Inappropriate Technology: Evidence from Global Agriculture

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August 24, 2022
EEA-ESEM Meeting in Milan

Global R&D is highly concentrated in the rich world

25% of total R&D in the US vs. 3.6% in Africa and South Asia combined (US NSF, 2020)

Two opposing interpretations:

1. Ideas are broadly applicable and spread around the world from innovating countries

2. Technology is context specific and inappropriate in places dissimilar from frontier countries
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This paper: investigates the inappropriate technology hypothesis in global agriculture

European Maize Borer
Dominant threat: **US, Europe**
Effective GM Variety ✓

Maize Rootworm
Dominant threat: **US**
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Dominant threat: **sub-Saharan Africa**
Effective GM Variety ✗

This Paper: Inappropriate Technology in Global Agriculture

Measurement: potential inappropriateness from dissimilarity of pest/pathogen environment

- Comprehensive pest/pathogen-level distribution and host plant data from CABI
- Variation at crop-by-location-pair level

combined with global data on plant variety development and transfer + agricultural production

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Main Results: frontier technology's inappropriateness, driven by pest/pathogen dissimilarity,

- Inhibits international biotechnology transfer and adoption
- Lowers crop-specific output by distorting production choices

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Quantification: estimates, interpreted via model, suggest that

- Inappropriateness increases disparities by 10-15% (IQR of log productivity distribution)
- Consequences depend on: identity of technological leaders (e.g., "rise of BRICs"), ecological trends (e.g., climate-induced pest/pathogen migration)

Related Literature

- **Appropriate technology.** Atkinson and Stiglitz (1969); Salter (1969); David (1975); Stewart (1978); Basu and Weil (1999); Acemoglu and Zilibotti (2001), Caselli and Wilson (2004); Caselli and Coleman II (2006); Jerzmanowski (2007)
- **Technology diffusion.** Griliches (1957); Diamond (1997); Comin and Hobijn (2010); Comin and Mestieri (2018); Keller (2004); Kerr (2008); Costinot, Donaldson, Kyle, and Williams (2019); Kerr (2008); Conley and Udry (2010); Suri (2011); Atkin, Khandelwal, and Osman (2017)
- **Environmental conditions and development.** Montesquieu (1748); Kamarck (1976); Diamond (1997); Sachs and Warner (1997); Bloom and Sachs (1998); Gallup, Sachs, and Mellinger (1999); Sokoloff and Engermann (2000)
- **Disparities in agricultural productivity.** *General*: Caselli (2005); Adamopoulos and Restuccia (2011); Lagakos and Waugh (2013). *Technology focus*: Foster and Rosenzweig (1995, 1996, 2004, 2010); Evenson and Gollin (2003 a,b); Lansing (2009)
- **Neglected tropical (human) diseases.** Hotez et al. (2007, 2009, 2010); Hotez and Kamath (2009); Kremer (2002); Kremer and Glennerster (2004)

Outline

Pest and Pathogen Data: CABI Crop Pest Compendium

- Crop pest and pathogen (CPP) level information sheets compiled from extensive and collaborative research library (CABI, WB, FAO, USDA, CGIAR)
- Gold-standard for CPP measurement in ecological sciences e.g., Bebber et al. (2013, 2014)

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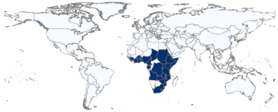
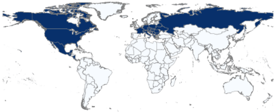
- Global distribution of 4,951 CPPs (viruses, bacteria, insects, fungi, weeds, and protists)

African Maize Stalk Borer
Busseola fusca



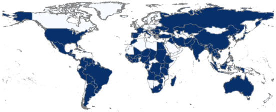
Affected crops: Maize; Sorghum; Rice; Sugarcane

Western Corn Rootworm
Diabrotica virgifera virgifera



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

Rice Blast Disease
Magnaporthe oryzae



Affected crops: Barley; Rice; Wheat

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- CPP-specific host plant lists: 132 host crops

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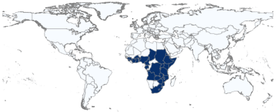

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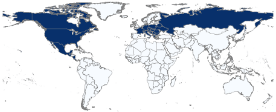

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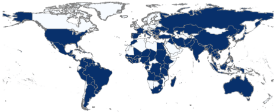

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- Global distribution of 4,951 CPPs (viruses, bacteria, insects, fungi, weeds, and protists)
- CPP-specific host plant lists: 132 host crops
- **Key information**: identity of all CPPs in country ℓ that damage crop k CPP-Level Innovation

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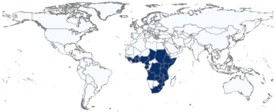

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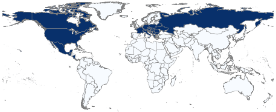

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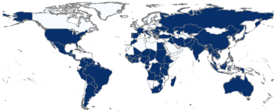

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Measuring CPP Mismatch

- Our measure of potential inappropriateness (crop-by-country-pair):

$$\text{CPPMismatch}_{k,\ell,\ell'} = 1 - \frac{\text{Number of Common CPPs}_{k,\ell,\ell'}}{\left(\text{Number of CPPs}_{k,\ell} \times \text{Number of CPPs}_{k,\ell'}\right)^{1/2}}$$

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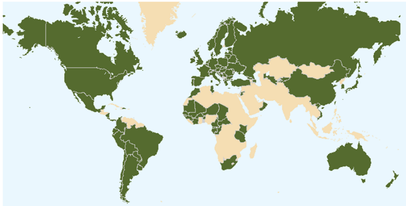
- Alternative measures, discussed in paper, based on...
  - Excluding "potentially invasive" CPPs as categorized by CABI
  - Measuring agro-climatic differences (e.g., temperature)

Global Innovation: UPOV Plant Variety Database



Map: UPOV Member Countries

- Seed certificates from all countries with variety protection
- Collected by the Union for the Protection of New Varieties of Plants (UPOV)
- Proprietary data obtained after UPOV council approval

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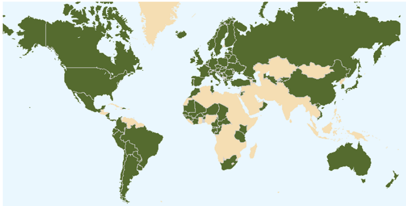

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Key feature: unique crop variety identifiers across countries Details

Outcome: $V_{k,\ell',\ell} =$ varieties of k developed for ℓ' transferred to ℓ since 2000

Direction of Global Innovation

Outline

Empirical Model: Technology Transfer

Crop-by-origin-by-destination estimating equation:

$$V_{k,\ell',\ell} = \beta \cdot \text{CPPMismatch}_{k,\ell,\ell'} + \chi_{\ell,\ell'} + \chi_{k,\ell} + \chi_{k,\ell'} + \epsilon_{k,\ell,\ell'} \quad (1)$$

- $V_{k,\ell',\ell}$ = transferred k-varieties from ℓ' to ℓ
- Fixed effects: Crop-by-origin, crop-by-destination, origin-by-destination
- *Model interpretation* in paper: absorb market size (origin, destination), bilateral trade cost

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Main hypothesis: $\beta < 0$, local focus and context specificity depresses technology diffusion

$\beta = 0$ if the context-specific component of technology

Inappropriateness Impedes Technology Transfer

Sensitivity Invasive Africa Agro-climatic

	(1)	(2)	(3)
Dependent Variable:	Biotech Transfer (asinh)	Any Biotech Transfer (0/1)	log Biotech Transfer
CPP Mismatch (0-1)	-0.0624**	-0.0275**	-1.202***
	(0.0235)	(0.0106)	(0.386)
Crop-by-Origin Fixed Effects	Yes	Yes	Yes
Crop-by-Destination Fixed Effects	Yes	Yes	Yes
Origin-by-Destination Fixed Effects	Yes	Yes	Yes
Observations	204,287	204,287	5,791
R-squared	0.439	0.383	0.797

Notes: The unit of observation is a crop-origin-destination. All possible two-way fixed effects are included in all specifications. The dependent variable is listed at the top of each column. Standard errors are double-clustered by origin and destination and *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Does Mismatch with Frontier Matter More?

Defining the Frontier, $L_{k,\ell'}$:

- Identify a set of crop-specific leaders $T_N(k)$ using the UPOV data, comprised of N countries with most variety development ($L_{k,\ell'} = \mathbb{I}\{\ell' \in T_N(k)\}$)

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Augmented estimating equation:

$$y_{k,\ell,\ell'} = \beta_1 \cdot \text{CPPMismatch}_{k,\ell,\ell'} + \beta_2 \cdot L_{k,\ell'} \times \text{CPPMismatch}_{k,\ell,\ell'} + \chi_{\ell,\ell'} + \chi_{k,\ell} + \chi_{k,\ell'} + \epsilon_{k,\ell,\ell'} \quad (2)$$

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Interpretation: $\beta_2 < 0$ means effects driven by dissimilarity to technological leaders

Does Mismatch with Frontier Matter More? Yes

	(1)	(2)	(3)
	Dependent Variable is (asinh) Biotech Transfers		
Frontier defined as:	Top Variety Developer	Top 2 Variety Developers	Top 3 Variety Developers
CPP Mismatch (0-1)	-0.0229**	-0.0181*	-0.0136
	(0.00986)	(0.00917)	(0.00884)
CPP Mismatch (0-1) x Frontier (0/1)	-0.332***	-0.343***	-0.322***
	(0.0699)	(0.0623)	(0.0535)
Crop-by-Origin Fixed Effects	Yes	Yes	Yes
Crop-by-Destination Fixed Effects	Yes	Yes	Yes
Country Pair Fixed Effects	Yes	Yes	Yes
Observations	204,287	204,287	204,287
R-squared	0.384	0.385	0.385

Notes: The unit of observation is a crop-origin-destination. The definition of a leader in each secification is noted at the to of each column and the dependent variable is noted in the panel heading. Standard errors are double-clustered by origin and destination and *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Outline

Empirical Model: Agricultural Output

Crop-by-country estimating equation:

$$\log \text{Output}_{k,\ell} = \beta \cdot \text{CPPMismatchFrontier}_{k,\ell} + \chi_k + \chi_\ell + \Omega'_{k\ell}\Gamma + \epsilon_{k,\ell} \quad (3)$$

where $\text{CPPMismatchFrontier}_{k,\ell}$ is (technology weighted) CPP mismatch with the frontier set:

$$\text{CPPMismatchFrontier}_{k,\ell} = \sum_{\ell' \in T_N(k)} \left(\text{Share Varieties}^{\text{UPOV}}_{k,\ell'}\right) \times \left(\text{CPPMismatch}_{k,\ell,\ell'}\right)$$

