Climate Change and Migration: the case of Africa

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Motivation

- Implications of climate change ($C\Delta$): at the center of the policy debate

- Drastic (potential) consequences for Sub-Saharan Africa (SSA):
  - High dependence on agriculture
  - Low usage of modern inputs
  - Rapid population growth

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- Great Climate Migration (Lustgarten, 2020):
    - High vulnerability of SSA (in terms of migration responses to $C\Delta$)
    - Rigaud et al. (2018): intranational climate migration $\sim$ millions by 2050

Research Questions and Outline

1. How can CΔ lead to migration flows in SSA (within/across countries)?
2. How economic mechanisms and potential policies interact with CΔ effects?

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This project: Data + Model = long-run GE effects of climate change

1. Climate change: agricultural productivity shock
   - FAO-GAEZ data: variation at location-crop level
2. Embed it in a multi-sector spatial GE model to quantify:
   - CΔ migration by the end of the 21st century
   - Role of migration and trade policies on CΔ effects

Main Results and Takeaways

1. Aggregate CΔ effects:
   - Migration flows (4 million) and real GDP pc losses (-1.2%)
   - Magnitude of results: determined by spatial frictions
2. Distributional effects:
   - Heterogeneous migration responses across space [-38K, 42K]
   - Country-level welfare effects: [-6%, 6.5%]
   - Production adaptation across sectors + trade: mitigate CΔ effects
3. SSA as the European Union ($\downarrow$ trade and migration barriers):
   - EU's migration and trade policies: aggregate and distributional gains
   - Main channel: CΔ-induced structural change

Contribution more

1. Introduce CΔ migration into the structural change/development literature:
   - Climate shocks: push-factors of migration (past and future) (Henderson et al., 2017; Rigaud et al., 2018; Benveniste et al., 2020; Burzyński et al., 2022)
   - Mobility barriers: obstacle for migration, structural change, and development (Gollin et al., 2014; Bryan et al., 2014; Bustos et al., 2016; Lagakos et al., 2018; Bryan and Morten, 2019; Pellegrina and Sotelo, 2021; Imbert et al., 2022; Henderson and Turner, 2020)

2. Contribution to the spatial climate change literature: (Desmet et al., 2021; Balboni, 2021; Conte et al., 2022; Cruz and Rossi-Hansberg, 2021)
   - Crop-level CΔ (Costinot et al., 2016) and migration
   - CΔ, structural change (the "food problem"), and migration (Gollin et al., 2007; Nath, 2022; Conte et al., 2021; Cruz, 2021)
   - Carefully quantified real-world policies and their interaction with CΔ effects

Road Map

1. Data:
   - Main data sources
   - Motivating evidence

2. Theory:
   - Theoretical model
   - Model quantification

3. Counterfactuals for Climate Migration:
   - Main counterfactuals
   - Policy experiment: SSA as the EU
   - Additional experiments and robustness

4. Final remarks and further work

Data

Spatial Data: $1^\circ \times 1^\circ$ grid cells ($\sim$ 2000 cells) more

1. GDP and Population:
   - 2000: both values from (G-Econ, Nordhaus et al., 2006)
   - 1975: population from (GHSP, Florczyk et al., 2019)
   - 2080: population estimates (UN's Population Prospects, at the country level)

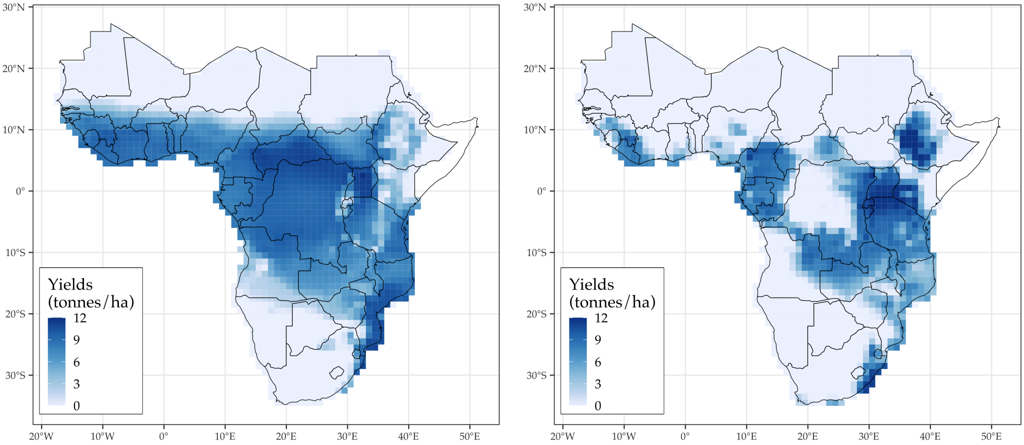
2. Transportation network: African extract from gROADS and transportation friction surface from Weiss et al. (2018)

3. Agriculture: GAEZ agro-climatic potential yields (IIASA and FAO, 2012):
   - Unit: tons/ha, subsistence (rainfed) technology
   - Crops: cassava, maize, millet, rice, sorghum, wheat
   - Time periods: 1975, 2000 and 2080 (RCP 8.5)

CΔ and Agricultural Productivity

spatial–crop heter. production

Figure 1: CΔ effects on potential yields of cassava for 2000 (left) and 2080 (right).



Model

Model Outlook

- Static, multi-sector spatial GE model

- Ingredients from quantitative spatial economics (Allen and Arkolakis, 2014; Redding and Rossi-Hansberg, 2017):
  - Love for varieties (consumers) **+**
  - Trade frictions (production and trade) **+**
  - Congestion forces (location choice) **=**
  - Spatial allocation of economic activity

- Main outcomes: sectoral production takes place in the most productive regions

- Sectoral specialization: disciplined by barriers to structural change (agricultural goods $\equiv$ subsistence)

Environment

- N locations $i, j \in S = \{1, ..., N\} \in$ country $c \in C$ countries, $K - 1$ crops (agriculture), $K \equiv$ non-agric. sector:
  - Sector-specific fundamental productivity $A_i^k \in \mathcal{A} = \{A_1^1, ..., A_N^K\}$
  - Amenity value $u_i \in \mathcal{U}$

