The Economic Case for Global Vaccinations:

An Epidemiological Model with International Production Networks

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COVID-19 is a Global Crisis

- COVID-19 pandemic has caused loss of lives and livelihoods across the globe, no country is spared.
- Vaccines are a game changer and can stop the pandemic in a given country/economy.
- Given the global interconnections between countries, even if a country achieves universal vaccination of its citizens, that country may still suffer economic costs if rest of the world is not vaccinated.

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Our work estimates these economic costs:

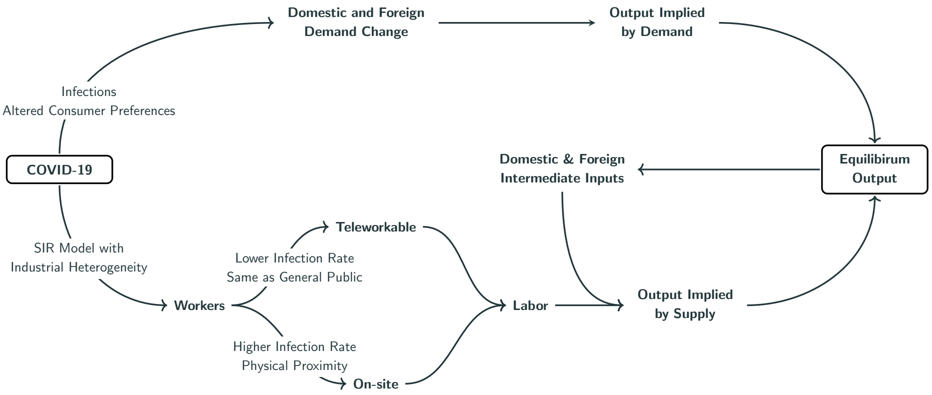
1. What is the economic impact of not vaccinating poorer nations, on richer nations?
2. How much of the global costs the rich nations bear even if they achieve universal vaccinations in their own economies?
3. Which sectors in rich economies are especially vulnerable?

Framework: Data-Driven

Framework

- Favors tractability, easily mapped to data.
- Short run with fixed prices weekly estimation in 2021.
- Demand determined output with labor supply constraint.
- Allows full amplification via I-O network through possible non-linearities.
- Caveat: No price and labor adjustment.
  $\Rightarrow$Data requirement to take these into account will be much greater.

Combine Epidemiological Sectoral Heterogeneity with Global Sectoral Linkages



Our previous work focus the effects of declining domestic and foreign sectoral demand—Cakmakli et al., May 2020, "COVID-19 and Emerging Markets: A SIR Model, Demand Shocks and Capital Flows", IMF WP.

A Data-Driven Framework, Rich in Country-Sector Heterogeneity

- **Supply**
  - Domestic labor supply is a function of infections —SIR Model
    - Worker/Sector Heterogeneity $\Rightarrow$ Teleworkable & Physical Proximity
  - Domestic + Imported Intermediate Inputs

    Assume Leontief production function (e.g, Baqaee and Farhi (2020a))
    $\Rightarrow$ based on evidence of strong complementarity in the short run (e.g., Boehm et al. (2019, 2020))

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- **Infection Dynamics—SIR Model**
  - Country and sector specific.
  - Severe cases $>$ ICU capacity: Endogenous Lockdowns
  - Demand normalizes when active cases $<$ Population$/20,000$

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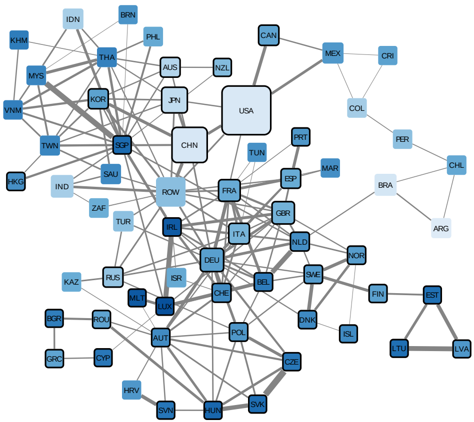
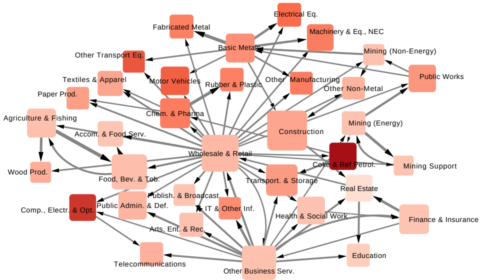
- **Open Economy**
  - Infection dynamics of each country affect its exports and imports.

