Inappropriate Technology: Evidence from Global Agriculture

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December 6, 2025

Motivation

- Motivating Question: most R&D is concentrated in a small number of rich countries. How does this shape global disparities in productivity?
  $\rightarrow$ 1st answer: tech can be applied everywhere equally $\rightarrow$ tech diffusion will erode disparities in the long run.
  $\rightarrow$ 2nd answer: new tech are attached to specific conditions and characteristics of production $\rightarrow$ low diffusion $\rightarrow$ disparities in productivity are driven by incentives of innovators.
- Case study: The Corn Rootworm is nicknamed the "Billion-Dollar Bug" in the US biotechnology industry for its impact on corn production. Significant R&D effort is devoted to develop genetically modified varieties that are toxic to only Corn Rootworm.
  $\rightarrow$ These tools are precisely engineered to target a pest that is common in the US but not anywhere else, like the Maize StalkBorer that is endemic to sub-Saharan Africa

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  3. To what extent does this force explain the immense cross-country disparities in agricultural productivity?

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  3. To what extent does this force explain the immense cross-country disparities in agricultural productivity?
     Inappropriateness reduces average global agricultural productivity by 58% and explains 15% of global productivity disparities measured by the inter-quartile range.

Data and Measurement

- Background info: CPPs—including viruses, bacteria, fungi, insects, and parasitic plants—are a dominant threat to agricultural productivity. Experts estimate that between 50-80% of global output is lost each year to CPP damage.
- Crop Protection Compendium (CPC): For each species, includes two key pieces of information: CPP's global geographic distribution and all the host species that each pest or pathogen affects.
- The determinants of the cross-sectional distribution of each CPP, according to ecologists, depend on "numerous [and] sometimes idiosyncratic" factors.
    1. While features of the environment, most prominently temperature, affect CPP presence, they often have limited predictive power.
    2. CPP distributions appear unrelated to patterns of trade, travel, or tourism, suggesting that agricultural activity plays a limited role in shaping broad patterns in the cross-sectional distribution of CPPs.

Data and Measurement

African Maize Stalk Borer
Busseola fusca

Affected crops: Maize; Sorghum; Rice; Sugarcane

Western Corn Rootworm
Diabrotica virgifera virgifera

Affected crops: Maize; Millet; Pumpkins; Sunflower; Soybeans

Rice Blast Disease
Magnaporthe oryzae

Affected crops: Barley; Rice; Wheat

Witches' Broom Disease
Moniliophthora perniciosa

Affected crops: Cocoa

Ringspot Virus

Affected crops: Cucumbers; Melons; Papayas; Peas; Pumpkins

Desert Locust
Schistocerca gregaria

Affected crops: Barley; Cassava; Castor; Cotton; Dates; Pigeon Peas; Sesame; Sorghum; Wheat; Maize; Sugarcane

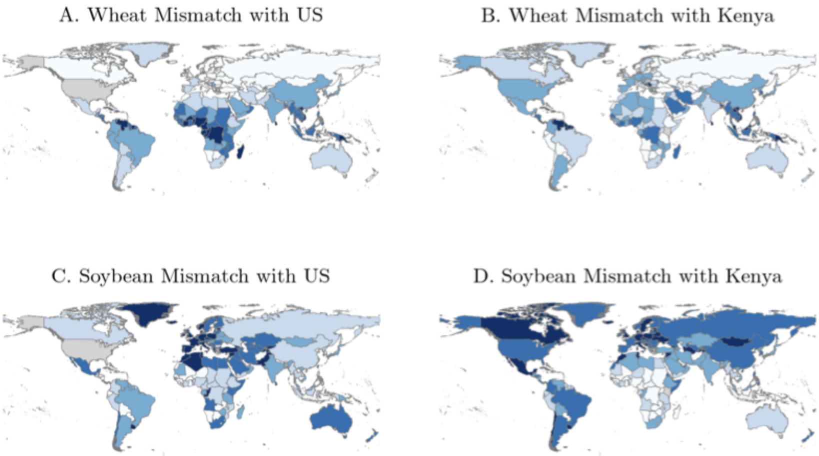
Data and Measurement

- For CPPs affecting crop k in each location l or l', we compute the following measure of CPP mismatch at the location-pair-by-crop level:

$$\text{CPP Mismatch}_{k,l,l'} = 1 - \frac{\text{Number of Common CPPs}_{k,l,l'}}{(\text{Number of CPPs}_{k,l} \times \text{Number of CPPs}_{k,l'})^{1/2}}$$