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- Initial population $\mathcal{L} = \{L_i^0\}_{i \in S}$, inelastic supply, earn w_j:
  - Heterogeneous w.r.t. location choice $\sim G(\theta, u_j L_j^{-\alpha})$
  - Migration barriers $\bar{m}_{ij} = \text{dist}\,(i,j)^{\phi} \times m_{c(j)} \geq 1 \in \mathcal{M}$
  - Mobility on S: subj. to congestion forces $\left(\theta, \alpha, \phi, \{m_c\}_{c=1}^{C}\right)$

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  - $\tau_{ij} = \text{dist}(i,j)^{\delta} \times \tau_{ij}^F$, $\tau_{ij}^F = \tau^F > 1$ if i and j belong to different countries

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- Technology: Labor as input, linear technology, $A_i^k \equiv$ fundamental productivity, $b_i^k \equiv$ efficiency shifter, $\boldsymbol{b_i^k A_i^k \equiv \text{TFP}_i^k}$
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- Consumption choice: Multi–level CES demand over location–sector varieties q_{ij}^k and CES aggregates C_j^k
  - $\eta_k, \gamma_a, \sigma \equiv$ lower, middle, and upper level CES
  - Bilateral expenditure shares: $\lambda_{ij}^k = \left(p_{ij}^k / P_j^k\right)^{1-\eta_k} \equiv g\left(\boldsymbol{w}, \boldsymbol{b^k}, \boldsymbol{A^k}, \mathcal{T}\right) \; \forall i, j, k$

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- Non-/Agricultural expenditures: shares μ_j^k, $k = a, K$
  - Non–homothetic upper-tier (Comin et al., 2021):

$$\mu_j^k = \Omega_k \times \underbrace{\left(P_j^k / P_j\right)^{1-\sigma}}_{\text{substitution effect}} \times \underbrace{\left(w_j / P_j\right)^{\varepsilon_k - (1-\sigma)}}_{\text{income effect}}$$

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- Location choice: workers choose destination j s.to an i.i.d. preference shock $\varepsilon_j \sim G_j(z) = e^{-z^{-\theta} \times u_j L_j^{-\alpha}}$
  - $L_{ij} \equiv h\left(\boldsymbol{w}/\boldsymbol{P}, \mathcal{U}, \mathcal{M}, \theta, \alpha, \mathcal{L}\right) \ \forall i, j$
  - $\theta \equiv$ elasticity of L_{ij} w.r.t. real wages in j

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From Theory to Data: Calibration and Validation

From Theory to Data: Matching SSA in 2000

Preference parameters	Description	Reference / Moment Matched
Lower–tier CES:		
$\eta_k = 9.5$	Lower-tier CES (agric.)	Pellegrina and Sotelo (2021)
$\eta_K = 5.5$	Lower-tier CES (non-agric.)	Pellegrina and Sotelo (2021)
Mid–tier CES:		
$\gamma_a = 2.5$	Mid-tier CES (agric.)	Sotelo (2020)
Upper–tier CES:		
$\sigma = 0.26$	Upper-tier CES	Nath (2022)
$\varepsilon_a = 0.29$	Non-homoth. CES (agric.)	Nath (2022)
$\varepsilon_K = 1$	Non-homoth. CES (non-agric.)	Nath (2022)
$\{\Omega_k\}_k$	Sectoral preference shifters	Aggregate sectoral expenditure
Location choice:		
$\alpha = 0.32$	Congestion to pop. density	Desmet et al. (2018)
$\theta = 2$	Migration elasticity	Morten and Oliveira (2018), Monte et al. (2018)

From Theory to Data: Matching SSA in 2000

Fundamentals	Subset	Description	Data source / Moment matched
$\mathcal{L}$	–	SSA's initial population	Population data in 2000 and 1990
$\{b_i^k\}_{i\in S}$	–	Productivity shifters	Spatial-sectoral output distribution
$\mathcal{A}$	$\{A_i^k\}_{i\in S,k\neq K}$	Agricultural productivities	FAO-GAEZ data go
	$\{A_i^K\}_{i\in S}$	Non–agricultural productivities	Spatial distribution of GDP
$\mathcal{U}$	–	Amenities	Spatial distribution of population
$\mathcal{T}$	dist(i,j)	Bilateral travel distances	Transportation data
	$\delta = 0.3$	Distance elasticity of τ	Moneke (2020) new price data
	$\tau^F = 2.175$	Tariffs	Aggregate bilateral trade flows
$\mathcal{M}$	dist(i,j)	Bilateral travel distances	Transportation data
	$\phi = 0.5$	Distance elasticity of m_{ij}	Aggregate internal migration
	$\{m_c\}_{c=1}^C$	Country migration barriers	Country-level bilateral migration flows

quant. algorithm | results: outer loops | results: trade network | results: fundamentals | model validation

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Climate Change and Migration: Counterfactuals and Policy Experiments

Main Counterfactual

- Solve for 2080's equilibrium with $\mathcal{G}(S)$ but using:
  - $\mathcal{L}$ for 2080 **+**

1. $\{A_i^k\}_{k \neq K}$ with CΔ **-**
2. $\{A_i^k\}_{k \neq K}$ (no CΔ)

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2. $\{A_i^k\}_{k \neq K}$ (no CΔ)

- Results: CΔ migration ($\sim$ 4 million), welfare losses (real GDP pc $\downarrow$ 1.2%), non-agricultural employment ($\downarrow$ 0.85%) CΔ migration empl. results welfare results

		Location Level			Country Level			
	Aggregate	Bottom decile	Median	Top decile	Angola	Senegal	Nigeria	Tanzania
Δ Population (K)	4,024.38	-38.29	0.59	41.88	-79.34	-582.84	339.75	479.95
Δ Non–agric.	-0.85%	-4.96%	0.00%	9.41%	2.92%	8.10%	-0.44%	-2.53%
Δ Real GDP pc	-1.18%	-15.59%	-2.66%	3.30%	-0.36%	-14.07%	-2.58%	2.77%

Underlying Mechanisms and Policy Experiments

A. **Migration:** key adaptation (Bryan and Morten, 2019; Lagakos et al., 2018)

- No migration barriers: reverses welfare losses, but with more CΔ migration (100 mi) and higher regional inequality
- Interaction with trade and ”the food problem”: migration and sectoral specialization as substitutes (Conte et al., 2021; Cruz, 2021)