Global Trade and Production Network: OECD ICIO Tables





35 industries in 65 countries, giving us a matrix of 2275 × 2275 entries

Epidemiology

SIR Model – Basics

Population is divided in three categories:

- Susceptible (S_t)
- Infected (I_t)
- Recovered or Removed (R_t)
- Initial $I_{t=0}, S_{t=0}, R_{t=0}$ from data.

SIR Dynamics:

$$\begin{aligned}\Delta S_t &= -\beta S_{t-1}\frac{I_{t-1}}{N} \\ \Delta R_t &= \gamma I_{t-1} \\ \Delta I_t &= \beta S_{t-1}\frac{I_{t-1}}{N} - \gamma I_{t-1}\end{aligned}$$

Dynamics of pandemic is governed by:

$$R_0 \equiv \beta/\gamma$$

SIR with Sectoral Heterogeneity

- K sectors, indexed by $i = 1, \ldots, K$
- Non-working population: N_{NW}
- Industry i has L_i workers, some teleworkable (TW_i), some needs to be on-site (N_i) with:

$$L_i = TW_i + N_i$$

- Any given time, number of staying at home (will be denoted by subscript 0):

$$N_0 = N_{NW} + \sum_{i=1}^{K} TW_i.$$

SIR with Sectoral Heterogeneity

- Infection rate for at-home group is β_0.
- Industries have different physical proximity requirements, Prox_i.
- The rate of infection for each industry i, β_i:

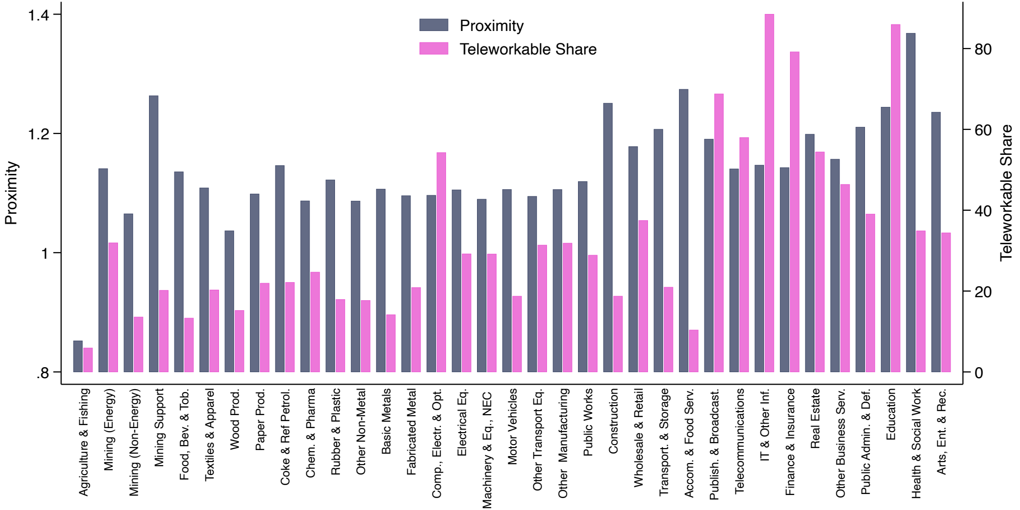
$$\beta_i = \beta_0 \text{Prox}_i \qquad \text{for} \quad i = 1, \ldots, K$$

- Population weighted average of all βs (on-site workers can be infected at-home and on-site).

$$\beta_0 \frac{N_0}{N} + \sum_{i=1}^{K} (\beta_0 + \beta_i) \frac{N_i}{N} = \beta$$

$$\beta_0 = \beta \left(1 + \sum_{i=1}^{K} \frac{\text{Prox}_i N_i}{N} \right)^{-1}$$