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Controls, derived from model, are

- **Absorbed effects**: Aggregate differences across crops (χ_k) and countries (χ_ℓ)
- **Measures of innate suitability** ($\Omega'_{k\ell}$):
    1. Predicted output from agronomic models (FAO GAEZ)
    2. Flexible controls for geography and CPP presence selected by post-double LASSO

Inappropriateness ⇒ Lower Output

Mismatch Metrics · Agro-climatic · Areas · Mismatch with US · Invasive

	(1)	(2)	(3)	(4)
	Dependent Variable is log Output			
CPP Mismatch (0-1)	-7.136***	-5.721***	-7.202***	-6.288***
	(0.959)	(0.663)	(0.461)	(0.501)
log(FAO-GAEZ-Predicted Output)		0.353***		
		(0.0499)		
Included in LASSO Pool:				
Top CPP Fixed Effects	-	-	Yes	Yes
Ecological Features x Crop Fixed Effects	-	-	No	Yes
Controls in LASSO Pool			335	3935
Crop Fixed Effects	Yes	Yes	Yes	Yes
Country Fixed Effects	Yes	Yes	Yes	Yes
Observations	6,704	2,353	6,707	5,903
R-squared	0.600	0.609		

Notes: The unit of observation is a country-crop pair. Columns 1-2 report OLS estimates and columns 3-4 report post double LASSO estimates. The set of ecological features includes: temperature, precipitation, elevation, ruggedness, growng 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 and *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Inappropriateness and Output: Sensitivity and Additional Results Adoption

Sensitivity Analysis:

- Falsification tests using CPP mismatch non-technology leader countries Link
- Additional controls and robustness FE Controls

Additional Results:

- Within-country estimates from Brazil and India Link
- Additional outcomes, including exports (↓) and price volatility (↑) Link
- Effects on technology adoption using farm-level micro-data from eight African countries sub-Saharan Africa Link

Effect of Changes in Technological Leadership:

- The impact of US biotech's rise on *changes* in global specialization (1990-2020) Link
- The impact of the Green Revolution on *changes* in modern variety adoption and agricultural output (1960-1980) Link

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The Effects of Inappropriateness: Present and Future

Results so far: effects of inappropriateness in current equilibrium
Natural question: what about other scenarios? e.g.,

- "No inappropriateness," to highlight magnitudes at stake
- Different technological leaders or global ecology, to model ongoing changes to the world

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- External estimate of elasticity of supply
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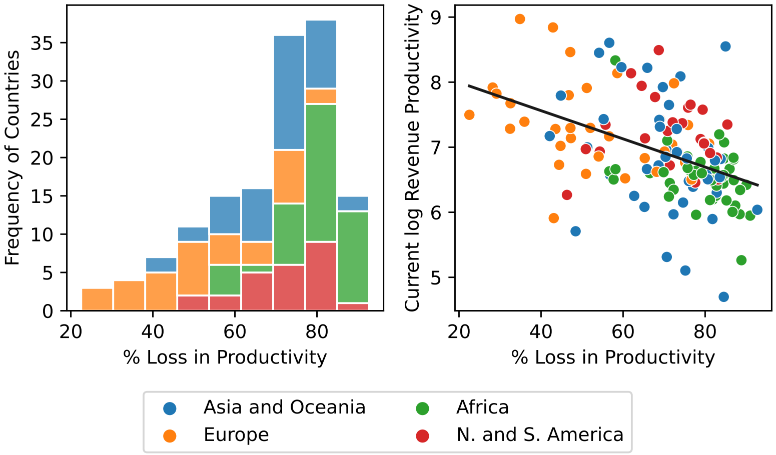
Total Effects: Productivity and Disparities

Sensitivity | Non-CPP Mismatch

Level Effect: **57.9%**
Units: % Reduction



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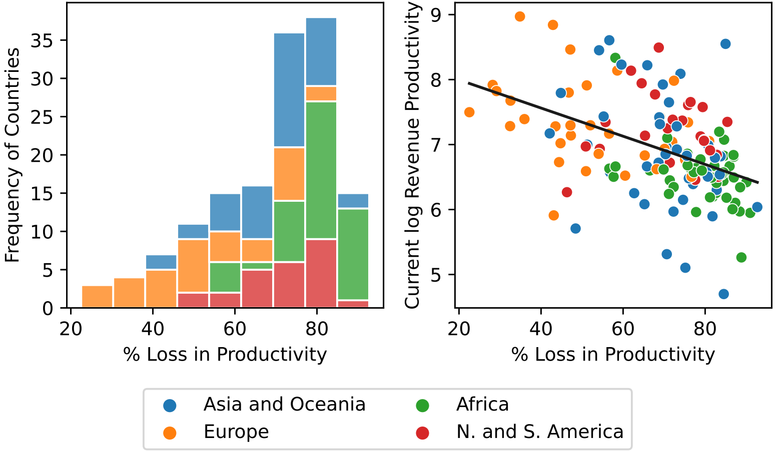
Disparity Effect: **14.4%**
Units: % Increase in IQR of log productivity



Applications and "Real-World" Counterfactuals

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Crop-level estimates of "best" countries suggest targeting China, India and parts of Africa

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   Findings suggest $\nearrow$ ecological similarity and hence $\nearrow$ appropriateness of frontier technology

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   Findings suggest $\nearrow$ ecological similarity and hence $\nearrow$ appropriateness of frontier technology

3. **How would the emergence of BRIC (Brazil, Russia, India, and China) as ag-tech leaders reshape world productivity?** Link
   Rise of BRIC increases productivity on average, especially in Africa and Asia

Conclusion

We studied effects of inappropriate technology in agriculture, focusing on mismatch of ecology and plant-specific pests and pathogens

We found empirically that inappropriateness shapes. . .

1 The global transfer of agricultural technology

2 Global agricultural specialization and output

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Future work:

- How could policy address gaps in access to appropriate technology?
- How does climate change affect the appropriateness of agricultural technology and how "globally appropriate" is modern climate-resilient technology?
- How do the lessons from this paper apply to other sectors?

Producers and Technology Demand Details

- Crops $k \in \{1, \ldots, K\}$, with global prices $(p(k))_{k=1}^{K}$
- Locations $\ell \in \{1, \ldots, L\}$, each with farmers $i \in [\ell - 1, \ell)$ and where L is "Leader"

Tractable model of (agricultural) specialization

as in Eaton and Kortum, 2002; Costinot, et al., 2016

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- Farmer $i \in [\ell - 1, \ell)$, growing k, has productivity

$$\psi_{k,i} = \Big(\underbrace{X_{k,i}}_{\text{Technology}} \Big)^{1-\gamma} \Big(\underbrace{\omega_{k,\ell}}_{\text{Suitability}} \times \underbrace{\theta_{k,\ell}}_{\text{Technology Quality}} \times \underbrace{\epsilon_{k,i}}_{\text{Fréchet shock } (\eta)} \Big)^{\gamma}$$

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New: endogenous and locally-tuned technologies

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where $\alpha \in (0, 1)$ and $\mathcal{T}(k, \ell) \subset \mathbb{N}$ are sets of pests and pathogens, normalized to $T > 0$

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Innovators and Technology Supply Back

A representative, profit-maximizing innovator in L, develops technologies Back

- Benefits = revenue from seed sales, net of bilateral frictions $\exp(-\rho_{\ell,L})$
- Costs = convex "research costs" with **local knowledge spillovers**
    - *Knowledge gaps*: more "scientific inputs" for pest/pathogen threats in L Evidence
      Abstractions: Romer (1986). Realities: breeding practices, germplasm, ...

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Definition: Equilibrium

An equilibrium is a vector of production $(Y_{k,\ell})$, total input demands $(X_{k,\ell',\ell})$, prices (p_k), and CPP technology development $(B_{t,k,\ell',\ell})$ such that

1. Farmers optimize, given correct conjectures of prices, and aggregate production and input demand is consistent with a LLN over realized idiosyncratic shocks.
2. Innovators optimize, given correct conjectures of prices and revenue productivities
3. Markets clear for each crop, or $(p_k)_{k=1}^K = d((Y_k)_{k=1}^K)$ where $Y_k = \sum_{\ell=1}^L Y_{k,\ell}$.

Result: Environmental Mismatch and Technology Transfer Back

Mismatch: Let $\delta_{k,\ell,L}$ denote the share of (k,ℓ) pest and pathogen threats *not* present in L

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Proposition: Technology Transfer

Technology diffusion from the leader L to any country ℓ can be written as

$$\log X_{k,L,\ell} = \beta_{k,L} \cdot \delta_{k,L,\ell} + \chi_{k,L} + \chi_{k,\ell} + \chi_{\ell,L}$$

where the χ are additive fixed effects and $\beta_{k,L} \leq 0$, with equality if all technology is context-neutral or there is no knowledge spillover.

Result: Environmental Mismatch and Specialization

Back

Proposition: Production and Specialization

Production of crop k in country ℓ can be written as

$$\log Y_{k,\ell} = \pi_{k,L} \cdot \delta_{k,L,\ell} + \eta \cdot \log \omega_{k,\ell} + \chi_\ell + \chi_k$$

where the χ are additive fixed effects, $\omega_{k,\ell}$ is innate suitability, and $\pi_{k,L} \leq 0$, with equality if all technology is context-neutral or there is no knowledge spillover.