B. **Policy Experiment:** SSA as the European Union (trade/migration policies)

		A: Migration Frictions		B: SSA as frictionless as the EU (details)		
	Baseline	No country barriers	No bilateral mig. frictions	Migration (m_c)	Trade (τ^F)	Both ($\tau^F + m_c$)
Δ Pop. (K)	4,020	62,050	114,640	29,150	2,790	21,090
Δ Non–agric.	-0.85%	0.27%	1.36%	-0.64%	0.33%	0.64%
Δ GDP pc	-1.18%	3.65%	9.23%	0.03%	-0.31%	0.54%
[bottom, top]	[-6%, 6.5%]	[-9.3%, 19.6%]	[-13.2%, 49.5%]	[-7%, 12.3%]	[-2.9%, 1.6%]	[-2.7%, 5.4%]

Additional Experiments and Robustness Checks details

1. Additional Experiments
   - One-crop vs. multi-crop: larger welfare losses
   - Homothetic preferences: major welfare gains (economy substitute out agricultural goods for non-agric.)
   - Endogenous fertility: reduces population growth in damaged locations
     - Less climate migration
2. Robustness:
   - CΔ assumptions: RCP 4.5 (less severe)
   - Frictions to mobility: goods and labor

Final Remarks

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- Study and quantify climate migration in SSA by combining:
  - Rich spatial data for SSA
  - Tractable, transparent spatial GE model
- Main results: CΔ effects on migration, welfare, and structural change
  - Sector adaptation and trade: key adaptation mechanisms
  - Trade and migration policies: powerful mitigation tools (EU as benchmark)
- Beyond the (current) scope:
  - Rest of the world, land, other CΔ effects, innovation, political economy, ...

Thank you!

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Appendix

Contribution to the Literature: Details back

- **Weather shocks and migration:** empirical literature (Baez et al., 2017; Cai et al., 2016; Gröger and Zylberberg, 2016; Henderson et al., 2017)

- **Spatial structural change** (Desmet and Rossi-Hansberg, 2014; Eckert and Peters, 2018; Fan et al., 2021; Fajgelbaum and Redding, 2022; Takeda, 2022)

- **Migration (barriers) and development** (Bryan and Morten, 2019; Caliendo et al., 2021; Morten and Oliveira, 2018; Lagakos et al., 2018)

- **Market integration and development** (Asturias et al., 2019; Donaldson, 2018; Nagy, 2022; Ducruet et al., 2020; Sotelo, 2020; Atkin and Donaldson, 2015; Donaldson and Hornbeck, 2016; Atkin et al., 2021)

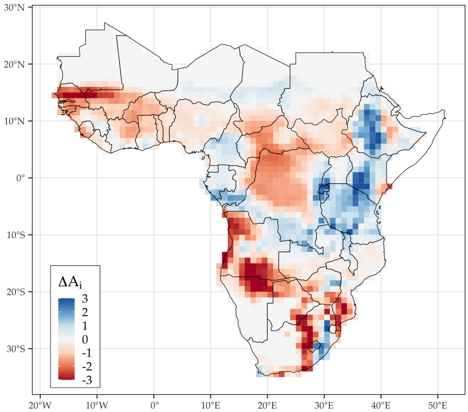
Additional Data Sources

back

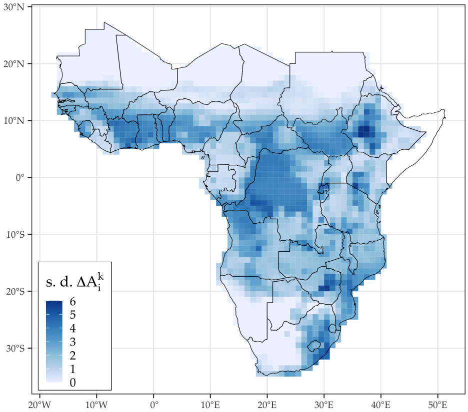
- Sectoral production data (2000 circa):
  - Crop-cell-level production (tons, FAO-GAEZ)
  - Crop-country-level production (US$, FAOSTAT)
  - Country-level sectoral VA (WBDI)
- Trade data: country-pair-sector tradeflows (1990-2005) from the International Trade and Production Database (ITPD-E, Borchert et al., 2021)
- Migration data: country-pair flows (1990-2005, from Abel and Cohen, 2019)

Heterogeneous Effects of CΔ back

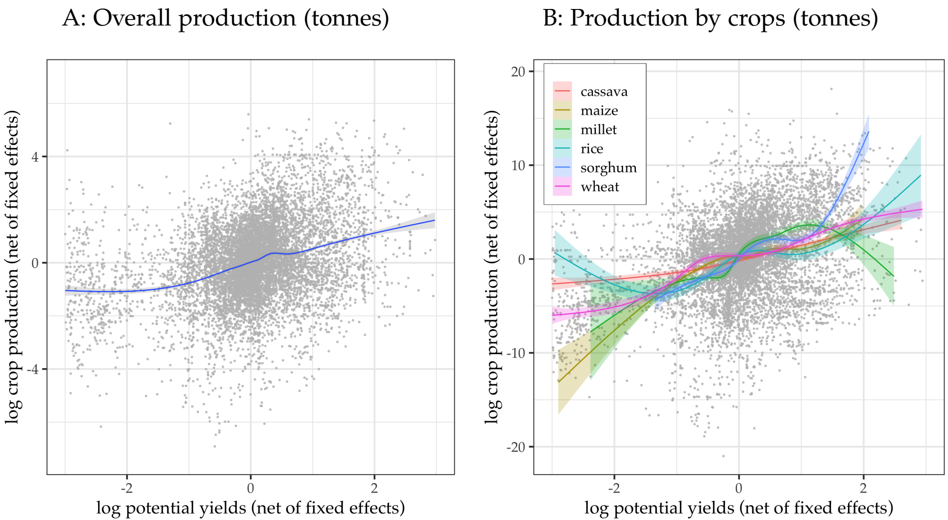
A: Change in average suitability to agriculture (ton/ha)