- This is one of several standard divergence measures in ecological sciences that satisfy basic properties of density invariance, replication invariance, and monotonicity.
- 2 additional strategies to fully purge our measure of inappropriateness of any potential consequences of human activity.
  1. Include eradicated CPPs and remove invasive species.
  2. Also include a measure of predetermined agro-climatic mismatch, which capture differences in other environmental characteristics, like temperature, rainfall, and soil composition.

Data and Measurement



Data and Measurement

- Technology diffusion measurement: UPOV. The data are a comprehensive record of all plant variety certificates in UPOV member countries. Note that crop $\neq$ variety.
- We count the number of varieties of each crop k, newly registered in country l, and originating from country l' . For our main analysis, focus on a static cross-section and sum over all final registrations after 2000.
- Using global patent data, measure technology transfer in the patent data using two complementary strategies:
  1. Patent Family: defines the first issued patent in each family as the focal patent and all subsequently filed patents that are part of the same families as international transfers.
  2. Citations: counts the number of (crop-specific) agricultural patents in a destination that cite agricultural patents from a given origin.
- Data on agricultural output, harvested areas, and yields across crops and countries from the UN FAO statistics database.

Model: Setup

- Set of countries $l \in \{1, ..., L\}$, set of crops $k \in \{1, ..., K\}$, continuum of farms $i \in (0, 1)$ in each country.
- Output of farm i that produces crop k is $(X_{i,k,l})^{1-\gamma}(\theta_{k,l}\omega_{k,l}\varepsilon_{i,k,l})^{\gamma}$, where $X_{i,k,l}$ is agricultural input amount (available at price $q_{k,l}$), $\theta_{k,l}$ is the productivity of that input, $\omega_{k,l}$ is the natural suitability, and $\varepsilon_{i,k,l}$ is an idiosyncratic shock with a Frechet distribution with mean 1 and shape parameter η.
- A set of possible environmental features $\mathcal{T} \subset \{0, 1, 2, ..\}$. Each location-crop pair has a set of features $\mathcal{T}_{k,l} \subset \mathcal{T}$
- Technologies have general characteristic A_k and specific ecological features $(B_{t,k,l})_{t \in \mathcal{T}_{k,l}}$. These components determine the productivity:

$$\theta_{k,l} = \exp(\alpha \log A_k + \frac{1-\alpha}{T} \sum_{t \in \mathcal{T}_{k,l}} \log B_{t,k,l})$$

Model: Innovation

- One innovative technology leader country called L, can produce units of technology at a constant MC normalized to 1.
- Innovation market: innovator markets the technology in each country l, but there are competitive copycats inventors that can replicate the tech at MC $1 \leq C_l \leq \frac{1}{1-\gamma}$
- "iceberg cost" $\rho_l \in [0, 1]$, representing trade costs, licensing, and IP protection, $\rightarrow$ The innovator's profit per unit of technology is:

$$\mu_l = (1 - \rho_l)C_l - 1$$

- Innovator can make costly investment to adapt their technology to each ecological characteristic: if does invest for crop k and characteristic t, $B_{t,k,l} = \bar{B} \geq 1$, otherwise $B_{t,k,l} = \underline{\mathrm{B}} = 1$
- The investment has a fixed cost $\underline{\mathrm{c}}$ if the characteristic is local to the leader country L, and $\bar{c} \geq \underline{\mathrm{c}}$ otherwise.