Sector Specific Infection Increases with Proximity



Evolution of Pandemic with Sectoral Heterogeneity

- $S_{i,t}$, $I_{i,t}$ and $R_{i,t}$: number of susceptible, infected and recovered individuals in sector i ($N_i = S_{i,t} + I_{i,t} + R_{i,t}$).
- Initial $I_{i,t=0} = \frac{N_i}{N} I_{t=0}, S_{i,t=0} = \frac{N_i}{N} S_{t=0}, R_{i,t=0} = \frac{N_i}{N} R_{t=0}$
- For at-home group:

$$\Delta S_{0,t} = -\beta_0 S_{0,t-1} \frac{I_{t-1}}{N}$$

- On-site workers in industry i, can be infected at work or with general public:

$$\Delta S_{i,t} = -\beta_i S_{i,t-1} \frac{I_{i,t-1}}{N_i} - \beta_0 S_{i,t-1} \frac{I_{t-1}}{N}$$

- Recovery rate is the same for all groups:

$$\Delta R_{i,t} = \gamma I_{i,t-1}$$

- Number of Infected in each group changes with:

$$\Delta I_{i,t} = -\left(\Delta R_{i,t} + \Delta S_{i,t}\right)$$

SIR with Sectoral Heterogeneity

Evolution of infections in the extended multi-sector SIR model can be written as

$$\Delta \mathcal{I}_t = F \mathcal{I}_{t-1} - \gamma \, \mathbb{I}_{\mathbb{K}} \, \mathcal{I}_{t-1}$$

where $\mathcal{I}_t = (I_{0,t}, I_{1,t}, \ldots, I_{i,t}, \ldots, I_{K,t})'$ together with

$$F = \begin{bmatrix} \beta_0 \frac{S_{0,t-1}}{N} & \beta_0 \frac{S_{0,t-1}}{N} & \cdots & \cdots & \beta_0 \frac{S_{0,t-1}}{N} & \beta_0 \frac{S_{0,t-1}}{N} \\ \beta_0 \frac{S_{1,t-1}}{N} & \beta_0 \frac{S_{1,t-1}}{N} + \beta_1 \frac{S_{1,t-1}}{N_1} & \beta_0 \frac{S_{1,t-1}}{N} & \cdots & \cdots & \beta_0 \frac{S_{1,t-1}}{N} \\ \beta_0 \frac{S_{2,t-1}}{N} & \beta_0 \frac{S_{2,t-1}}{N} & \beta_0 \frac{S_{1,t-1}}{N} + \beta_1 \frac{S_{1,t-1}}{N_2} & \beta_0 \frac{S_{2,t-1}}{N} & \cdots & \beta_0 \frac{S_{2,t-1}}{N} \\ \vdots & \vdots & & \ddots & & \vdots \\ \vdots & \vdots & & & \ddots & \vdots \\ \beta_0 \frac{S_{K,t-1}}{N} & \beta_0 \frac{S_{K,t-1}}{N} & \cdots & \cdots & & \beta_0 \frac{S_{K,t-1}}{N} + \beta_K \frac{S_{K,t-1}}{N_K} \end{bmatrix}$$

Production

Production Structure: Leontief

- Barrot and Sauvagnat (2016): CD breaks down in the SR (difficult to substitute among inputs or among different suppliers)

- Leontief production function is in line with the 66-sector input-output model of Baqaee and Farhi (2020a,b) with an elasticity of substitution among inputs that is 0
  $\Rightarrow$ Atalay (2017), Boehm et al. (2019, 2021)

- Our 65-country and 35-sector framework allows for all non-linearities and substitution within very narrow 4-6 digit sectors.

$$Y_{ci} = f(L_{ci}, \{Z_{j,ci}\}_{j \in \mathscr{S}_{ci}})$$

For country c, industry i: inputs from industry j can be from c or imported internationally.