B: Standard deviation of changes in crop suitabilities at the location level



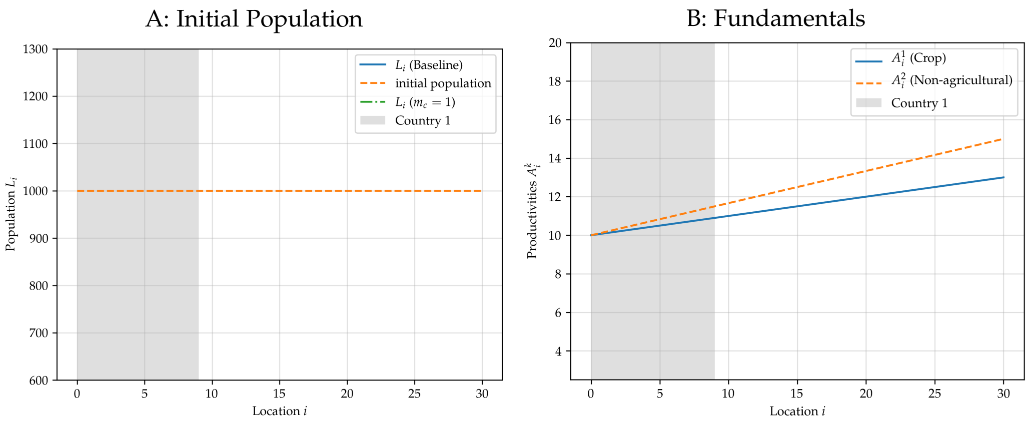
Potential Yields and Production in SSA back



Notes: The two panels plot the relationship between GAEZ potential yields and effective production at the location–crop level. The blue line stands for an estimated polynomial regression of production on yields and location and country–crop fixed effects. Grey–shaded areas stand for 95% confidence bands.

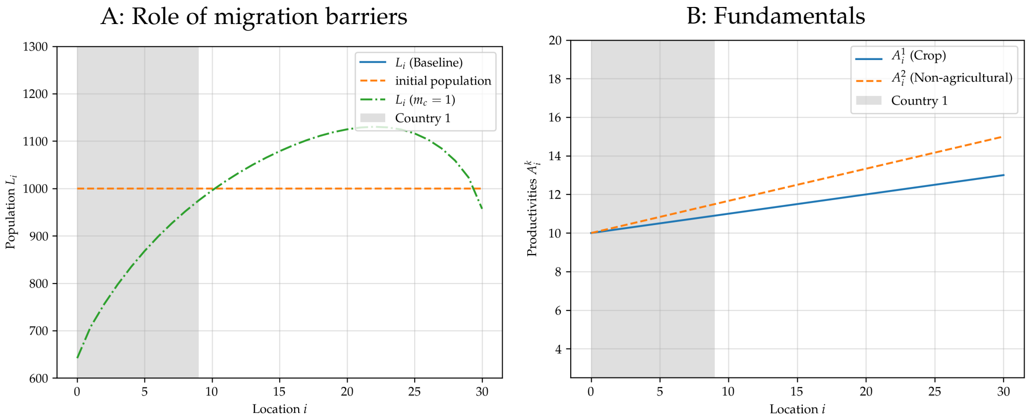
Model – Economy as a Line back

Figure 2: Role of bilateral migration frictions, trade frictions, country borders, crop choices, and non–homothetic preferences.



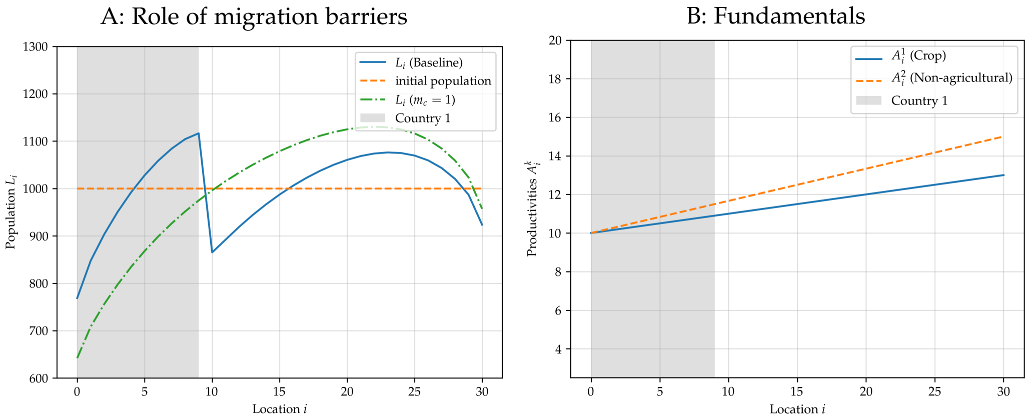
Model – Economy as a Line back

Figure 3: Role of bilateral migration frictions, trade frictions, country borders, crop choices, and non–homothetic preferences.



Model – Economy as a Line back

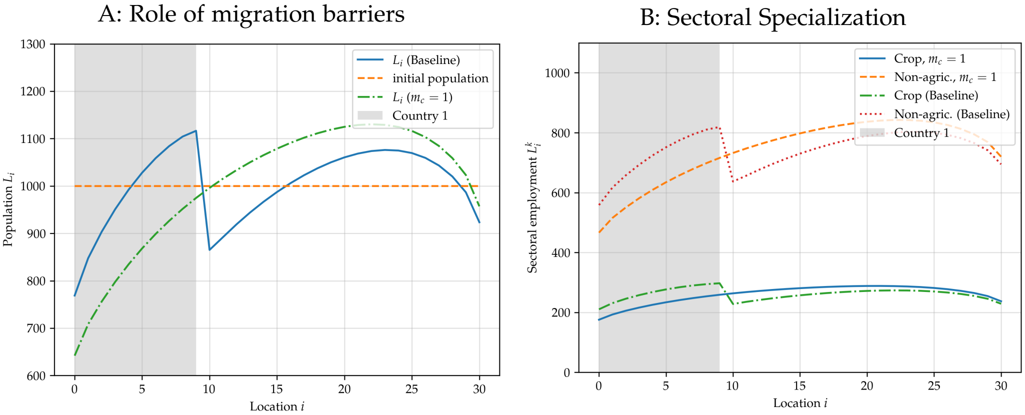
Figure 4: Role of bilateral migration frictions, trade frictions, country borders, crop choices, and non–homothetic preferences.