Model: Equilibrium

- Assume that prices $(p_k)_{k=1}^K$ lie on a global demand curve $(p_k)_{k=1}^K = d((Y_k)_{k=1}^K)$ where Y_k is total production of each crop.
- An equilibrium is a vector of production $(Y_{k,l})$, total input demands $(X_{k,l})$, prices p_k, and CPP technology development $(B_{t,k})$ such that:

  (i) farmers optimize given correct conjectures of prices
  (ii) innovators optimize given correct conjectures of prices, productivities, and local research.
  (iii) markets clear for each crop

The Uneven Focus on Innovation

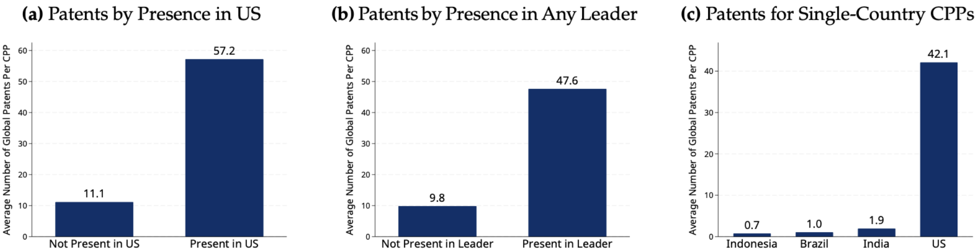
- Simplifying assumption: In equilibrium, technologies are developed *only* for the leader country: $B_{t,k,l} = \bar{B}$ iff $t \in \mathcal{T}_{k,L}$
- Three forces give the innovator incentives to direct research toward the ecological characteristics of the Leader country.
  1. It may be significantly cheaper to research local ecological characteristics versus non-local characteristics.
  2. The Leader market could simply be a larger market: primitively, this could be driven by $\omega_{k,L} \geq \omega_{k,l}, l \neq L$
  3. The leader market may have the largest profit margin, $\mu_{k,L} \geq \mu_{k,l}, l \neq L$. This could arise due to better enforcement of intellectual property (IP) law in L.
- Test for the assumption by estimating the regression:

$$y_{l,p} = \beta \text{Local}_{l,p} + \gamma \text{RevenueOpportunity}_p + \delta_l + \varepsilon_{l,p}$$

where $y_{l,p}$ is a measure of patenting activity related to CPP p by inventors in country l

The Uneven Focus on Innovation

Figure 3: Global Patenting Related to CPPs



The Uneven Focus on Innovation

Table 2: The Direction of Innovation Across CPPs

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Any Technology Development (0/1)				log Technology Development			
Local CPP presence (0/1)	0.0668	0.0575	0.0454	0.0479	0.2281	0.2329	0.0988	0.1807
	(0.0134)	(0.0114)	(0.0096)	(0.0105)	(0.0819)	(0.0714)	(0.0620)	(0.0664)
Global CPP presence (log area weighted)		0.0035	0.0004			0.0312	-0.0186	
		(0.0007)	(0.0002)			(0.0250)	(0.0167)	
Global CPP presence (IP weighted)			0.0014				0.0181	
			(0.0003)				(0.0040)	
Global CPP presence (log GDP weighted)			0.0003				-0.0214	
			(0.0003)				(0.0230)	
Country Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
CPP Fixed Effects	No	No	No	Yes	No	No	No	Yes
Observations	492,422	428,400	428,400	492,422	9,082	8,795	8,795	8,557
R-squared	0.136	0.149	0.154	0.202	0.239	0.243	0.252	0.557

Notes: The unit of observation is a country-CPP pair. In columns 1-4, the outcome variable is an indicator that equals one if there is any patent related to the CPP by an inventor in the country, and in columns 5-8 it is the log number of patents related to the CPP by an inventor in the country. CPPs related to each patent were determined by searching for each CPP scientific name in the titles and abstracts of all patents related to agricultural technology. Country fixed effects are included in all specifications and CPP fixed effects are included in columns 4 and 8. Standard errors are clustered by country.