Production Under COVID with Labor Supply Shock

- During the pandemic, on-site workers and teleworkable workers have different infection dynamics:

$$L'_{ci} = \underbrace{(N_{ci} - I_{ci})}_{\text{On-site non-infected}} + TW_i \underbrace{\times \left(1 - \frac{I_{c0}}{N_{c0}}\right)}_{\text{At-home non-infected share}} .$$

- The output in country c in industry i declines by $\hat{Y}_{ci}$, relative to pre-pandemic level:

$$\hat{Y}_{ci} \equiv \frac{Y'_{ci}}{Y_{ci}} = \min \left\{ \hat{L}_{ci}, \left\{ \hat{Z}_{j,ci} \right\}_{j \in \mathscr{S}_{ci}} \right\}.$$

- We map this equation to data.

Demand

Sector Demand Profiles

- Normal times consumption expenditure: From national accounts.
- Peak of pandemic consumption: Credit card purchases by sector.
- Consumption switch between these two extremes, as a function of infection rates.
- Cobb-Douglass utility function, as a function of expenditure (e_i):

$$U(e_1, \ldots, e_K) = \prod_{i=1}^{K} e_i^{\alpha_i},$$

  with $\sum_{i=1}^{K} \alpha_i = 1$ and $0 < \alpha_i < 1$ for all $i = 1, \ldots, K$.

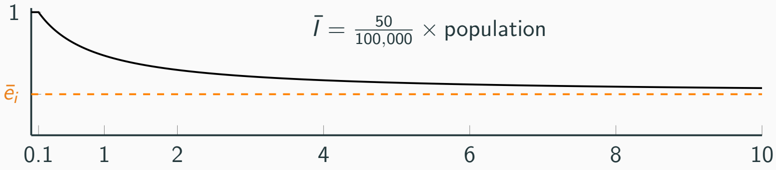
- Total income (w) equals total expenditure, i.e., $w = \sum_{i=1}^{K} e_i$ and $e_i = \alpha_i w$ for $i = 1, \ldots, K$ due to Cobb-Douglass utility function.

Changes in Demand During Pandemic

- During pandemic expenditure change in industry i in country c is a function of infection level I:

$$\hat{e}_i(I \,/\, \bar{I}) \equiv \frac{e_i'(I \,/\, \bar{I})}{e_i}$$

- $\bar{I}$ is proportional to the population and normalizes the infection numbers.



- For large I, which corresponds to the peak of the pandemic, $\lim_{I\to\infty} \hat{e}_i(I \,/\, \bar{I}) \equiv \bar{e}_i$.
- $\bar{e}_i$: **pinned down with credit card data.**

Changes in final good during pandemic.

- Introduce country heterogeneity: e_{mi} (m stands for importer).
- Consumers in country m can consume both domestic and imported goods in industry i. Denote goods in industry i coming from any country c to be consumed in m by $e_{mi,c}$.

$$e_{mi} = \sum_{c} e_{mi,c}$$

- Hence, the output of industry i of country c that is consumed as the final good is:

$$F_{ci} = \sum_{m} e_{mi,c}$$

- During pandemic, the demand drops in country m by $\hat{e}_i(I_m \,/\, \bar{I}_m)$ and the final good consumption of industry i of country c changes to:

$$F'_{ci} = \sum_{m} e_{mi,c} \hat{e}_i(I_m \,/\, \bar{I}_m)$$

Output to Satisfy Demand

- Output to satisfy the final demand (Leontief Inverse):

$$Y = (\mathrm{I} - \mathrm{A})^{-1} F$$

- Change in output:

$$\hat{Y} = \frac{(\mathrm{I} - \mathrm{A})^{-1} F'(I)}{(\mathrm{I} - \mathrm{A})^{-1} F}$$

- Constrained equilibrium:

$$\hat{Y}^{\mathrm{EQ}} = \min\left(\hat{Y}^{\mathrm{Supply}}, \hat{Y}^{\mathrm{Demand}}\right)$$

Data and Calibration

SIR Parameters

- We use time varying country specific infection rates, β_c (Cakmakli and Simsek, 2020).
- We set the rate of recovery/resolved as $\gamma = 0.07$,

  Essentially implies 14 days for the duration of recovery.

