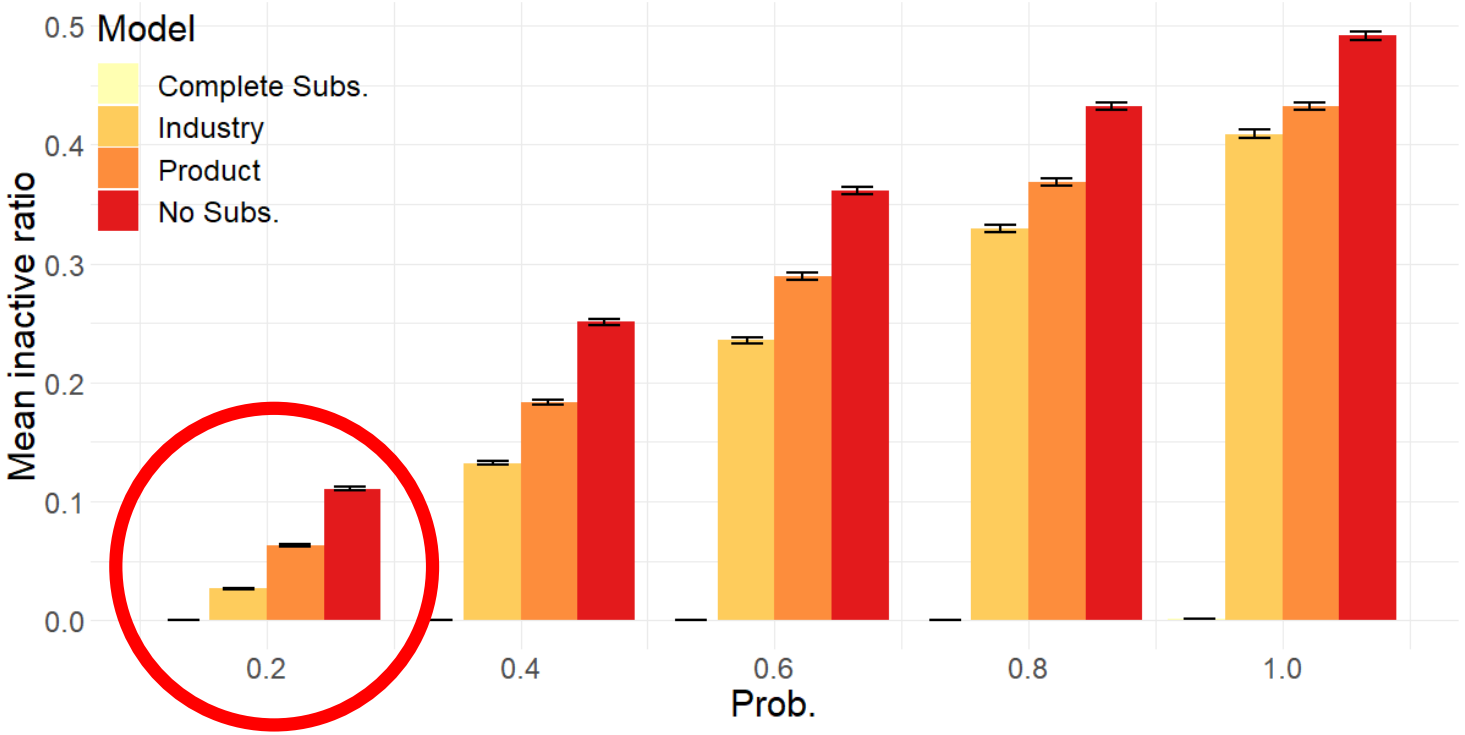
1. Multiple outputs ➔ ↑ output substitution ➔ ↓ propagation
2. Multiple inputs ➔ ↓ input substitution ➔ ↑ propagation