Mismatch and Technology Diffusion

- Farmers' profit maximization problem $\rightarrow$ demand for input:

$$X_{i,k,l} = (1-\gamma)^{\frac{1}{\gamma}} \theta_{k,l} \omega_{k,l} \varepsilon_{i,k,l} q_{k,l}^{\frac{-1}{\gamma}}$$

- Define ecological mismatch with the leader as the fraction of k-characteristics that are not shared between location l and L: $\delta_{k,l,L} = 1 - \frac{1}{T} |\mathcal{T}_{k,l} \cap \mathcal{T}_{k,L}|$
- Define the total quantity of technology diffusion for crop k to country l: $X_{k,L} = \int_{l-1}^{l} X_{k,i} di$
- **Proposition 1**: Equilibrium technology diffusion from the Leader to country l for crop k can be written as:

$$\log X_{k,L} = -\beta . \delta_{k,l,L} + \chi_{k,l} + \chi_{k,L} + \chi_{l,L}$$

where χ are additive effects, and $\beta \geq 0$ with equality if (i) technology is purely general purpose ($\alpha = 1$) or (ii) innovation is evenly focused ($B_{t,k,l} = \bar{B}$ for all $t \in \mathcal{T}_{k,l}$)

Mismatch and Technology Diffusion

- Estimate the following model at the level of crops k, origin countries l', and destination countries l:

$$\text{Technology Diffusion}_{k,l',l} = \beta.\text{CPP Mismatch}_{k,l',l} + \chi_{l,l'} + \chi_{k,l} + \chi_{k,l'} + \varepsilon_{k,l',l}$$

- The model includes two-way fixed effects at the origin-by-destination, crop-by-origin, and crop-by-destination levels.
- Crop-by-origin fixed effects control for R&D intensity in the origin country.
- Crop-by-destination fixed effects control for current or future market opportunities for innovators, abundance of complementary inputs, and potential barriers to technology adoption.
- Origin-by-destination fixed effects absorb bilateral trade costs and distance, which could affect the transfer of all products or ideas.

Mismatch and Technology Diffusion

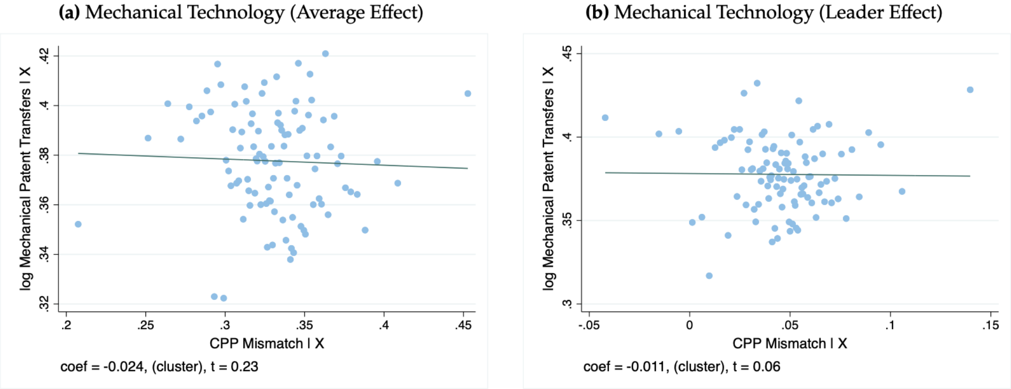
Table 3: CPP Mismatch Inhibits International Technology Transfer

	(1) Any Transfer (0/1)	(2) Total Transfer (Top-coded)	(3) log Total Transfer
	Panel A: Crop Variety Transfers		
CPP Mismatch (0-1)	-0.0275	-0.3148	-1.2018
	(0.0106)	(0.1153)	(0.3861)
Observations	204,287	5,791	5,687,379
R-squared	0.383	0.797	0.625
	Panel B: Patented Technology Transfers		
CPP Mismatch (0-1)	-0.0072	-0.1122	-0.0828
	(0.0017)	(0.0424)	(0.0362)
Observations	5,661,392	5,661,392	80,210
R-squared	0.6254	0.6775	0.9386
	Panel C: Patented Technology Citations		
CPP Mismatch (0-1)	-0.0015	-0.0075	-0.0379
	(0.0006)	(0.0040)	(0.1328)
Observations	5,661,392	5,661,392	10,156
R-squared	0.5167	0.5737	0.9332
Crop-by-Origin Fixed Effects	Yes	Yes	Yes
Crop-by-Destination Fixed Effects	Yes	Yes	Yes
Origin-by-Destination Fixed Effects	Yes	Yes	Yes