- We set the basic reproduction rates using $R_{0,c} = \frac{\beta_c}{\gamma}$ for each country.
- Endogenous Lockdowns when ICU capacity is reached: 14 days of lockdowns with $\beta_c = 0$.
- Infection dynamics after Lockdowns: β_c gradually increases to pre-lockdown level.

SIR with Sectoral Heterogeneity

- Teleworkable occupations from Dingel and Neiman (2020).
    - Based on task descriptions. Not based on physical proximity.
- Occupation level proximity requirements from O*NET.
    (1) I don't work near other people (beyond 100 ft.);
    (2) I work with others but not closely (e.g., private office)
    (3) Slightly close (e.g., shared office);
    (4) Moderately close (at arm's length);
    (5) Very close (near touching).
- Occupation level information converted to industry level using Occupational Employment Statistics.
- Employment by sector data from OECD's Trade in employment (TiM) database.
- ICU data from WHO/JHU.

Global Trade and Production Network

- OECD Inter-Country Input-Output (ICIO) Tables.
- ICIO provides us with input usages of industry i in country c from any industry in any country.

  $\Rightarrow$ Combines I-O structural links with exports and imports
- 35 industries in 65 countries, giving us a matrix of 2275×2275 entries.

Economic Losses Change Under Different Scenarios of Vaccinations and Lockdowns, Depending on the Channel of Amplification

Health Shock is amplified via I-O Linkages

How much global and local amplification can we get from the health shock, affecting demand and labor supply in a given country through I-O links?

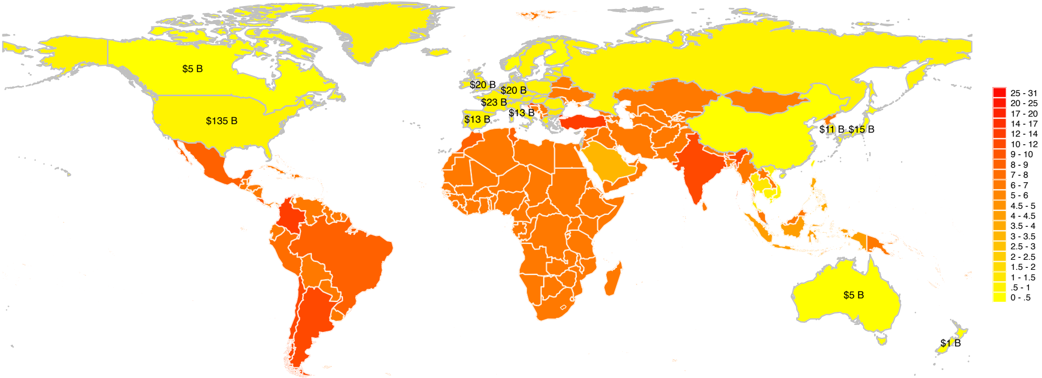
Specification	Demand ↓ Domestic and Foreign	Intermediate Inputs ↓ Domestic and Foreign	Health Shock Amplification
NO IPN	Yes	No	Labor
IPN	Yes	Yes	Amplification via Inter-country / Inter-industry I-O

Vaccination eliminates the labor supply shock and normalizes demand

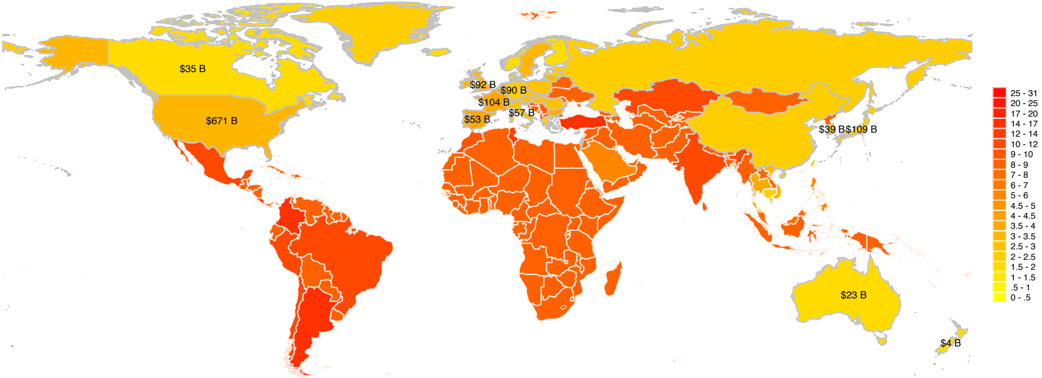
Total Cost for the World, AEs and EMDEs in terms of 2019 USD (billions)