Model – Economy as a Line

back

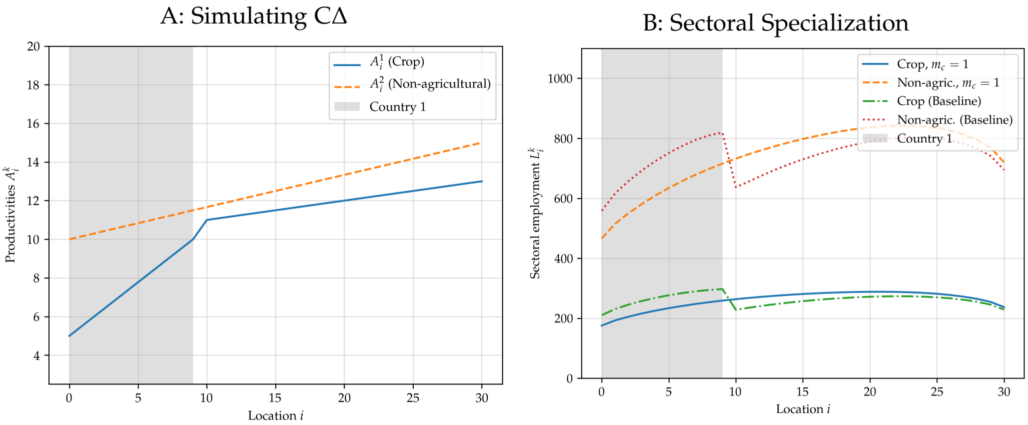
Figure 5: Role of bilateral migration frictions, trade frictions, country borders, crop choices, and non–homothetic preferences.



Model – Economy as a Line

back

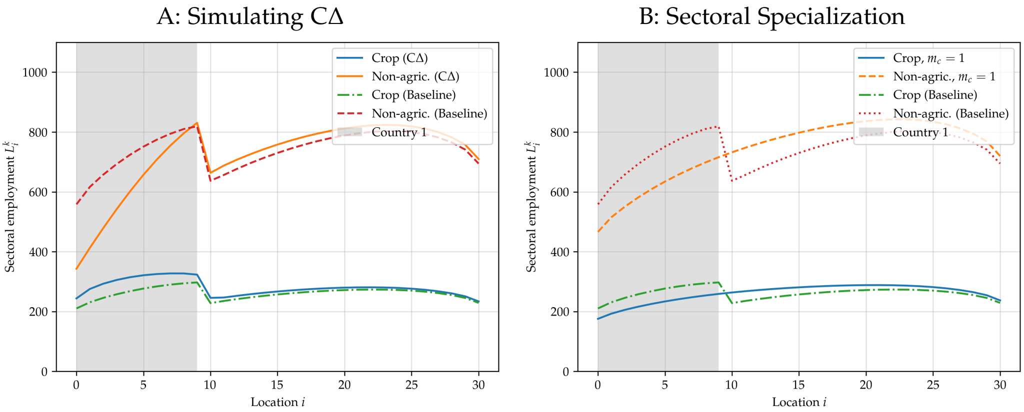
Figure 6: Role of bilateral migration frictions, trade frictions, country borders, crop choices, and non–homothetic preferences.



Model – Economy as a Line

back

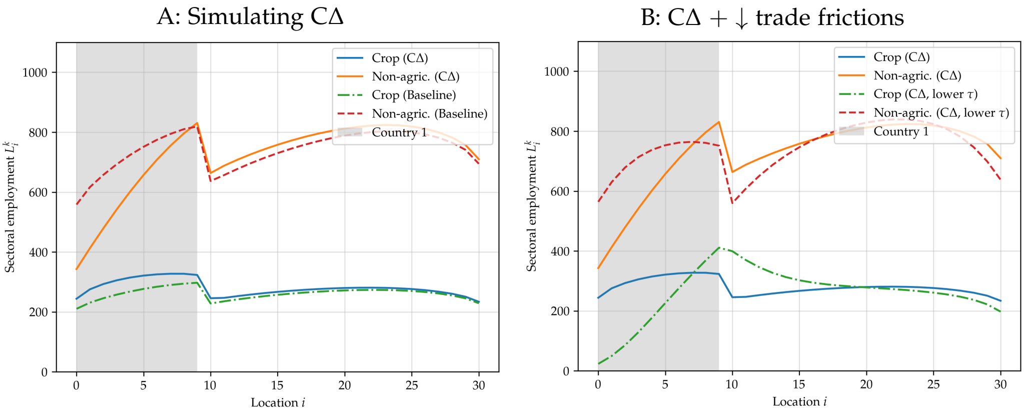
Figure 7: Role of bilateral migration frictions, trade frictions, country borders, crop choices, and non–homothetic preferences.



Model – Economy as a Line

back

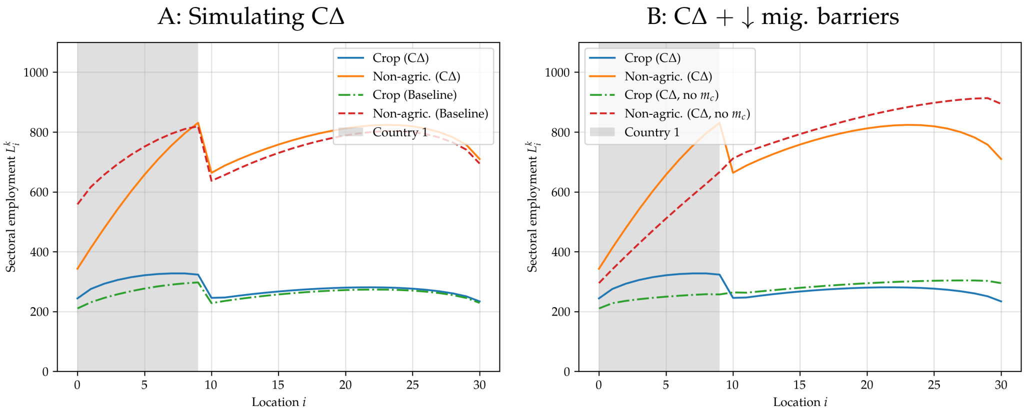
Figure 8: Role of bilateral migration frictions, trade frictions, country borders, crop choices, and non–homothetic preferences.



Model – Economy as a Line

back

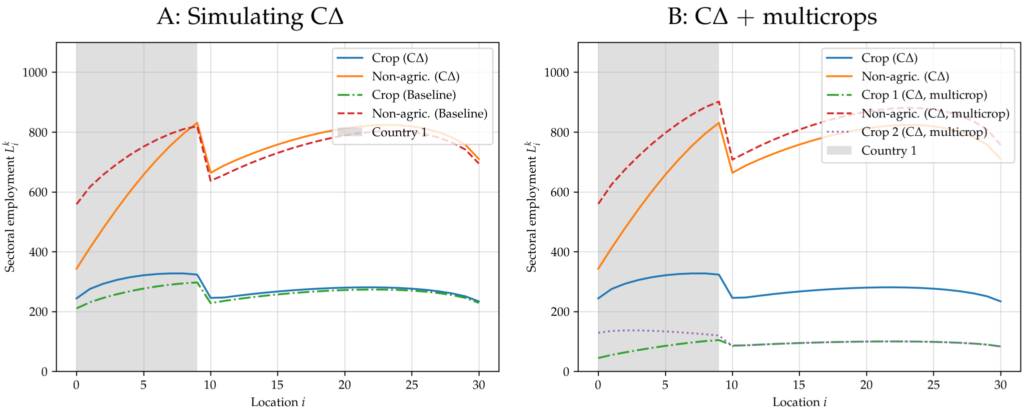
Figure 9: Role of bilateral migration frictions, trade frictions, country borders, crop choices, and non–homothetic preferences.