Validation of Premise: Disparities in CPP Innovation Back

- Text analysis matching all global patents (*Patsnap*) to CPPs and inventor countries
- Measure *patents per CPP* for all CPPs and inventor countries

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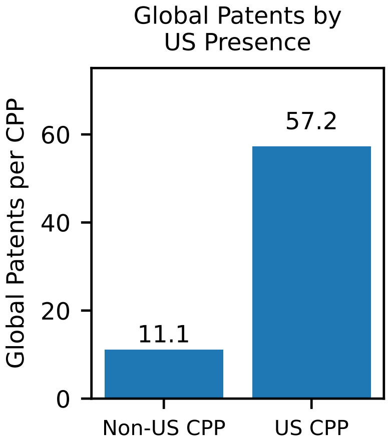
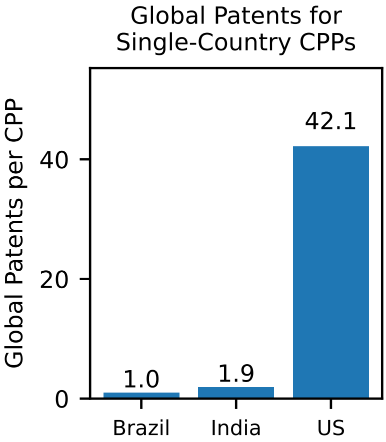




Alternative Metric: Jaccard (1900,1901)

- Robustness using simplest and most historical measure of divergence (Jaccard, 1900,1901):

$$\text{CPPMismatch}^{J}_{k,\ell,\ell'} = 1 - \frac{\text{Number of Common CPPs}_{k,\ell,\ell'}}{\text{Number of Unique CPPs}_{k,\ell\cup\ell'}}$$

- **Simple interpretation**: number of common CPPs divided by number of unique CPPs in the country-pair-by-crop triplet

Back

Intermediate Result: Optimal Planting Back

Frechet structure generates simple relationship between average productivity (unobserved) and planting and technology choices (observed):

Lemma

The measure of farmers planting crop k is given by

$$\log x(\ell, k) = -\eta \log \Phi(\ell, k) + \eta \log \omega(\ell, k) + \eta \log p(k) - \eta \log \Xi(\ell) \quad (4)$$

where $\Phi(\ell, k)$ and $\Xi(\ell)$ are productivity indices:

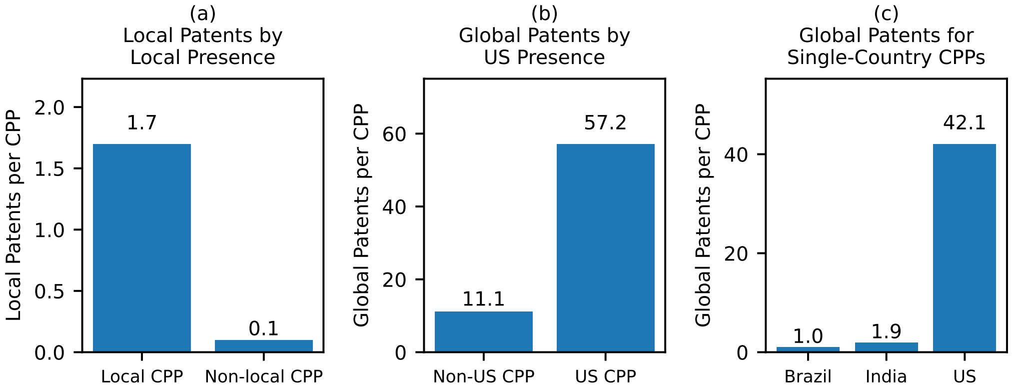
$$\Phi(\ell, k) := \left(\sum_{\ell'} \theta(\ell', k)^{\eta} \delta(\ell, k, \ell')^{-\eta} \right)^{-\frac{1}{\eta}} \qquad \Xi(\ell) := \left(\sum_{k} p(k)^{\eta} \omega(\ell, k)^{\eta} \Phi(\ell, k)^{\eta} \right)^{\frac{1}{\eta}} \quad (5)$$

The measure of farmers in ℓ planting crop k using the technology of ℓ' is given by

$$\log \pi(\ell, k, \ell') = \log x(\ell, k) - \eta \delta(\ell, k, \ell') + \eta \log \theta(\ell', k) + \eta \log p(k) + \eta \log \Phi(\ell, k) \quad (6)$$

Global Focus of CPP Innovation Back

- Text analysis of all global patents (*Patsnap* Database) to patented technologies to CPPs
- 33% of all biological or chemical agricultural patents associated with ≥ 1 CPP in our data



Inappropriateness Impedes Technology Transfer: Sensitivity Back

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Dependent Variable is (asinh) Biotechnology Transfers						
CPP Mismatch (0-1)	-0.0605**	-0.120**	-0.0848***	-0.0509**	-0.0556**	-0.0434**	-0.0486***
	(0.0241)	(0.0481)	(0.0258)	(0.0231)	(0.0222)	(0.0189)	(0.0169)
Jaccard (1900, 1901) Distance Metric		✓					
Broad CPP Presence Classification			✓				
Control for bilateral crop-level trade				✓			
Control for log bilateral distance x Crop FE					✓		
Exclude country pairs <1000km apart						✓	
Exclude country pairs <2000km apart							✓
Mean of CPP Distance Metric	0.423	0.327	0.413	0.423	0.423	0.423	0.423
Crop-by-Origin Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Crop-by-Destination Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country Pair Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	204,287	204,287	204,345	204,287	189,302	185,344	156,007
R-squared	0.439	0.439	0.439	0.442	0.461	0.405	0.372

Notes: The unit of observation is a crop-origin-destination. Specification details are noted at the bottom of each column. Standard errors are double-clustered by origin and destination and *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Robustness to country-level controls

Back

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Dependent Variable is log Output							
	Panel A: CPP Distance to the US							
CPP Distance (0-1)	-9.122***	-8.849***	-9.573***	-9.323***	-9.186***	-9.661***	-10.10***	-10.83***
	(1.152)	(1.105)	(1.217)	(1.345)	(1.221)	(1.316)	(1.295)	(2.115)
Observations	6,915	6,678	6,433	4,949	6,719	6,032	3,729	2,946
R-squared	0.600	0.632	0.612	0.634	0.614	0.626	0.671	0.786
	Panel B: CPP Distance to Estimated Frontier Set							
CPP Distance (0-1)	-6.963***	-6.838***	-7.351***	-7.206***	-6.895***	-7.172***	-7.337***	-7.250***
	(0.934)	(0.879)	(1.029)	(1.065)	(0.980)	(1.011)	(1.058)	(1.743)
Observations	6,693	6,458	6,227	4,765	6,499	5,838	3,631	2,864
R-squared	0.600	0.632	0.611	0.633	0.613	0.623	0.669	0.781
Crop Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
log Per Capita GDP x Crop FE	No	Yes	No	No	No	No	No	Yes
Trade Share (% GDP) x Crop FE	No	No	Yes	No	No	No	No	Yes
Gini Coefficient x Crop FE	No	No	No	Yes	No	No	No	Yes
Share Arable Land x Crop FE	No	No	No	No	Yes	No	No	Yes
log Agricultural Value Added x Crop FE	No	No	No	No	No	Yes	No	Yes
R&D Share (% GDP) x Crop FE	No	No	No	No	No	No	Yes	Yes

Notes: The unit of observation is a crop-country pair. Panel A uses CPP dstance to the US and Panel B uses CPP dstance to the estimated set of technological leader countries. Controls included in each specification are noted at the bottom of the column. Standard errors are double-clustered by crop and country and *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Global Direction of Crop-Specific of Innovation

Back to UPOV

$$\ln(\text{BioTech}_k) = \delta_1 \cdot \ln \text{WrldArea}_k + \delta_2 \cdot \ln \text{GDPArea}_k + \delta_3 \cdot \ln \text{IPArea}_k + \epsilon_k$$

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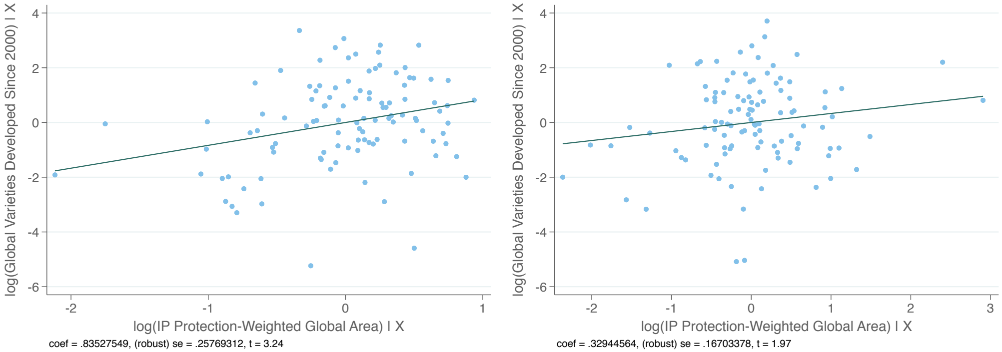


- **Magnitude**: incremental R^2 on second two regressors: 29% (total R^2: 48%) Quantification
- **Mechanism**: combination of home bias and global focus Results

Empirical Model: Home Bias versus Global Focus? Back

$$\ln(\text{BioTech}_{k,\ell}) = \delta_0 \cdot \text{lnArea}_{k,\ell} + \delta_1 \cdot \text{lnWorldArea}_k + \delta_2 \cdot \text{lnGDPArea}_k + \delta_3 \cdot \text{lnIPArea}_k + \chi_\ell + \epsilon_{k,\ell}$$

asinh(Local Area Harvested)	0.227***	0.213***	0.209***	0.204***	0.204***	0.155***
	(0.0125)	(0.00986)	(0.0112)	(0.00977)	(0.00982)	(0.00842)
asinh(Global Area Harvested)		0.0565***	-0.0451	-0.0155	-0.0551	
		(0.0208)	(0.0540)	(0.0310)	(0.0459)	
asinh(Income-Weighted Area Harvested)			0.0925		0.0512	
			(0.0606)		(0.0620)	
asinh(IP-Protection-Weighted Area Harvested)				0.0814***	0.0625*	
				(0.0309)	(0.0369)	
Country Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Crop Fixed Effects	No	No	No	No	No	Yes
Observations	6,758	6,758	6,758	6,758	6,758	6,758
R-squared	0.495	0.501	0.505	0.506	0.507	0.600

Notes: The unit of observation is a crop-by-country pair. The dependent variable is the number of varieties developed in the country for the crop since 2000. Standard errors, clustered by crop, are included in parentheses and *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Measuring International Technology Transfer in UPOV Data

Back

Snapshot of the raw data:

UPOV Code	Country	Denomination	Botanical Name	Common Name	App. Date
GOSSY_HIR	AU	Sicot 53	Gossypium hirsutum	Cotton	14-Sep-99
GOSSY_HIR	AU	Sicot 41	Gossypium hirsutum	Cotton	14-Sep-99
GOSSY_HIR	AR	Sicot 41	Gossypium hirsutum L.	Algodonero	13-Aug-01
GOSSY_HIR	AU	Sicot 71	Gossypium hirsutum	Cotton	07-Aug-02
GOSSY_HIR	BR	Sicot 53	Gossypium hirsutum L.	Algodao	11-Nov-03

Coding:
- SICOT 41: Invented in Australia, transferred to Argentina
- SICOT 53: Invented in Australia, transferred to Brazil
- SICOT 71: Invented in Australia, not transferred

"SICOT": product line produced by Australian "Cotton Seed Distributors." *Includes Bollgard Roundup Ready* ("Bt") *traits*, among other anti-pest traits.

Key outcome: $V(k,\ell', \ell)$ = varieties of k developed in ℓ' transferred to ℓ since 2000.