AEs:	Immediate Full Vaccination		Immediate Full Vaccination		Full Vaccination by mid-2021	
EMDEs:	No Vaccination		No Vaccination		Half Vaccination by end-2021	
Lockdowns:	No Lockdowns		Endogenous Lockdowns		Endogenous Lockdowns	
	No IPN	**IPN**	**No IPN**	**IPN**	**No IPN**	**IPN**
	(a)	(b)	(a)	(b)	(a)	(b)
(1) World	2,946	4,273	1,479	6,144	1,844	3,763
(2) AEs	509	1,589	204	2,584	399	1,855
(3) EMDEs	2,437	2,685	1,275	3,561	1,445	1,908
(4) Share of AEs (%)	17.3	37.2	13.8	42.0	**21.7**	**49.3**
			Relative Declines			
(5) World	3.81	5.53	1.91	7.94	2.38	4.87
(6) AEs	0.75	2.33	0.30	3.79	**0.59**	**2.72**
(7) EMDEs	12.06	13.29	6.31	17.62	7.15	9.44

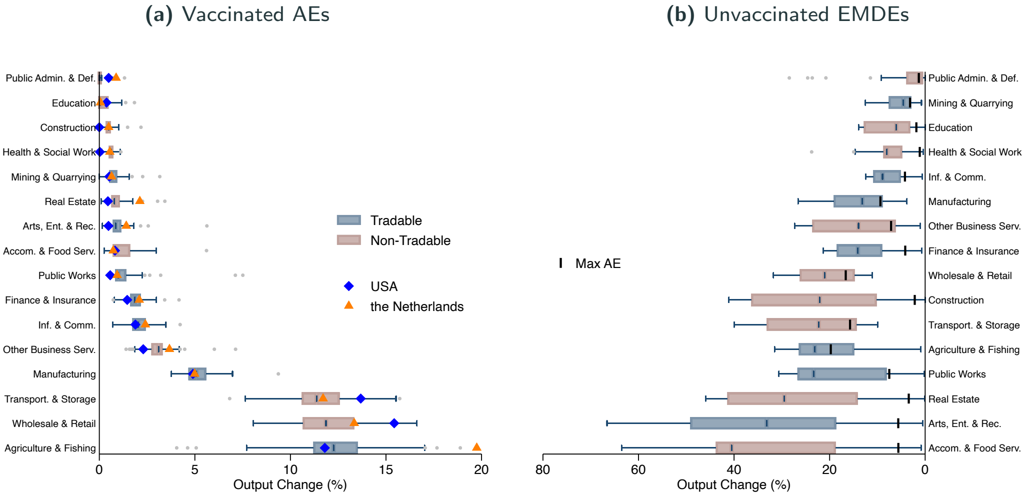
Losses (% GDP): No Amplification via International Production Network



Losses (% GDP): Full Amplification



Country-Sector Heterogeneity in Economic Costs under Inequitable Vaccinations: The Amplification Role of Global Trade/Production Network

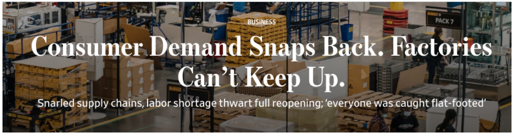


Potential 2021 Supply Chain Disruptions

Recently in the News...

(a) Feb. 22, 2021

THE WALL STREET JOURNAL.



(b) Jan. 9, 2021

THE WALL STREET JOURNAL.