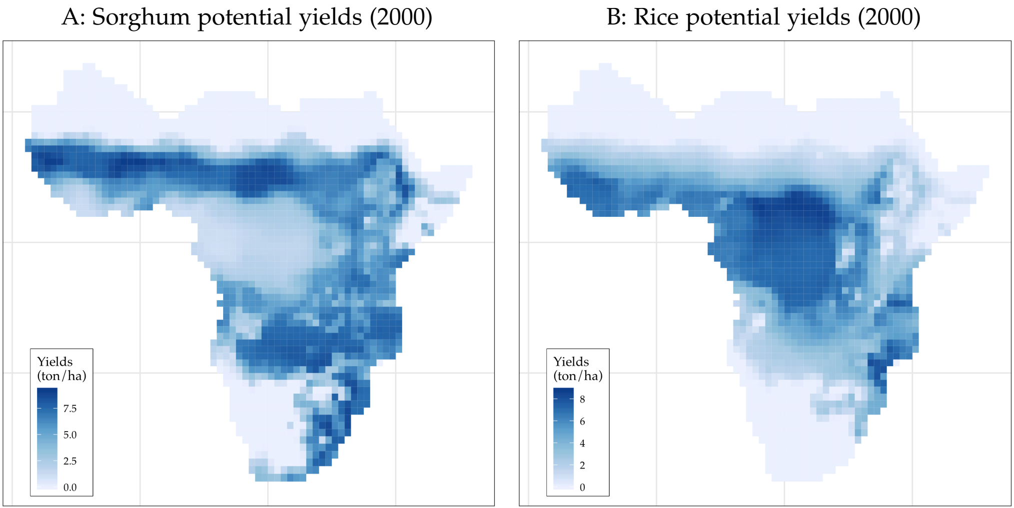
Model – Economy as a Line

back

Figure 10: Role of bilateral migration frictions, trade frictions, country borders, crop choices, and non–homothetic preferences.



Drawing $\{A_i^k\}$ from FAO-GAEZ back



Quantification Algorithm back

Method: invert the spatial equilibrium to (numerically) solve for:

1. $\{A_i^K, b_i^k, \Omega_a, \Omega_K, \tau^F\}_{i,k}$ (technology-side; inner/outer loop)
   - Inner loop: conditional on τ^F, pins dows $A_i^K, b_i^k, \Omega_a, \Omega_K$ targetting (respectively) the spatial distribution of GDP, of sectoral output, and aggregate (relative) non-agric. expenditure Note: normalize $A_i^K = 1$ (cannot separate from b_i^k)
   - Outer loop: iterates over $\tau^F \in [1, ..., 3]$ to match aggregate bilateral (and observed) country trade flows

2. $\{u_i, m_c, \phi\}_{i,c}$ (location-choice-side; inner/outer loop)
   - Inner loop: conditional on ϕ, pins down u_i, m_c targetting (respectively) the spatial distribution of population and country-level migration inflows
   - Outer loop: iterates over $\phi \in [1, ..., 2]$ to match aggregate internal migration flows $\sim$ 50 million (Myers, 1997, 2002; Brown et al., 2007; Gemenne et al., 2022)

Quantification Algorithm: Production/Consumption back

Inner loop: I use the market clearing condition of the model to build the equations for nominal GDP, sectoral wage bills, and aggregate sectoral expenditure shares (and invert them to solve for the elements of interest):

$$w_j L_j = \sum_{i \in S} \sum_{k \neq K} \lambda_{ji}^k \Xi_i^k \mu_i^a w_i L_i + \sum_{i \in S} \lambda_{ji}^K \mu_i^K w_i L_i \tag{1}$$

$$X_j^k = \sum_{i \in S} \lambda_{ji}^k \Xi_i^k \mu_i^a w_i L_i \quad \forall k \neq K \tag{2}$$

$$X_j^K = \sum_{i \in S} \lambda_{ji}^K \mu_j^K w_i L_i \tag{3}$$

$$X_K / X_a = \frac{\sum_{j \in S} \sum_{i \in S} \lambda_{ji}^K \mu_i^K w_i L_i}{\sum_{k \neq K} \sum_{j \in S} \sum_{i \in S} \lambda_{ji}^k \Xi_i^k \mu_i^a w_i L_i}. \tag{4}$$

Quantification Algorithm: Production/Consumption back

$$A_j^K = \left[\frac{w_j L_j - \sum_{i \in S} \sum_{k \neq K} \lambda_{ji}^k \Xi_i^k \mu_i^a w_i L_i}{\sum_{i \in S} \left(w_i \tau_{ji} / b_j^K P_i^K \right)^{1-\eta_K} \mu_i^K w_i L_i} \right]^{\frac{1}{\eta_K - 1}} \tag{5}$$

$$b_j^k = \left[\frac{X_j^k}{\sum_{i \in S} \left(w_j \tau_{ji} / A_j^k P_i^k \right)^{1-\eta_k} \Xi_i^k \mu_j^a w_i L_i} \right]^{1/(\eta_k - 1)} \qquad \forall k \neq K \tag{6}$$

$$b_j^K = \left[\frac{X_j^K}{\sum_{i \in S} \left(w_j \tau_{ji} / A_j^K P_i^K \right)^{1-\eta_K} \mu_j^K w_i L_i} \right]^{1/(\eta_K - 1)} \tag{7}$$

$$\Omega_K / \Omega_a = \frac{X^K}{X^a} \times \frac{\sum_{k \neq K} \sum_{j \in S} \sum_{i \in S} \lambda_{ji}^k \Xi_i^k \left(P_i^a / P_i \right)^{1-\sigma} \left(w_i / P_i \right)^{\varepsilon_a - (1-\sigma)} w_i L_i}{\sum_{j \in S} \sum_{i \in S} \lambda_{ji}^K \left(P_i^K / P_i \right)^{1-\sigma} \left(w_i / P_i \right)^{\varepsilon_K - (1-\sigma)} w_i L_i}. \tag{8}$$