The US as the Technology Frontier Back

- 52% global private R&D in North America (Fuglie, 2016)
- 46% of global biological and chemical agricultural patents related to CPPs since 2000 (as we measure them) were assigned to US inventors
- Over 3x as many as the next highest country (Japan)
- 25% of global agricultural science publications in 2000; over 30% after citation-weighting

Agro-climatic differences and technology transfer Back Measurement

	(1)	(2)	(3)
	Dependent Variable is (asinh) Biotechnology Transfers		
CPP Mismatch (0-1)	-0.0783**	-0.0737**	-0.0752**
	(0.0314)	(0.0309)	(0.0311)
Mismatch in:			
Temperature		-0.0107*	
		(0.00619)	
Precipitation		-0.0141*	
		(0.00807)	
Elevation		-0.00589*	
		(0.00311)	
Ruggedness		-0.000652	
		(0.00246)	
Soil Clay Content		-0.00596	
		(0.00568)	
Soil Silt Content		0.00342	
		(0.00575)	
Soil Coarse Fragment Content		0.000883	
		(0.00318)	
Soil pH		-0.00825**	
		(0.00355)	
Growing Season Length		-0.00453	
		(0.00519)	
Available Water Capacity		-0.00561	
		(0.00466)	
Overall Agro-Climatic Mismatch			-0.0412***
			(0.0129)
p-value joint significance	-	0.007	-
Crop-by-Origin Fixed Effects	Yes	Yes	Yes
Crop-by-Destination Fixed Effects	Yes	Yes	Yes
Country Pair Fixed Effects	Yes	Yes	Yes
Observations	153,038	153,026	153,038
R-squared	0.464	0.464	0.464

- Estimate "mismatch" at $\ell \times k \times \ell'$ level by calculating the value of each agro-climatic characteristic on k-land from *EarthStat* Database
- For crop k, and countries ℓ and ℓ', the agro-climatic index is:

$$d_{k,\ell,\ell'} := \frac{1}{|\mathcal{X}|} \sum_{x \in \mathcal{X}} |\hat{x}_{k,\ell} - \hat{x}_{k,\ell'}|$$

where $\hat{x}_{k,\ell}$ is measured on the crop-k land of country ℓ

Agro-climatic differences and Output

Back Measurement

	(1)	(2)	(3)
	Dependent Variable is log Output		
CPP Mismatch (0-1)	-10.17***	-8.996***	-9.393***
	(1.559)	(1.425)	(1.518)
Mismatch in:			
Temperature		-0.582***	
		(0.155)	
Precipitation		-0.329*	
		(0.186)	
Elevation		0.150	
		(0.0924)	
Ruggedness		-0.254*	
		(0.135)	
Soil Clay Content		0.0649	
		(0.0969)	
Soil Silt Content		0.0283	
		(0.123)	
Soil Coarse Fragment Content		-0.323**	
		(0.134)	
Soil pH		-0.0720	
		(0.106)	
Growing Season Length		0.0681	
		(0.124)	
Available Water Capacity		-0.255**	
		(0.116)	
Overall Agro-Climatic Mismatch			-1.319***
			(0.285)
	-	0.000	-
Crop Fixed Effects	Yes	Yes	Yes
Country Fixed Effects	Yes	Yes	Yes
Observations	5,285	5,270	5,285
R-squared	0.575	0.591	0.582

- Estimate "mismatch" at $\ell \times k \times \ell'$ level by calculating the value of each agro-climatic characteristic on k-land from *EarthStat* Database
- Determine mismatch with *frontier* as in main results
- For (k, ℓ), the agro-climatic index is:

$$d_{k,\ell,L} := \frac{1}{|\mathcal{X}|} \sum_{x \in \mathcal{X}} |\hat{x}_{k,\ell} - \hat{x}_{k,L}|$$

  where $\hat{x}_{k,\ell}$ is measured on the crop-k land of country ℓ
- **Magnitudes**: standardized coefficient for CPP mismatch is -0.54 and for the agro-climatic index is -0.15.

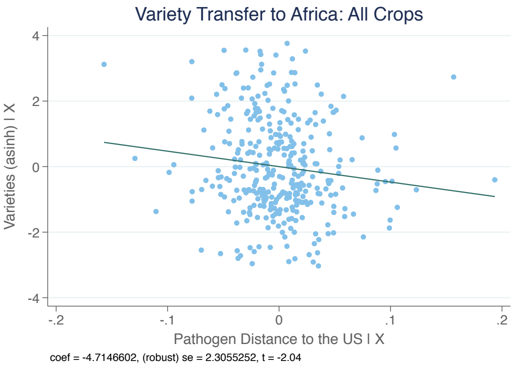
Variety Introduction in Africa Back 1 Back 2

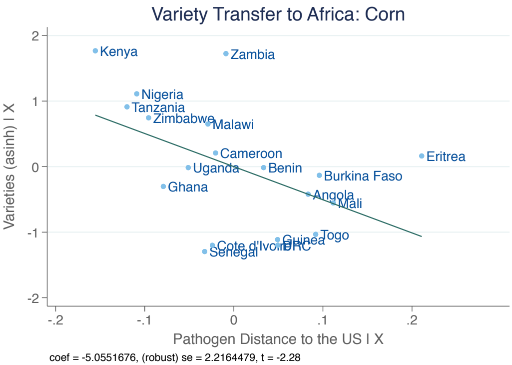
- Most countries in Africa are not UPOV compliant—not in our technology transfer data
- CGIAR's Diffusion and Impact of Improved Varieties in Africa (DIIVA) project collected data on improved crop varieties in Africa south of the Sahara
- For 28 countries and 19 crops provide number of improved varieties introduced since 1960
- Estimating equation for African data:

$$y_{k,\ell} = \beta \cdot \text{CPPDistFrontier}_{k,\ell} + \chi_k + \chi_\ell + \epsilon_{k,\ell} \quad (7)$$

- **Absorbed effects**: Aggregate differences across crops (χ_k) and countries (χ_ℓ)
- **Hypothesis**: $\beta < 0$; in places where tech frontier is "inappropriate," less tech introduced

Inappropriateness $\Longrightarrow$ Less variety introduction in Africa Back





$\beta = -4.71 \;\; (2.31)$
$N = 345$

$\beta = -5.06 \;\; (2.21)$
$N = 19$

Additional Outcomes: Trade and Price Volatility

Back

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Baseline Measure	*Trade*		*Producer Price Volatility*			
Dependent Variable:	log Output	log Exports	log Imports	Price SD (Norm. by Global Mean)		log Price SD	
	Panel A: CPP Mismatch wih the US						
CPP Mismatch (0-1)	-9.285***	-8.768***	1.269	0.523***	0.317***	1.026***	0.671***
	(1.199)	(1.200)	(1.295)	(0.126)	(0.109)	(0.237)	(0.224)
Observations	6,926	5,495	5,854	4,580	4,559	4,580	4,559
R-squared	0.599	0.531	0.647	0.244	0.263	0.661	0.667
	Panel B: CPP Mismatch wih the Estimated Frontier Set						
CPP Mismatch (0-1)	-7.136***	-5.386***	-0.415	0.364***	0.212**	0.628***	0.349**
	(0.959)	(0.877)	(0.871)	(0.101)	(0.0978)	(0.177)	(0.176)
Observations	6,704	5,332	5,687	4,481	4,461	4,481	4,461
R-squared	0.600	0.535	0.649	0.243	0.262	0.662	0.668
Crop Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Control for log Output	No	No	No	No	Yes	No	Yes

Notes: The unit of observation is a crop-country pair. The dependent variable is listed at the top of each column and control set listed at the bottom. Standard errors are double-clustered by crop and country and *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

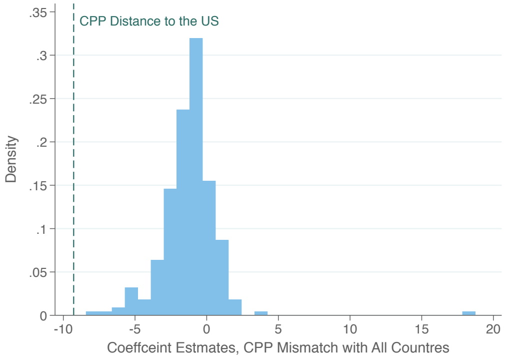
Inappropriateness ⇒ Lower Output: Alternate Mismatch Metrics

Back

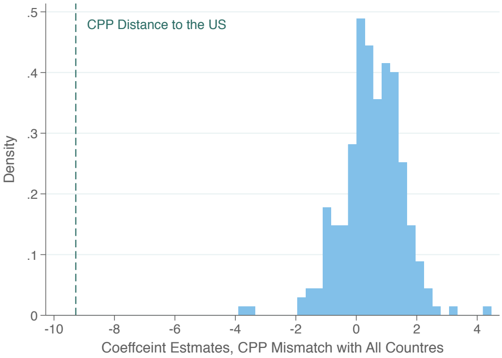
	(1)	(2)	(3)	(4)	(5)	(6)
	Dependent Variable is log Output					
	CPP Distance to US			CPP Dstance to Estimated Frontier Set		
CPP Mismatch (0-1)	-9.122***	-9.336***	-8.480***	-6.963***	-7.483***	-6.653***
	(1.152)	(1.172)	(0.909)	(0.934)	(1.067)	(0.710)
Baseline	✓			✓		
Broad CPP Presence Classification		✓			✓	
Jaccard (1900, 1901) Distance Metric			✓			✓
Crop Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Country Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	6,915	6,915	6,915	6,693	6,693	6,693
R-squared	0.600	0.601	0.604	0.600	0.601	0.603

Notes: The unit of observation is a crop-country pair. The dependent variable s log of crop output and the distance metric used in each specification is noted at the bottom of each column. Columns 1-3 use CPP dstance to the US and columns 4-6 use CPP dstance to the estimated set of technological leader countries. Standard errors are double-clustered by crop and country and *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Falsification: Effect of CPP Mismatch with All Countries Back



(a) Unconditional



(b) Conditional on CPP Mismatch with the US

Inappropriateness ⇒ Lower Output: Crop × Continent FE

Back

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Dependent Variable is log Output							
	CPP Mismatch with the US				CPP Mismatch with the Estimated Frontier			
CPP Mismatch (0-1)	-8.809***	-9.831***	-8.780***	-8.198***	-8.780***	-8.198***	-6.999***	-6.385***
	(1.124)	(2.608)	(0.769)	(0.742)	(0.769)	(0.742)	(0.595)	(0.614)
log(FAO-GAEZ-Predicted Output)		0.239***				0.273***		
		(0.0704)				(0.0770)		
Included in LASSO Pool:								
Top CPP Fixed Effects	-	-	Yes	Yes	-	-	Yes	Yes
Ecological Features x Crop Fixed Effects	-	-	No	Yes	-	-	No	Yes
Crop x Continent Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	6,844	2,334	6,920	6,069	6,631	2,334	6,696	5,903
R-squared	0.680	0.694			0.679	0.689		