➔ Results imply 1 < 2

Effect of Input Substitution Using Establishment Network

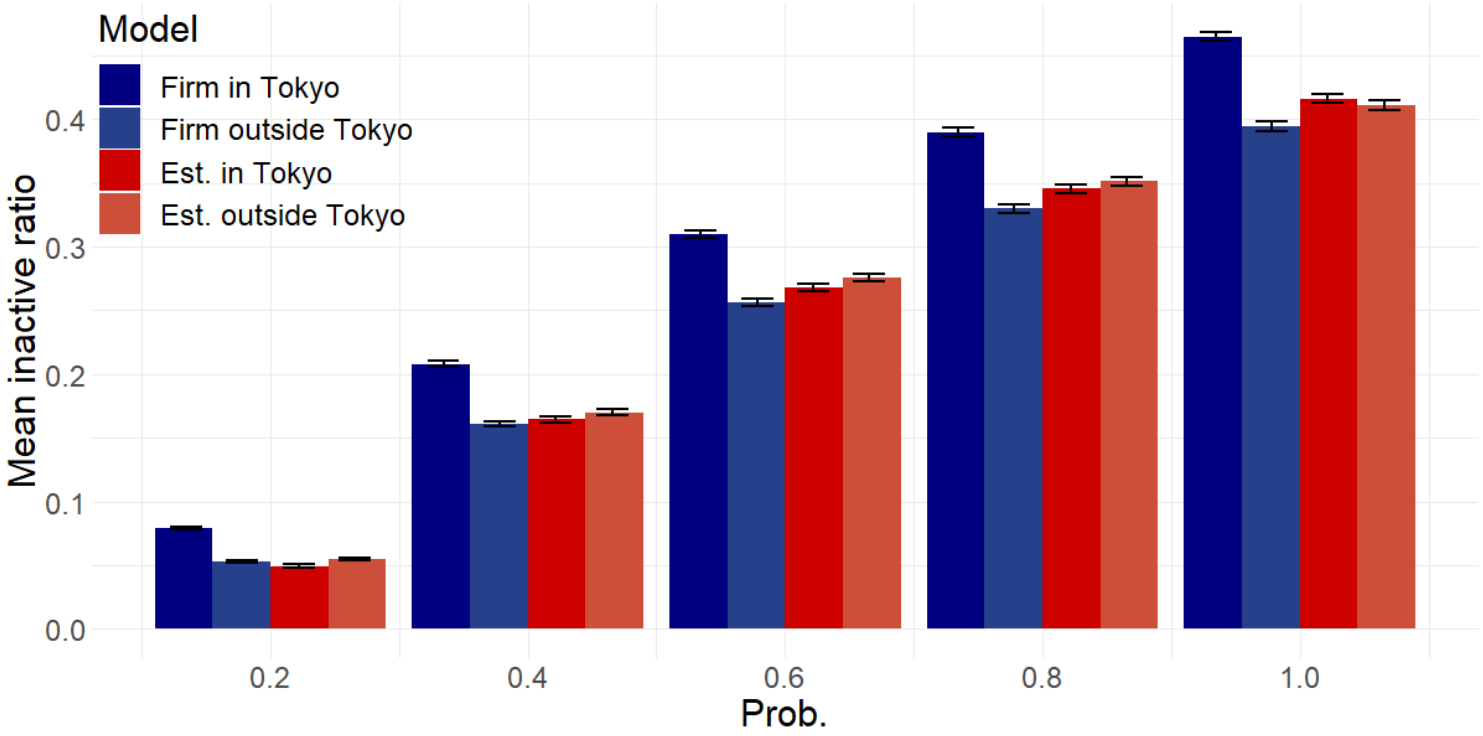
Different assumptions on the level of substitution

- All products are the same (complete substitution)
- Outputs of the same industry are the same (moderate substitution)
- Products defined in the data are substitutable (benchmark)
- All products are unique (no substitution)



➔ The degree of input substitution is a major factor of propagation.

Differences in the Geographic Origin of the Shock: In versus outside Tokyo



Shocks from Tokyo have a larger effect using **firm network**

But, no significant difference using **establishment network**

← Supply chains of firms in Tokyo are overvalued in firm network

Summary and Conclusions

- Contribution
  - Construct establishment-level supply chains
    from firm-level supply-chain data
    and establishment-level data with output products
- Main findings
  - The establishment-level network is denser than firm-level.
  - **Analysis using the firm-level network undervalues propagation.**
- Future studies
  - Incorporate trade data to analyze import disruptions
  - Best to incorporate customs data now available in Japan
    (institutional difficulty…)
  - Invoice data?