Quantification Algorithm: Location Choice back

Inner loop: I optimal location choice equation to calculate L_i and L_c. Then, I invert them to pin down amenities and country barriers as a function of the former:

$$m_c = \left[L_c^{-1} \times \sum_{j \in c} \sum_{i \notin c} \frac{\left(w_j / P_j\right)^{\theta} m_{ij}^{-\theta} u_j}{\sum_{s \in c(j)} \left(w_s / P_s\right)^{\theta} m_{is}^{-\theta} u_s + \sum_{s \notin c(j)} \left(w_s / P_s\right)^{\theta} m_{is}^{-\theta} m_{c(s)}^{-\theta} u_s} L_{i0} \right]^{1/\theta} \tag{9}$$

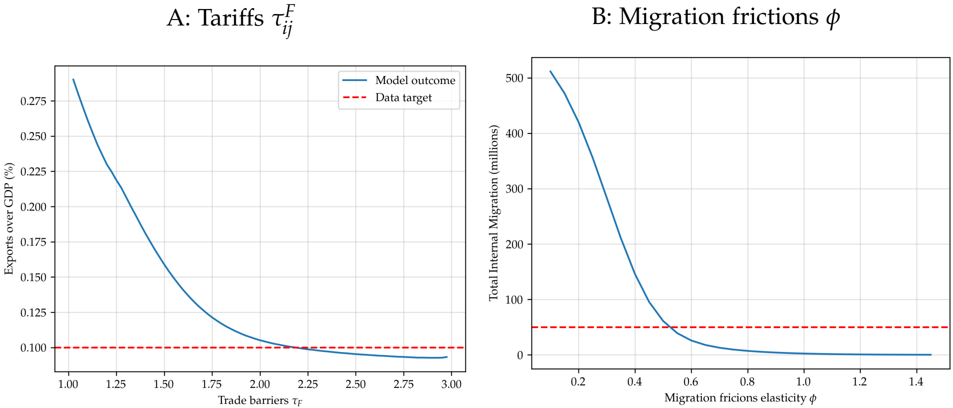
$$u_j = L_j \times \left[\sum_{i \in c(j)} \frac{\left(w_j / P_j\right)^{\theta} m_{ij}^{-\theta}}{\sum_{s \in c(j)} \left(w_s / P_s\right)^{\theta} m_{is}^{-\theta} u_s + \sum_{s \notin c(j)} \left(w_s / P_s\right)^{\theta} m_{is}^{-\theta} m_{c(s)}^{-\theta} u_s} L_{i0} + \right.$$

$$\left. \sum_{i \notin c(j)} \frac{\left(w_j / P_j\right)^{\theta} m_{ij}^{-\theta} m_{c(j)}^{-\theta}}{\sum_{s \in c(j)} \left(w_s / P_s\right)^{\theta} m_{is}^{-\theta} u_s + \sum_{s \notin c(j)} \left(w_s / P_s\right)^{\theta} m_{is}^{-\theta} m_{c(s)}^{-\theta} u_s} L_{i0} \right]^{-1} \tag{10}$$

Quantification Results: Outer Loops

back

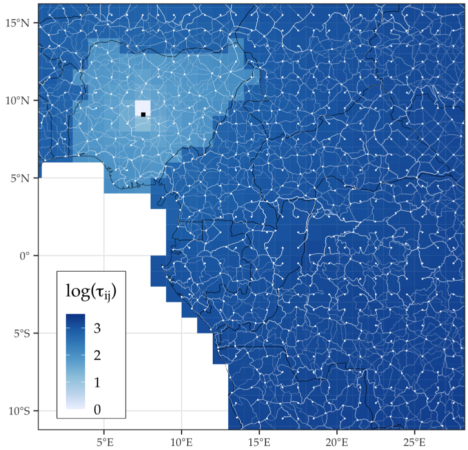
Figure 11: Results of the outer loops that solve for τ_{ij}^F and ϕ

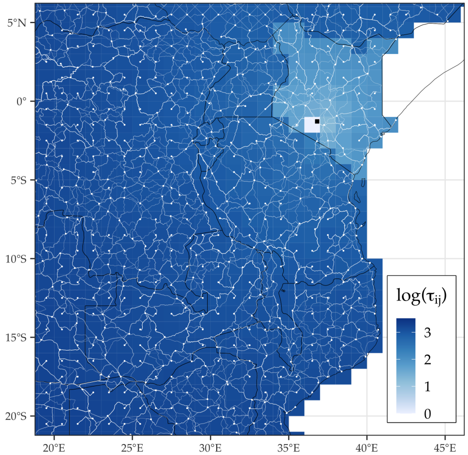


Notes: Panel A: Grid search over τ_{ij}^F (x-axis) and the resulting model-generated international trade flows (y-axis). The dashed red line stands for the target of the observed trade flows in the data. Panel B: analogous grid search over ϕ and the resulting model-generated internal migration flows.

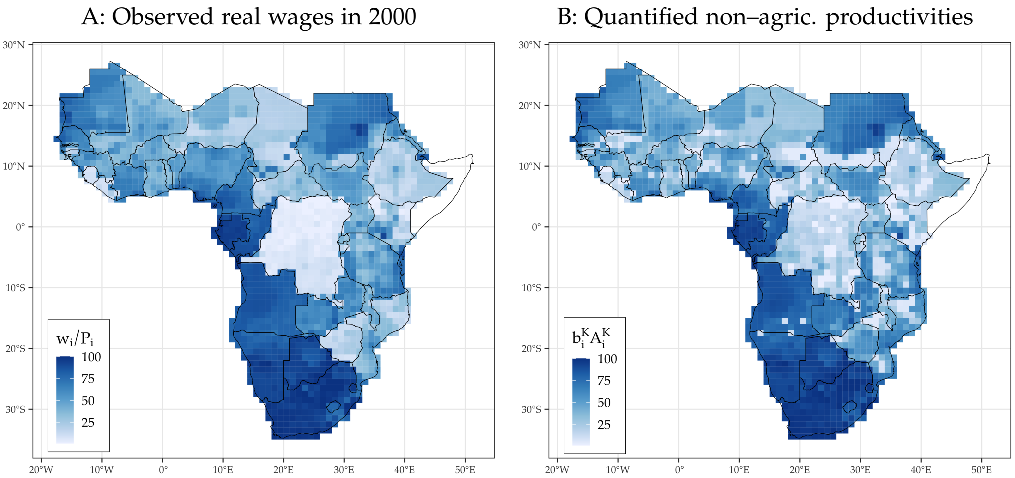
Geographic trade friction: distance$(i,j)^{\delta}$, $\delta = 0.3$ (Moneke, 2020);
Trade costs: distance$(i,j)^{0.3} \times \tau_F$, $\tau_F = 2.175$ (quantified)