Notes: The unit of observation is a country-crop pair. Columns 1-4 use CPP mismatch with the US and columns 5-8 use CPP mismatch with the estimated set of technological leader countries. Columns 1-2 and 5-6 report OLS estimates and columns 3-4 and 7-8 report post double LASSO estimates. Country and crop-by-continent fixed effects are included in all specifications, and included in the amelioration set in thet post-double LASSO specifications. The Top CPPs are defined as the top 200 CPPs defined by (i) the number of countries in whch 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, growng 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 and *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Inappropriateness ⇒ Lower Output: Additional Controls

Back

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Dependent Variable is log Output							
	Panel A: CPP Distance to the US							
CPP Distance (0-1)	-9.122***	-8.849***	-9.573***	-9.323***	-9.186***	-9.661***	-10.10***	-10.83***
	(1.152)	(1.105)	(1.217)	(1.345)	(1.221)	(1.316)	(1.295)	(2.115)
Observations	6,915	6,678	6,433	4,949	6,719	6,032	3,729	2,946
R-squared	0.600	0.632	0.612	0.634	0.614	0.626	0.671	0.786
	Panel B: CPP Distance to Estimated Frontier Set							
CPP Distance (0-1)	-6.963***	-6.838***	-7.351***	-7.206***	-6.895***	-7.172***	-7.337***	-7.250***
	(0.934)	(0.879)	(1.029)	(1.065)	(0.980)	(1.011)	(1.058)	(1.743)
Observations	6,693	6,458	6,227	4,765	6,499	5,838	3,631	2,864
R-squared	0.600	0.632	0.611	0.633	0.613	0.623	0.669	0.781
Crop Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
log Per Capita GDP x Crop FE	No	Yes	No	No	No	No	No	Yes
Trade Share (% GDP) x Crop FE	No	No	Yes	No	No	No	No	Yes
Gini Coefficient x Crop FE	No	No	No	Yes	No	No	No	Yes
Share Arable Land x Crop FE	No	No	No	No	Yes	No	No	Yes
log Agricultural Value Added x Crop FE	No	No	No	No	No	Yes	No	Yes
R&D Share (% GDP) x Crop FE	No	No	No	No	No	No	Yes	Yes

Notes: The unit of observation is a crop-country pair. Panel A uses CPP dstance to the US and Panel B uses CPP dstance to the estimated set of technological leader countries. Controls included in each specification are noted at the bottom of the column. Standard errors are double-clustered by crop and country and *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Inappropriateness ⇒ Lower Area Back

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Dependent Variable is log Area Harvested							
	CPP Mismatch with the US				CPP Mismatch with the Estimated Frontier			
CPP Mismatch (0-1)	-9.517***	-12.08***	-9.541***	-7.855***	-7.139***	-7.020***	-7.200***	-5.837***
	(1.212)	(2.892)	(0.595)	(0.635)	(0.941)	(0.725)	(0.437)	(0.496)
log(FAO-GAEZ-Predicted Output)		0.303***				0.363***		
		(0.0768)				(0.0487)		
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	6,675	2,268	6,683	5,908	6,469	2,268	6,474	5,748
R-squared	0.612	0.612			0.609	0.603		

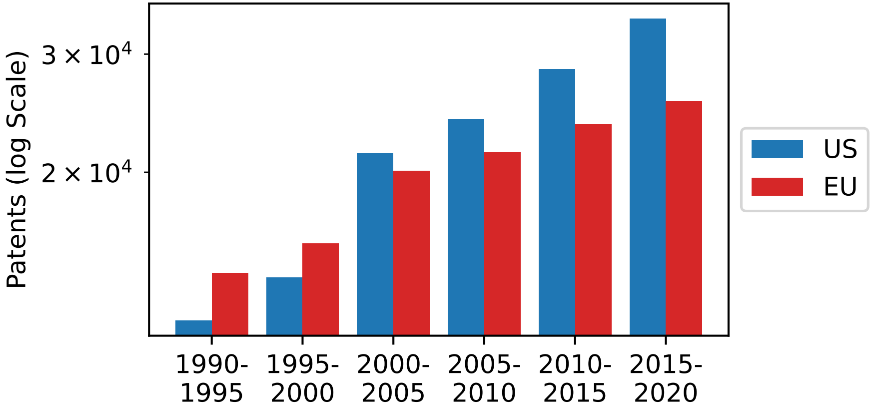
Notes: The unit of observation is a country-crop pair. Columns 1-4 use CPP mismatch with the US and columns 5-8 use CPP mismatch with the estimated set of technological leader countries. Columns 1-2 and 5-6 report OLS estimates and columns 3-4 and 7-8 report post double LASSO estimates. Country and crop fixed effects are included in all specifications, and included in the amelioration set in thet post-double LASSO specifications. The Top CPPs are defined as the top 200 CPPs defined by (i) the number of countries in whch 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, growng 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 state and *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Inappropriateness of US ⇒ Lower Ouput Back

	(1)	(2)	(3)	(4)
	Dependent Variable is log Output			
CPP Mismatch (0-1)	-9.285***	-10.60***	-9.325***	-8.454***
	(1.199)	(3.024)	(0.617)	(0.652)
log(FAO-GAEZ-Predicted Output)		0.298***		
		(0.0814)		
Included in LASSO Pool:				
Top CPP Fixed Effects	-	-	Yes	Yes
Ecological Features x Crop Fixed Effects	-	-	No	Yes
Controls in LASSO Pool	-	-	335	3935
Crop Fixed Effects	Yes	Yes	Yes	Yes
Country Fixed Effects	Yes	Yes	Yes	Yes
Observations	6,915	2,353	6,920	6,069
R-squared	0.600	0.617		

Notes: The unit of observation is a country-crop pair. Columns 1-2 report OLS estimates and columns 3-4 report post double LASSO estimates. The set of ecological features includes: temperature, precipitation, elevation, ruggedness, growng 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 and *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Rise of the US and *Changes* in Output Back



$$\Delta \log y_{k,\ell}^{90-10} = \beta_1 \cdot \text{CPPMismatch}_{k,\ell}^{US} + \beta_2 \cdot \text{CPPMismatch}_{k,\ell}^{EU} + \gamma \cdot \log y_{k,\ell}^{1990} + \chi_\ell + \chi_k + \epsilon_{k,\ell}$$

Rise of the US and *Changes* in Output Back

	(1)	(2)	(3)	(4)
	Δ log Output		Δ log Area Harvested	
CPP Mismatch with the US	-0.999*	-0.974*	-1.004**	-1.044*
	(0.520)	(0.572)	(0.502)	(0.533)
CPP Mismatch with the EU	0.644	0.251	0.352	0.222
	(0.512)	(0.531)	(0.529)	(0.534)
Crop Fixed Effects	Yes	-	Yes	-
Country Fixed Effects	Yes	Yes	Yes	Yes
Crop x Continent Fixed Effects	-	Yes	-	Yes
p-value, Dist US - Dist EU	0.097	0.249	0.172	0.216
Observations	6,414	6,338	6,183	6,107
R-squared	0.281	0.366	0.262	0.353

Notes: The unit of observation is a country-crop pair. Both CPP mismatch with the US and CPP mismatch with the EU are included in all specifications. All columns include crop and country fixed effects, as well as the pre-period value of the dependent variable, and columns 2 and 4 also include crop by continent fixed effects. In columns 1-2, the dependent variable is the change in log output from the 1990s to 2010s and in columns 3-4 it is the change in log area harvested from the 1990s to 2010s. Standard errors are double-clustered by country and crop and *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

The Role of Invasive Species

Back (Output) Back (Diffusion)

- Potentially important mechanism, but also potentially correlated with omitted factors and important to make sure they alone do not drive the result
- Use CABI Invasive Species Compendium (ISC), a list of global invasive species and species with high invasion potential
- The ISC identifies 748 CPPs as invasive, or 15% of the sample
- Estimate all versions of CPP mismatch after restricting to non-invasive species

The Role of Invasive Species

Back (Output) Back (Diffusion)

	(1)	(2)	(3)	(4)	(5)
	Technology Trasnfer			Technology Adoption	Output
Dependent Variable:	asinh Biotech Transfer	Any Biotech Transfer	log Biotech Transfer	Improved Seed (=1)	log Output
CPP Mismatch Without Invasive Species	-0.0712***	-0.0304***	-0.5451		
	(0.0241)	(0.0096)	(0.34)		
CPP Mismatch with the Frontier Without Invasive Species				-0.248***	-6.335***
				(0.0743)	(0.948)
Crop-by-Origin Fixed Effects	Yes	Yes	Yes	-	-
Crop-by-Destination Fixed Effects	Yes	Yes	Yes	-	-
Country Pair Fixed Effects	Yes	Yes	Yes	-	-
Country Fixed Effects	-	-	-	Yes	Yes
Crop Fixed Effects	-	-	-	Yes	Yes
Observations	202,154	202,154	5,752	115,397	6,858
R-squared	0.4397	0.3831	0.7965	0.213	0.584

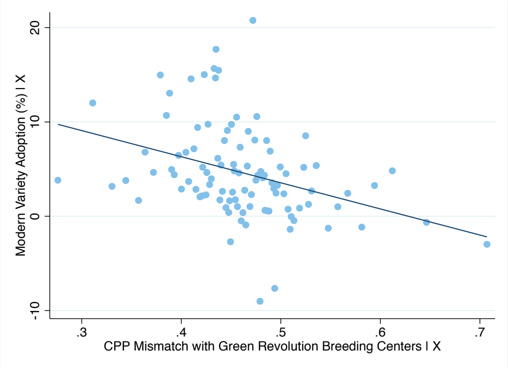
Notes: The unit of observation is a crop-origin-destination in columns 1-3 and a crop-country pair in columns 4-6. Standard errors are double-clustered by origin and destination in columns 1-3, clustered y crop-country in columns 4-5, and double clustered by crop and country in column 6. CPP mismatch with the frontier is computed as CPP mismatch with the US. In all cases, the independent variable is constructed after excluding invasive CPPs. The fixed effects included in each specification are noted at the bottom of each column. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Inappropriateness and the Impacts of the Green Revolution Back

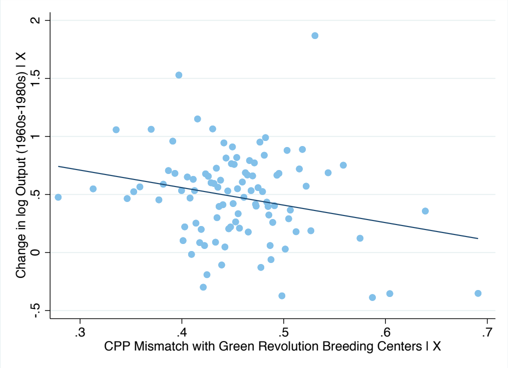
- A coordinated international effort to develop high-yielding varieties (HYVs) of staple crops for countries with high risk of famine
- But effects differed drastically across locations (Evenson, 2005) potentially due to ecological differences between the international agricultural research centers where varieties were developed and large parts of the world (Pingali, 2012; Lansing, 2009)
- Measure CPP mismatch with Green Revolution breeding centers by identifying the country where breeding took place for each corp:

$$\text{CPPDistGR}_{k,\ell} = \sum_{\ell'} \text{CPPMismatch}_{k,\ell,\ell'} \times \mathbb{I}\{\text{IARC for } k \text{ is in } \ell\}$$

CPP Mismatch ↘ Adoption of GR Technology and Output Growth Back



(c) Modern Variety Adoption



(d) Δ log Output (1960-1980)

Notes: Binned partial correlation plots, after absorbing country and crop-by-continent fixed effects, in which the independent variable is $\text{CPPDistGR}_{k,\ell}$ and the dependent variable is listed at the top of each sub-figure. In (a), the dependent variable is the share of production using modern varieties in 1980 ($p = 0.006$) and in (b), it is the change in log output between the 1960s and the 1980s ($p = 0.017$).