Home World U.S. Politics Economy **Business** Tech Markets Opinion Life & Arts Real Estate WSJ. Magazine

(c) Jan. 28, 2021

FINANCIAL TIMES

Carmakers braced for prolonged chip shortage

Executives warn supply is unlikely to meet demand in the first half of the year

(d) Mar. 1, 2021

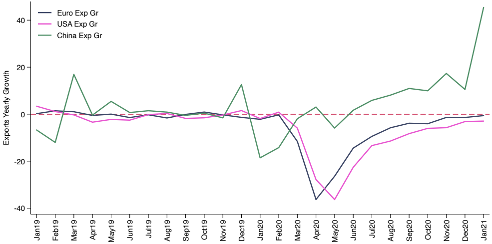
REUTERS

HEALTH JANUARY 28, 2021 / 12:19 PM / UPDATED A MONTH AGO

Taiwan asks Germany to help obtain coronavirus vaccines

Observed Changes in Aggregate Trade (Source: CPB)

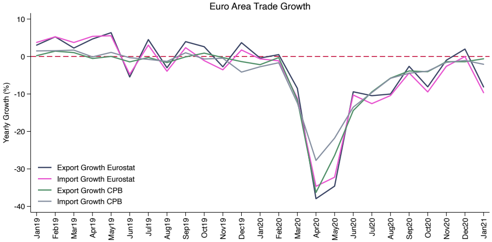
(a) Growths in Exports



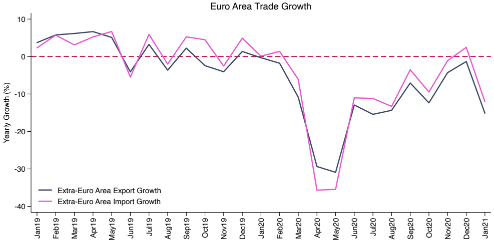
(b) Growths in Imports

Euro Area Trade: CPB vs. Eurostat

(a) All Euro Area Trade



(b) Euro Area Trade with External Countries



Inventories during Pandemic

- During normal times (no supply shock), inventory investment is procyclical:

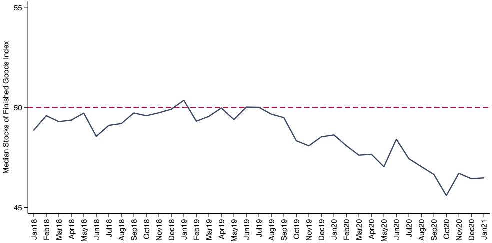
$$\text{Strong Demand} \quad \Rightarrow \text{Inventories} \quad \Uparrow$$
$$\text{Weak Demand} \quad \Rightarrow \text{Inventories} \quad \Downarrow$$

- During the pandemic (supply is constrained), inventory investment is counter-cylical (demand - supply matters):

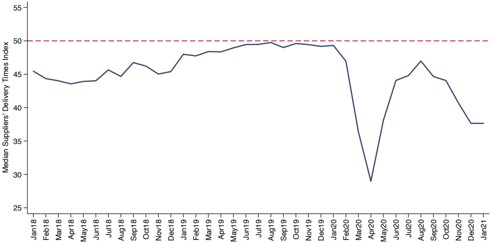
$$\text{Strong Demand} \quad \Rightarrow \text{Inventories} \quad \Downarrow$$
$$\text{Weak Demand} \quad \Rightarrow \text{Inventories} \quad \Uparrow$$