Notes: The unit of observation is a crop-origin-destination triplet. All possible two-way fixed effects are included in all specifications. In Panel A, the outcome variable is constructed using variety transfer data from the UPOV database; in Panel B, it is constructed from patent tranfer data using patent family information; and in Panel C, it is constructed from patent citation data using the full citation network of all patented agricultural technologies. CPP mismatch is constructed at the crop-country-pair level as one minus the number of common CPPs normalized by the square root of the product of the number of CPPs in the origin and destination. In column 1, the outcome is an indicator for any transfer; in column 2, it is the total number of transfers, top-coded at the 95th percentile; and in column 3, it is the log of the number of transfers. Standard errors are double-clustered by origin and destination.

Mismatch and Technology Diffusion

Figure 5: Effect of CPP Mismatch on Transfer: Mechanical Technologies



Mismatch and Agricultural Production

- The model predicts that countries produce less of crops for which their local conditions are mismatched with those of the Leader.
- **Proposition 2**: Production of crop k in country l, $Y_{k,l}$, $l > 0$, can be written as:

$$\log Y_{k,l} = -\beta.\delta_{k,l,L} + \chi_k + \chi_l + \eta.\log \omega_{k,l}$$

where $\beta \geq 0$ with equality if (i) technology is purely general purpose ($\alpha = 1$) or (ii) innovation is evenly focused ($B_{t,k,l} = \bar{B}$ for all $t \in \mathcal{T}_{k,l}$)

Mismatch and Agricultural Production

- The estimating equation at the level of crops k and countries l is:

$$\log \text{Production}_{k,l} = \beta.\text{CPP Mismatch Frontier}_{k,l} + \chi_l + \chi_k + \Omega'_{k,l}\Gamma + \epsilon_{k,l}$$

- The outcome is (log) average production from 2000 to 2018 and $\Omega_{k,l}$ is a vector of potential controls. All specifications include country and crop fixed effects.
- CPP Mismatch Frontier$_{k,l}$ measures the extent to which technology developed by R&D leaders is environmentally inappropriate for growing crop k in country l. Given a set $T_N(K)$ of the N top countries for k-variety releases, we calculate:

$$\text{CPP Mismatch Frontier}_{k,l} = \sum_{l' \in T_N(k)} (\text{Share Varieties}^{UPOV}_{k,l'}) \times (\text{CPP Mismatch}_{k,l,l'})$$

- Results also hold when run on state-level data in Brazil and India, thus holding fixed all country-by-crop unobserved and observed characteristics.

Mismatch and Agricultural Production

Table 5: CPP Mismatch Reduces Agricultural Output

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Dependent Variable is log Output							
	CPP Mismatch with Estimated Frontier				CPP Mismatch with the US			
CPP Mismatch (0-1)	-7.136	-5.721	-7.202	-6.288	-9.285	-10.600	-9.325	-8.454
	(0.959)	(0.663)	(0.461)	(0.501)	(1.199)	(3.024)	(0.617)	(0.652)
log(FAO-GAEZ-Predicted Output)		0.353				0.298		
		(0.0499)				(0.0814)		
Included in LASSO Pool:								
Top CPP Fixed Effects	-	-	Yes	Yes	-	-	Yes	Yes
Ecological Features x Crop Fixed Effects	-	-	No	Yes	-	-	No	Yes
Controls in LASSO Pool			335	3935	-	-	335	3935
Crop Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	6,704	2,353	6,707	5,903	6,926	2,353	6,931	6,069
R-squared	0.600	0.609			0.599	0.617		

Notes: The unit of observation is a country-crop pair. Columns 1-4 use CPP mismatch with the estimated set of technological leader countries and columns 5-8 use CPP mismatch with the US. Columns 1-2 and 5-6 report OLS estimates and columns 3-4 and 7-8 report post double LASSO estimates. Country and crop fixed effects are included in all specifications, and included in the amelioration set in the post-double LASSO specifications. The Top CPPs are defined as the top 200 CPPs defined by (i) the number of countries in which they are present and (ii) the number of host crops that they infect. Since the two sets overlap, the total number is 335. The set of ecological features includes: temperature, precipitation, elevation, ruggedness, growing season days, soil acidity, soil clay content, soil silt content, soil coarse fragment volume, and soil water capacity. Standard errors are double-clustered by crop and country.