Inappropriateness Within Countries

Back

- Zoom in further for Brazil and India, two of the worlds' largest agricultural economies
  - Production data from most recent, nationally representative Census of Agriculture
  - CPP data at state (s) level from CABI
- State-by-crop empirical model:

$$\log\left(\text{Output}_{k,s}\right) = \beta \cdot \text{CPPDistFrontier}_{k,s} + \chi_{k,\ell(s)} + \chi_s + \Omega'_{ks}\Gamma + \epsilon_{k,s} \tag{8}$$

- **Absorbed effects**: state (χ_s) and crop x country ($\chi_{k,\ell(s)}$) fixed effects $\Rightarrow$ measuring a different effect (e.g., holding fixed crop-specific research, trade, CPPs, etc.)
- **Capturing local suitability (Ω)**: Identical strategy, now measured at state-by-crop level
- **Hypothesis**: $\beta < 0$: inappropriateness $\rightarrow$ lower output for specific crops within states

Inappropriateness ⇒ Lower Output Within Countries

Separate Countries Back to Main

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Dependent Variable is log Output							
	CPP Mismatch with the US				CPP Mismatch with the Estimated Frontier			
CPP Mismatch (0-1)	-9.285***	-10.60***	-9.325***	-8.454***	-7.136***	-5.721***	-7.202***	-6.288***
	(1.199)	(3.024)	(0.617)	(0.652)	(0.959)	(0.663)	(0.461)	(0.501)
log(FAO-GAEZ-Predicted Output)		0.298***				0.353***		
		(0.0814)				(0.0499)		
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	6,926	2,353	6,931	6,069	6,704	2,353	6,707	5,903
R-squared	0.599	0.617			0.600	0.609		

Notes: The unit of observation is a country-crop pair. Columns 1-4 use CPP mismatch with the US and columns 5-8 use CPP mismatch with the estimated set of technological leader countries. Columns 1-2 and 5-6 report OLS estimates and columns 3-4 and 7-8 report post double LASSO estimates. Standard errors are double-clustered by crop and country and *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Ecological Mismatch I: Geographic Attributes

AgroClim Table (Technology) AgroClim Table (Output) Counterfactual Estimates

	Item	Unit	Description	Source
1	**Temperature**	deg C	Annual mean from 1981 to 2010	Willmott and Matsuura University of Delaware dataset
2	**Precipitation**	mm	Annual mean from 1981 to 2010	Willmott and Matsuura University of Delaware dataset
3	**Elevation**	m	Dist. above sea level	GTOPO30 Digital Elevation Model
4	**Ruggedness**	m^2	Rel. elevation to neighboring grid cells	Metric of by Riley, DeGloria, and Elliot (1999) as constructed by Nunn & Puga (2012)
5	**Growing season**	days	Sufficiently warm and moist days[1]	FAO GAEZ
6	**Soil acidity**	pH	in water to 250m	SoilGrids and WoSIS
7	**Clay content**[2]	% mass	to 250m	SoilGrids and WoSIS
8	**Silt content**	% mass	to 250m	SoilGrids and WoSIS
9	**Coarse fragments**	% volume	to 250m	SoilGrids and WoSIS
10	**Water capacity**	% volume	to 250m	SoilGrids and WoSIS

[1]Temperature > 5 C and (Precipitation + Soil Mosture) > 0.5 x Potential Evapotranspiration

[2]Soil types defined by particle diameter. Clay = 0 to 2 μm; Silt = 2 to 50 μm; Coarse fragments = over 2mm.

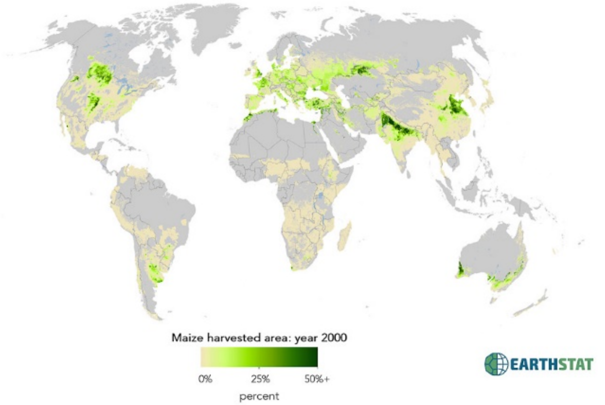
Ecological Mismatch II: Global Cropland Distributions

AgroClim Table | AgroClim Table (Output) | Counterfactual Estimates

Harvested area cross-section from EarthStat

http://www.earthstat.org/

Created by combining national, state, and county level census statistics with a recently updated global data set of croplands on a 5 minute by 5 minute (~10 km by 10 km) latitude/longitude grid. The resulting land use data sets depict circa the year 2000 the area (harvested) and yield of 175 distinct crops of the world.



Ecological Mismatch III: Constructing Agroclimatic Mismatch

AgroClim Table (Technology) AgroClim Table (Output) Counterfactual Estimates

Crop-level geographic distance. For crop k, between country ℓ and ℓ':

$$d_{k,\ell,\ell'} := \frac{1}{|\mathcal{X}|} \sum_{x \in \mathcal{X}} |\hat{x}_{k,\ell} - \hat{x}_{k,\ell'}| \tag{9}$$

where $\hat{x}_{k,\ell}$ is measured on the crop-k land of country ℓ
Assumption: exactly where crops are planted does not (entirely) reflect selection into low geographic mismatch from peers
Interpretation of functional form:

- Normalized characteristics, a crop-and-country specific average re-centered by global mean and normalized by global dispersion details
- Absolute value metric (like in Bazzi et al., 2016). Appealing simplicity: easy to separate out contribution of each component.

Constructing AgroClimatic Mismatch

AgroClim Table (Technology) AgroClim Table (Output) Counterfactual Estimates

x = attribute; $\ell \in \{1, \ldots, L\}$ = country; g = grid cell; k = crop

1. **Calculate cropland average per attribute.**

$$x_\ell := \sum_{g \in \ell} \frac{\text{AnyCropArea}_g}{\sum_{g \in \ell} \text{AnyCropArea}_g} \cdot x_g$$

e.g., avg. pH of soil in Brazilian farmland

2. **Calculate global mean and standard deviation.** For normalization.

$$\mu(x) := \frac{1}{L} \sum_{\ell} x_\ell \qquad \sigma(x) := \frac{1}{L^{1/2}} \left(\sum_{\ell} (x_\ell - \mu(x))^2 \right)^{1/2}$$

e.g., global distribution of pH

3. **Calculate crop-level attributes.**

$$x_{k,\ell} := \sum_{g \in \ell} \frac{\text{CropArea}_{k,g}}{\sum_{g \in \ell} \text{CropArea}_{k,g}} \cdot x_g$$

e.g., avg. pH of soil in Brazilian soybean land

4. **Calculate normalized (unitless) attributes.**

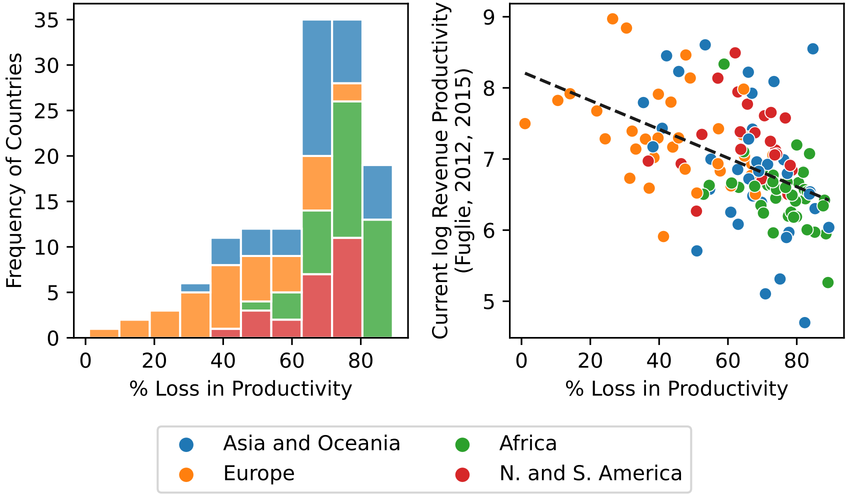
$$\hat{x}_{k,\ell} := \frac{x_{k,\ell} - \mu(x)}{\sigma(x)}$$