Inventories decline during pandemic: PMI Data

(a) Stocks of Finished Goods Index



(b) Suppliers' Delivery Times Index



Possible Supply Chain Disruptions - PMI Data, 2014M1—2020M12

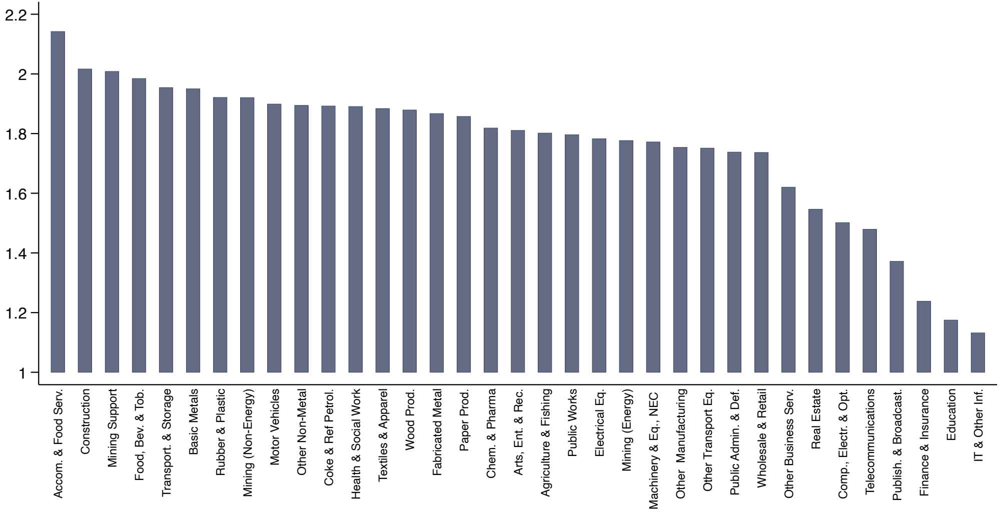
	(1) Inventories	(2) Inventories	(3) Inventories	(4) Inventories
Demand: New Orders$_{ct}$	0.11**	0.13**	0.11**	
	(0.05)	(0.05)	(0.05)	
Demand-Supply: Backlogs$_{ct}$				0.11*
				(0.06)
COVID19$_{t}$	-2.00***	7.22**	5.52	9.24**
	(0.46)	(3.32)	(4.26)	(4.21)
COVID19 x Demand$_{ct}$		-0.18**	-0.15*	
		(0.07)	(0.08)	
COVID19 x Demand-Supply$_{ct}$				-0.23**
				(0.08)
Country FE	No	No	Yes	Yes
Observations	1,881	1,881	1,881	1798
R-squared	0.10	0.12	0.30	0.23

Conclusion

- We demonstrated the economic case for global vaccinations on top of the moral case.
- Global costs can vary from 1 to 6 trillion, where AEs bear from 13 to 49 percent: hope for the best, prepare for the worst.
- Our results rely on the fact that no economy is an island and connected to global trade and finance through complex international linkages.
- The potential loss to advanced economies GDP (even-if they achieve universal inoculation) can be larger than the investment needed in global vaccination initiatives such as COVAX. Such investments now is in the best interest of the advanced economies.
- Given the extent of globalization, no economy fully recovers until every economy recovers, and hence a multilateral approach is a "must" to solve the pandemic.

APPENDIX

Sector Specific Effective Infection Rate



Total Cost for the World, AEs and EMDEs in terms of 2019 USD (billions)

AEs:	**Immediate Full Vaccination**			**Immediate Full Vaccination**			**Full Vaccination by mid-2021**		
EMDEs:	**No Vaccination**			**No Vaccination**			**Half Vaccination by end-2021**		
Lockdowns:	**No Lockdowns**			**Endogenous Lockdowns**			**Endogenous Lockdowns**		
	Spec. 1	**Spec. 2**	**Spec. 3**	**Spec. 1**	**Spec. 2**	**Spec. 3**	**Spec. 1**	**Spec. 2**	**Spec. 3**
	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)
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(7) EMDEs	12.06	12.99	13.29	6.31	14.89	17.62	7.15	8.89	9.44

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		(1) Inventories	(2) Inventories	(3) Inventories	(4) Inventories	(5) Inventories
1	Demand-Supply Proxy: Backlogs_{ct}	0.08	0.11*	0.11*	0.08	0.06
		(0.05)	(0.06)	(0.06)	(0.06)	(0.06)
2	COVID19_t	-2.07***	11.19***	9.24**	21.65	16.41
		(0.47)	(3.70)	(4.21)	(27.38)	(27.94)
3	COVID19 x Backlogs_{ct}		-0.27***	-0.23**	-0.19***	-0.16**
			(0.07)	(0.08)	(0.06)	(0.07)
4	Consumer Confidence_{ct}				0.24*	0.28***
					(0.13)	(0.09)
5	COVID19 x Consumer Conf._{ct}				-0.14	-0.10
					(0.27)	(0.27)
	Country FE	No	No	Yes	No	Yes
	Observations	1,798	1,798	1,798	1,632	1,632
	R-squared	0.06	0.09	0.23	0.11	0.24