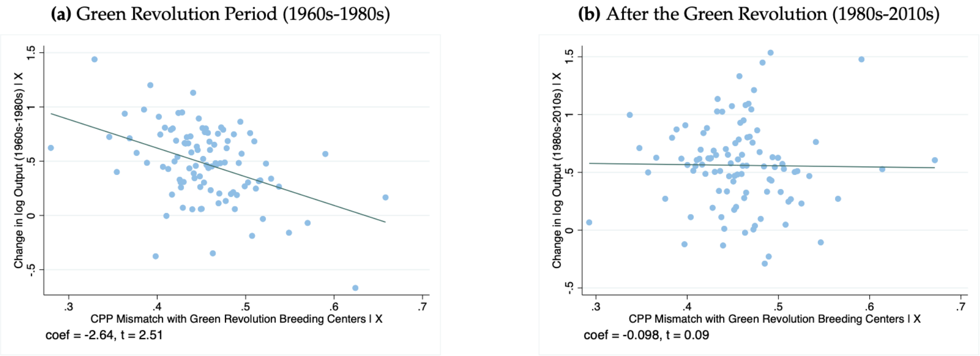
Mismatch and Agricultural Production: Dynamic Estimates

- So far studied the static effect of inappropriateness on production. Now investigate how changes in technological leadership over time influence production,by shifting global patterns of inappropriateness.
- Exploit a natural experiment that significantly shifted the geography of agricultural innovation: the Green Revolution of the 1960s and 1970s.
- The Green Revolution was a coordinated international effort, backed by philanthropic organizations, to develop high-yielding varieties of staple crops for countries with high risk of famine.
- Compute CPP mismatch with centers of Green Revolution breeding centers instead of leader countries and run the regression:

$$\Delta \log y_{k,l}^{80-60} = \beta.\text{CPPMismatchGR}_{k,l} + \tau.\log y_{k,l,1960,s} + \chi_l + \chi_{k,c(l)} + \varepsilon_{k,l}$$

Mismatch and Agricultural Production: Dynamic Estimates

Figure 9: Inappropriateness and the Impact of the Green Revolution



Inappropriate Technology and Productivity

- All else equal, countries that are more ecologically mismatched with the frontier are less productive.
- **Proposition 3**: Agricultural revenue per acre in country l can be written as

$$\log \Xi_l = \chi + \frac{1}{\eta} \log\left(\sum_{k=1}^{K} p_k^{\frac{\eta}{\gamma}} \omega_{k,l}^{\eta} C_l^{-\eta\frac{1-\gamma}{\gamma}} A_k^{\alpha\eta} e^{-\beta\delta_{k,l,L}}\right)$$

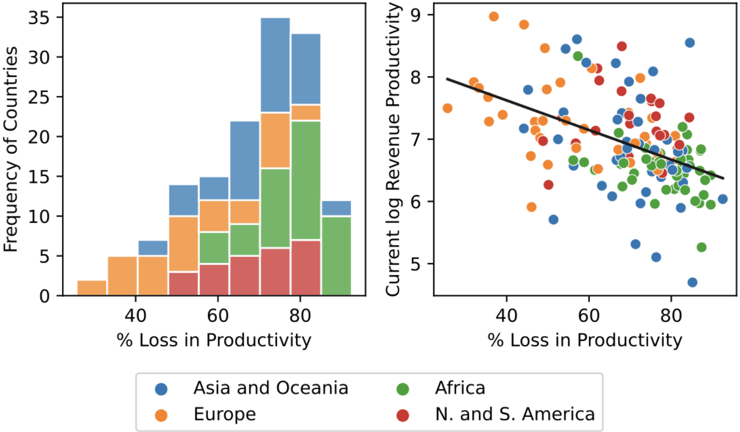
  where χ is a constant that does not depend on k or l.
- To be able to quantify productivity, the authors impose more assumptions on the model + calibration
  1. The Leader country is allowed to be different for each crop $\rightarrow$ better match the data.
  2. Microfound a demand system: assume there is a representative global consumer with its own utility $\rightarrow$ account for equilibrium responses of crop prices.
  3. Calibration from Costinot et al. (2016): $\eta = 2.46$, $\varepsilon = 2.82$ + baseline reduced-form estimate above $\beta = -7.14$