e.g., avg. Brazilian soybean pH, relative to global farmland pH

Total Causal Effects: CPP and non-CPP Mismatch

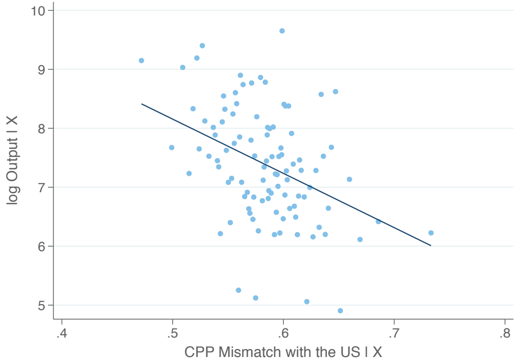
Measurement Back

Level Effect (% Reduction): **52%** Disparity Effect (% Increase): **16%**

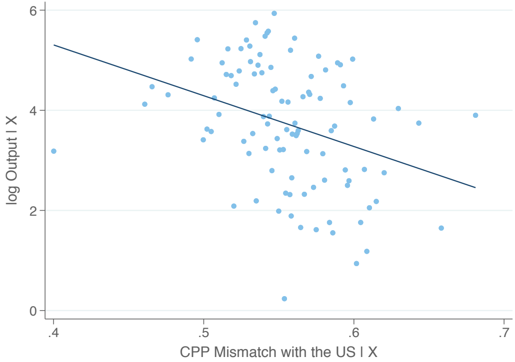


Within-Country Estimates: Inappropriateness ⇒ Less Production

Back



$\beta = -8.51 \ (2.72)$
$N = 1,052$



$\beta = -9.99 \ (4.82)$
$N = 384$

CPPs in the Patent Data

Back: Background Back: Theory

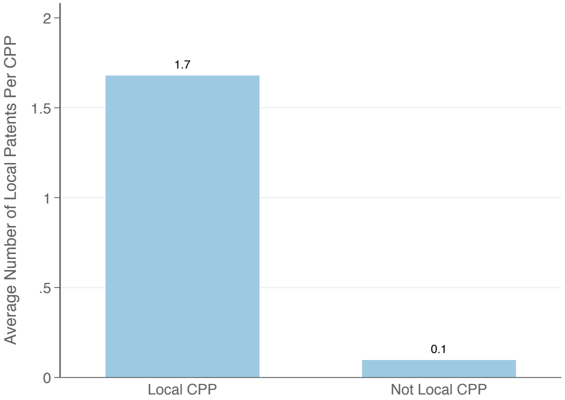
- Identify all global biological or chemical agricultural patents (CPC classes A01H and A01N) related to a CPP in our data via keyword searches of species names (33% of *total*)
- Link each patent to the country of origin of the inventor (*PatSnap* database)
- Construct patent data set at the CPP-by-country level ($>$400k observations)

CPPs in the Patent Data

Back: Background   Back: Theory

- Identify all global biological or chemical agricultural patents (CPC classes A01H and A01N) related to a CPP in our data via keyword searches of species names (33% of *total*)
- Link each patent to the country of origin of the inventor (*PatSnap* database)
- Construct patent data set at the CPP-by-country level (>400k observations)

Innovation focused on local CPPs:



Innovation focused on local CPPs

Back: Background Back: Theory

	(1)	(2)	(3)
	CPP-Specific Patents (asinh)	Any CPP-Specific Patent (0/1)	log CPP-Specific Patents
Local CPP	0.0972***	0.0479***	0.181***
	(0.0288)	(0.0106)	(0.0635)
Country Fixed Effects	Yes	Yes	Yes
CPP Fixed Effects	Yes	Yes	Yes
Observations	492,422	492,422	8,557
R-squared	0.211	0.202	0.557

Notes: The unit of observation is a CPP-by-country pair. The dependent variable is the number of patents registered to inventors in the country and with the CPP's scientific name in the title, abstract, or patent description. Standard errors, clustered by country and CPP, are included in parentheses and *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

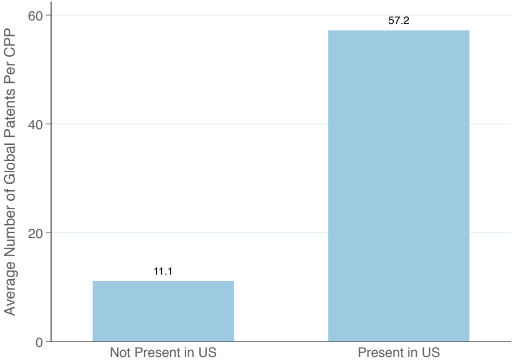
Larger Effects in US, Rich Countries
Back: Background Back: Theory

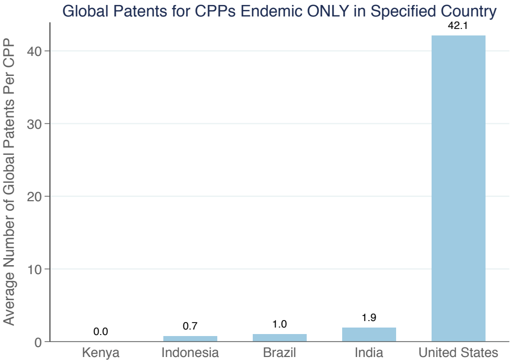
	(1)	(2)	(3)	(4)	(5)	(6)
	CPP-Specific Patents (asinh)	Any CPP-Specific Patent (0/1)	log CPP-Specific Patents	CPP-Specific Patents (asinh)	Any CPP-Specific Patent (0/1)	log CPP-Specific Patents
Local CPP	0.0720***	0.0395***	0.142*	0.147***	0.0679***	0.172***
	(0.0242)	(0.00887)	(0.0711)	(0.0418)	(0.0138)	(0.0521)
Local CPP x United States (0/1)	1.002***	0.334***	0.394***			
	(0.0274)	(0.0108)	(0.0825)			
Local CPP x log per-capita GDP (pre-period)				0.0860***	0.0366***	0.0492
				(0.0294)	(0.0101)	(0.0593)
Country Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
CPP Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	492,422	492,422	8,557	364,144	364,144	8,478
R-squared	0.233	0.214	0.559	0.240	0.228	0.557

Notes: The unit of observation is a CPP-by-country pair. The dependent variable is the number of patents registered to inventors in the country and with the CPP's scientific name in the title, abstract, or patent description. GDP is computed at the country level from 1990-2000 and normalized by the global mean. Standard errors, clustered by country and CPP, are included in parentheses and *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Inequality Across Countries: Raw Data

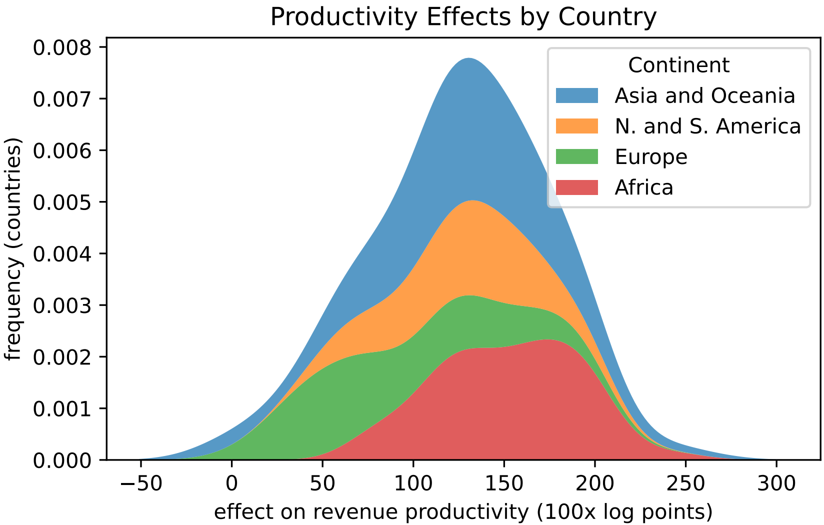
Back: Background Back: Theory





Production Moves Toward Africa and Asia

Back



Innovation locations to maximize productivity Back

Where would investment in innovation reduce technology mismatch the most?

For each country-crop, estimate productivity if that country became the frontier innovator

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(1)	(2)	(3)	(4)	(5)
Crop	Sites Chosen to Minimize Global Inappropriateness		Sites Chosen to Minimize Inappropriateness in Countries with Below Median Productivity	
	Best Site	Second Best Site	Best Site	Second Best Site
Wheat	China	India	India	Pakistan
Maize	China	USA	Nigeria	Tanzania
Sorghum	India	Nigeria	Nigeria	India
Millet	Nigeria	India	Nigeria	Zimbabwe
Beans	India	Brazil	India	Tanzania
Potatoes	China	India	India	Russia
Cassava	Nigeria	Ghana	Nigeria	DRC
Rice	China	India	India	Thailand

Notes: Column 1 reports the crop name. Columns 2-5 report the results of our analysis to select the two countries where breeding investment would have the largest positive effect on global output for each crop or output in countries with below median productivity.

Application: Rapid CPP Migration due to Climate Change Back

Key looming threat to ecological systems: climate-change induced migration

General: Parmesan et al., 2003, *Nature*. CPPs: Anderson et al., 2004, *Trends Ec. Evo.*; Bebber et al., 2013, *Nat. Clim. Change*

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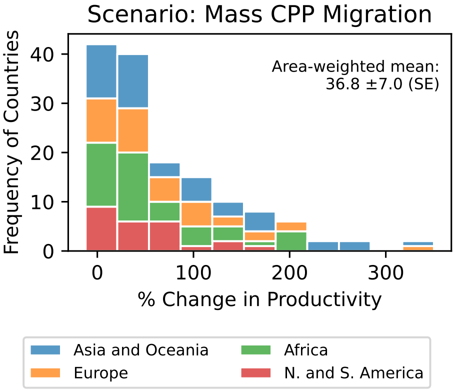

Application: BRIC Emerge as AgTech Leaders Back

Regime shift such that AgTech frontier becomes Brazil, Russia, India, and China (details)

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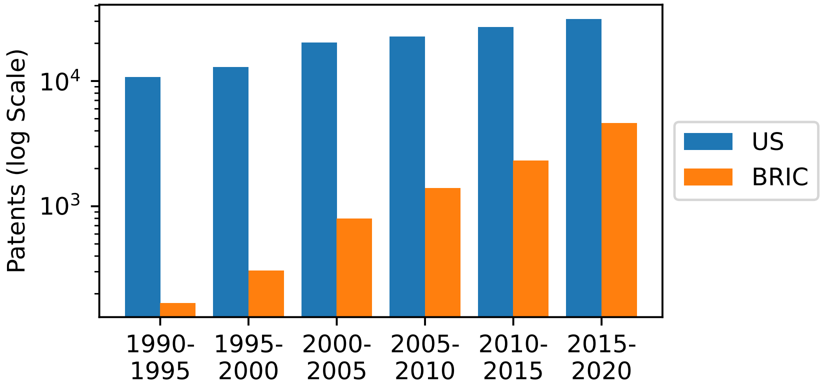

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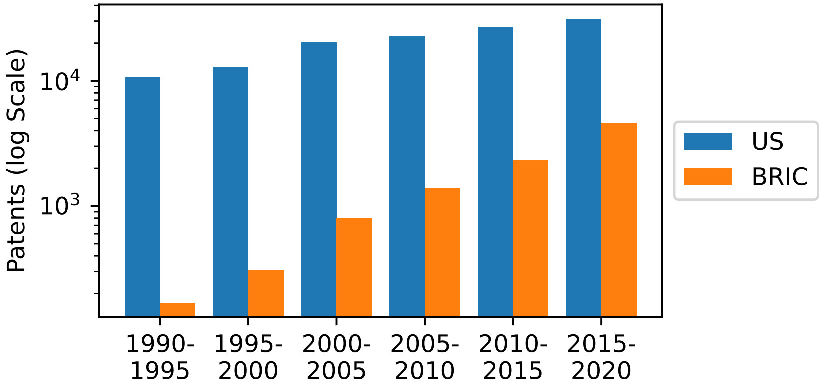

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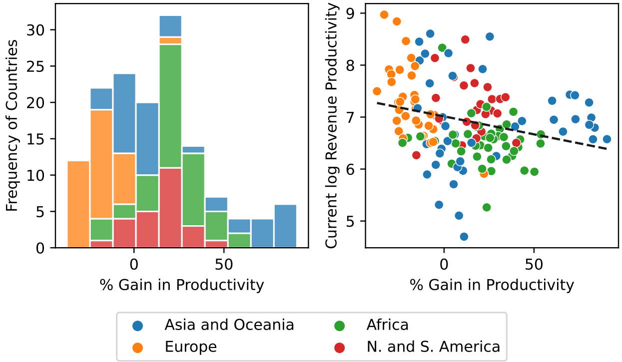

Finding: **31.2%** increase in global productivity

Primitives: Innovators and Technology Supply

Back

- The representative innovator in L develops context-specific attributes of technology for all crops + countries, to maximize profits net of research costs (assume "general" component A_k fixed)
- **Cost structure**: marginal cost $(1-\gamma)^2$ (chosen for convenience) and convex, additively-separable research costs with a knowledge spillover

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$$\max_{(B_{t,k,\ell})_{t\in\mathcal{T}_{k,\ell}}} \left\{ \frac{(1-\gamma)}{\exp(\rho_{L,\ell})} \hat{\Xi}_\ell^{1-\eta} \hat{p}_k^{\frac{\eta}{\gamma}} \omega_{k,\ell}^{\eta} A_k^{\alpha\eta} \prod_{t\in\mathcal{T}_{k,\ell}} B_{t,k,\ell}^{\frac{\eta(1-\alpha)}{T}} - \sum_{t\in\mathcal{T}_{k,\ell}} \exp\Big(-\tau(\hat{B}_{t,k,L})\Big) \frac{B_{t,k,\ell})^{1+\phi}}{T(1+\phi)} \right\}$$

given conjectures $(\hat{p}_k, \hat{\Xi}_\ell)$ for crop prices and endogenous revenue productivity in each country ℓ and conjecture $(\hat{B}_{t,k,\ell',\ell'})$ for local research on each pest

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  e.g., Acemoglu and Zilibotti, 2001; Acemoglu, 2002
- *Knowledge gaps*: more "scientific inputs" for highly-researched pest/pathogen threats
  Abstractions: Romer (1986). Realities: breeding practices, germplasm, ...

Inappropriateness and the Impacts of the Green Revolution Back

- A coordinated international effort to develop high-yielding varieties at international agricultural research center (IARCs)
- Adoption of new tech differed drastically across locations (Evenson, 2005) potentially due to ecological mismatch with IARCs (Pingali, 2012; Lansing, 2009)

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Did change in the geography of R&D shift the geography of technology use and production?

CPP Mismatch Reduces Adoption of GR Tech, Output Growth Back

$$y_{k,\ell}^{1980} - y_{k,\ell}^{1960} = \beta \cdot \text{CPPMismatchGR}_{k,\ell} + \chi_\ell + \chi_{c(\ell),k} + X'\Gamma + \epsilon_{k,\ell}$$

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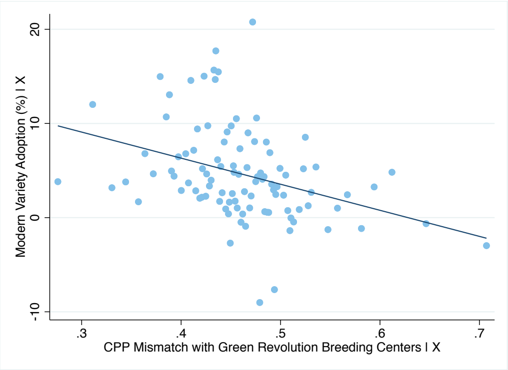
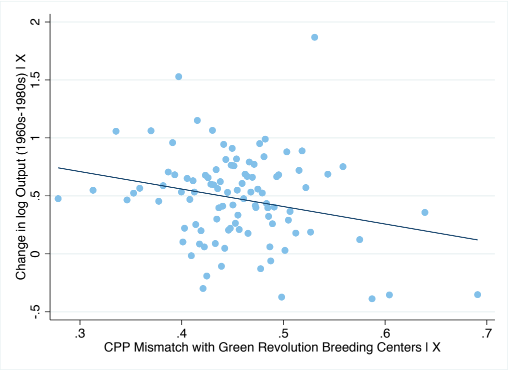


(g) Modern Variety Adoption ($p < 0.01$)



(h) Δ log Output (1960-1980) ($p < 0.05$)

Input Use by Modern Smallholders in sub-Saharan Africa Back

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Does the inappropriateness of technology drive part of the technology adoption gap?

Empirical Model: Technology Adoption Back

Estimating equation:

$$y_{z,k} = \beta \cdot \text{CPPMismatchFrontier}_{k,\ell(z)} + \chi_k + \chi_{\ell(z)} + \epsilon_{z,k} \tag{10}$$

where z indexes plots, $\ell(z)$ indexes countries, and k indexes crops.

- **Dependent Variable**: Indicator for improved seed use
- **Absorbed effects**: Aggregate differences across crops (χ_k) and countries/states ($\chi_{\ell(z)}$)
- **Prediction**: $\beta < 0$; less use of improved seeds when frontier technology inappropriate

Inappropiateness ⇒ Less Improved Seeds Usage

Back

	(1)	(2)	(3)	(4)	(5)	(6)
	Dependent Variable is Improved Seed Use (=1)					
CPP Mismatch (0-1)	-0.321***	-0.242***	-0.237***	-0.157***	-0.227***	-0.237***
	(0.0793)	(0.0805)	(0.0812)	(0.0563)	(0.0793)	(0.0812)
Quadratic Polynomial in Lat and Lon			✓	✓	✓	✓
log Area-Weighted Estimates				✓		
Broad CPP Presence Classification					✓	
Jaccard (1900, 1901) Mismatch Metric						✓
Crop Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Country Fixed Effects	Yes	-	-	-	-	-
State Fixed Effects	No	Yes	Yes	Yes	Yes	Yes
Observations	114,605	114,601	114,601	103,968	114,601	114,601
R-squared	0.213	0.246	0.247	0.235	0.246	0.246

Notes: The unit of observation is a plot. The controls included in each specification, as well as the mismatch metric when the baseline measure is not used, are noted at the bottom of each column. Standard errors are clustered by crop-country and *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

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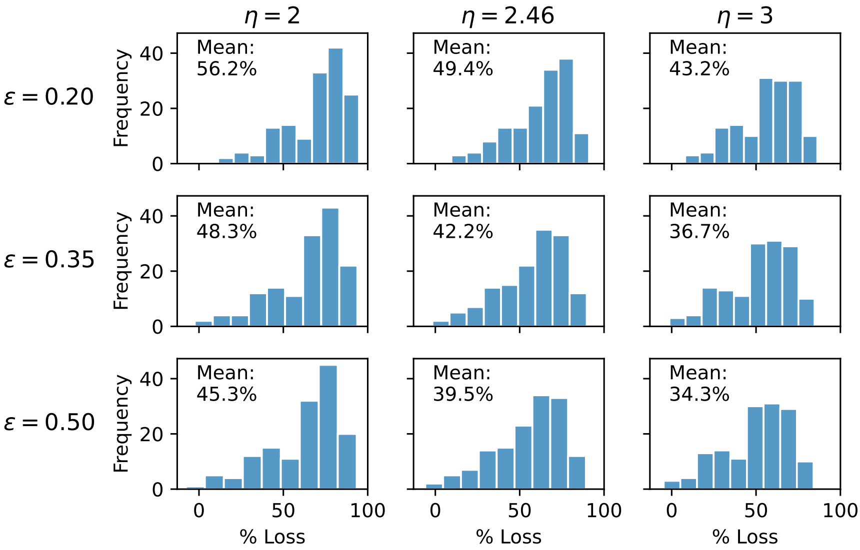
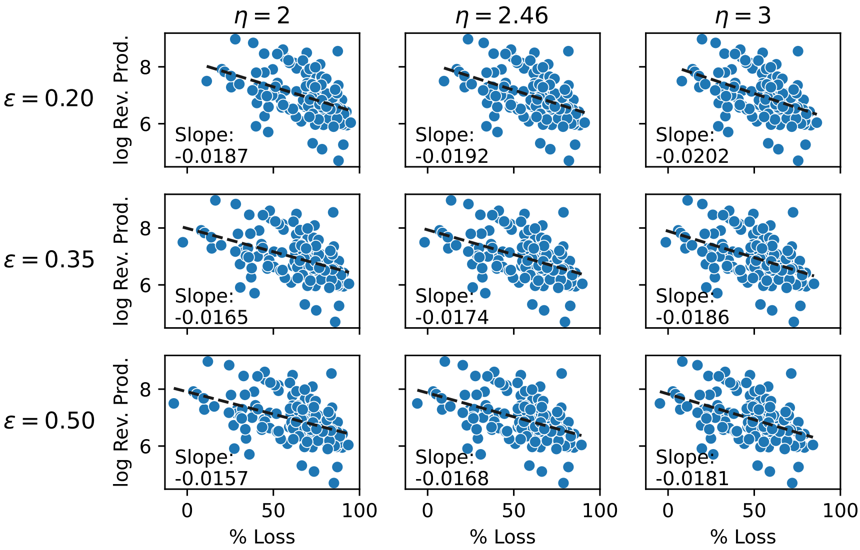
Global Productivity Effects: Sensitivity

Back



Global Disparities Effects: Sensitivity

Back



Calibration Parameters

Back

Name	Estimate	Specification/Source	Definition
β	-7.14	Output Regression	Effect of CPPMismatchFrontier on output
η	2.46	Costinot et al. (2016)	Elasticity of supply to productivity
ϵ	0.35	Muhammad et al. (2011)	Price elasticity of global food demand
$\pi_{k,\ell}$	—	FAOSTAT Database	Planted area for each crop in each country
Ξ_ℓ	—	Fuglie (2012, 2015)	Baseline revenue productivity by country