Counterfactual 1: Even Focus of Technology

- Counterfactual 1: global agricultural innovation becomes evenly focused, i.e., innovators invest in R&D for all ecological conditions and $B_{t,k,l} = \bar{B}$ for all $t \in \mathcal{T}_{k,l}$
- Inappropriateness reduces global productivity by 57.7% (SE: 4.85%) and explains 15.1% (SE: 0.42%) of global disparities, as measured by the inter-quartile range of the log productivity distribution.
- The largest losses from inappropriateness are concentrated in Africa and Asia, while the smallest are in Europe.
- Neglected agricultural ecosystems are disproportionately located in unproductive parts of the world.

Counterfactual 1: Even Focus of Technology

Figure 10: The Effects of Inappropriateness on Global Agricultural Productivity

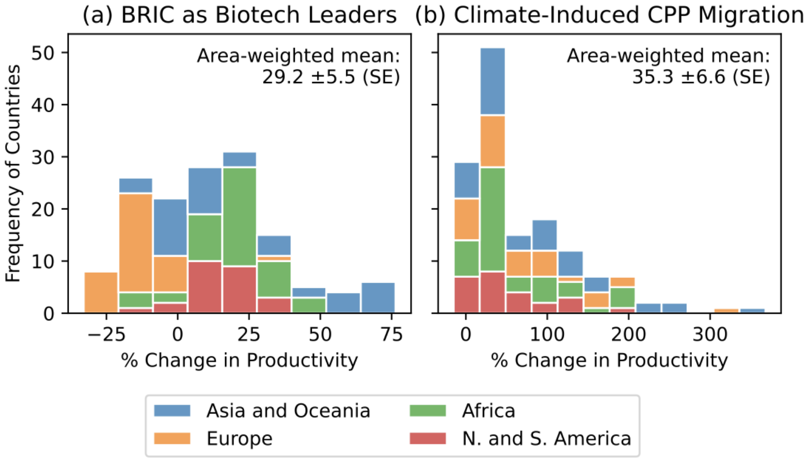


Counterfactual 2: The Rise of New Technology Leaders

- One of the biggest changes to global R&D in the coming decades could be the rise of large emerging economies such as the “BRIC” countries—Brazil, Russia, India, and China.
- Counterfactual 2: set mismatch $\delta_{k,l,L}$ with the leader equal to a (area-weighted average) of mismatch with the BRIC countries. Then compare a world in which BRIC has emerged as new technology leaders to the observed equilibrium.
- The “rise of BRIC”in global biotechnology increases average global productivity by 29.2%, due to the fact that the BRIC countries span more ecological diversity than the existing technological leaders.
- Africa and parts of Asia stand particularly to gain, on average, from this realignment. However, there are also clear losers in Europe and Asia.

Counterfactual 2: The Rise of New Technology Leaders

Figure 11: Counterfactuals: Rise of BRIC and Climate-Induced CPP Migrati



Conclusion and Discussion

- This paper investigates a long-standing hypothesis that global patterns of technology diffusion and productivity are shaped by the uneven focus of innovation.
- Find that agricultural innovation is concentrated on the ecological conditions of technology leaders and that ecological mismatch with these leaders substantially reduces both technology transfer and physical output.
- Estimates do not take into account the heterogeneous costs of conducting R&D in different parts of the world and on different applications. Measuring both private costs and social costs, which may be substantially different in the presence of large research externalities, would be important for designing efficient policy interventions.