Figure 12: Quantified trade network for two subsamples of SSA. back



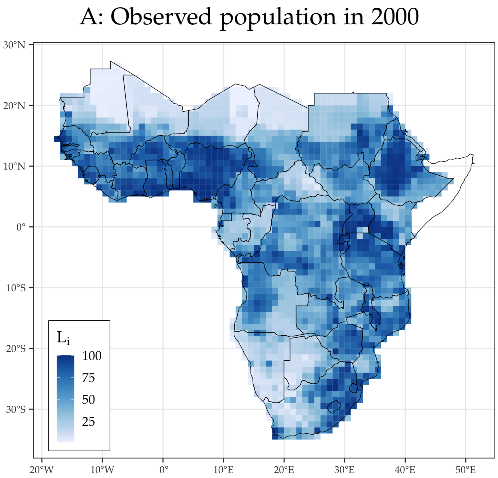


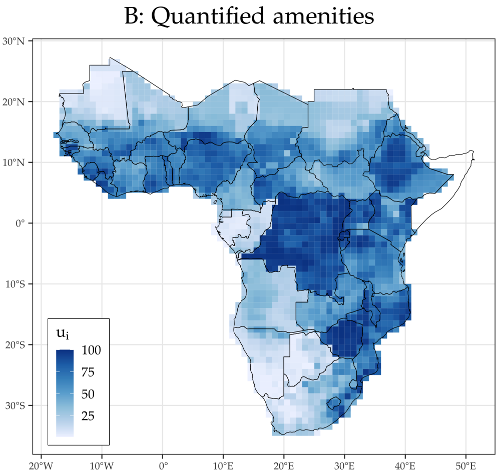
Quantification Results back



Notes: All results are shown in percentiles, where 1 (100) stands for the bottom (top) percentile of each sample. A and B document, respectively, the spatial distribution of the real wages in 2000 and the product of the quantified non–agricultural productivities productivity shifter of the non–agricultural sector.

Quantification Results back



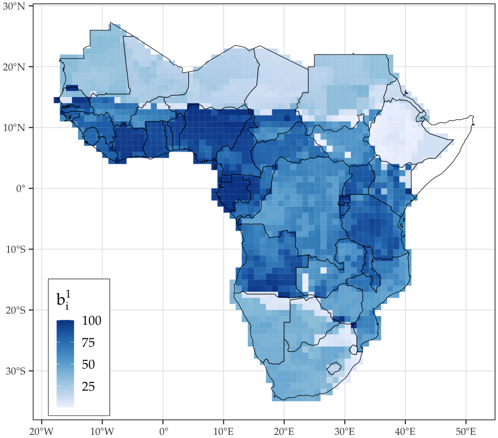


Notes: All results are shown in deciles, where 1 (100) stands for the bottom (top) decile of each sample. A and B document, respectively, the spatial distribution of observed population in 2000 and the quantified amenities .

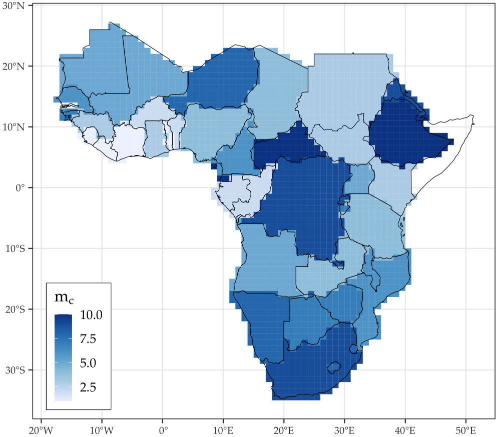
Quantification Results

back

A: Quantified shifters (cassava)



B: Quantified migration barriers

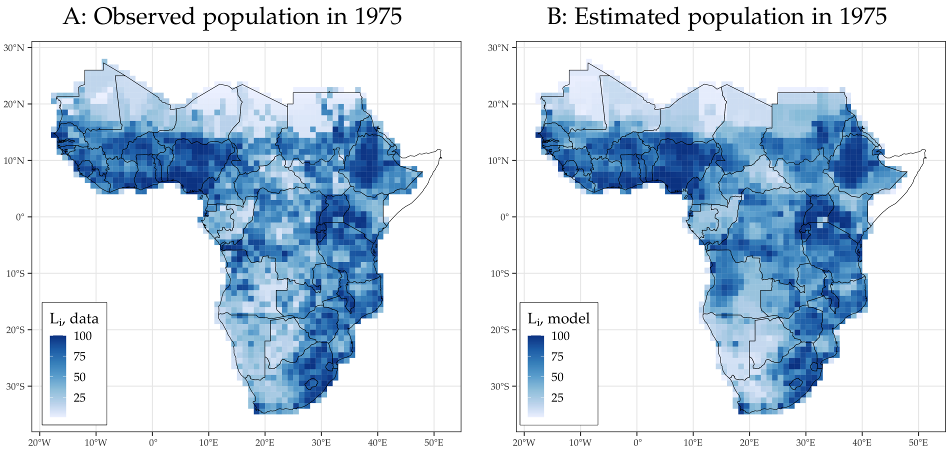


Notes: All results are shown in deciles, where 1 (100) stands for the bottom (top) decile of each sample. A and B document, respectively, the spatial distribution of the quantified cassava shifters and country migration barriers (the latter in deciles).

Validating the model: backcasting exercise using $\mathcal{L}$ and $\{A_i^k\}_{k \neq K}$ for 1975; check:

- model-implied population differences between 2000 and 1975
- extra: model-implied agricultural employment in 2000

Figure 13: Backcasting exercise: population distribution in 1975. back



Validating the model: backcasting exercise using $\mathcal{L}$ and $\{A_i^k\}_{k \neq K}$ for 1975; check:

- model-implied population differences between 2000 and 1975
- extra: model-implied agricultural employment in 2000.

Figure 14: Model goodness of fit: backcasting results for differences in population and labor shares in agriculture for 2000. back

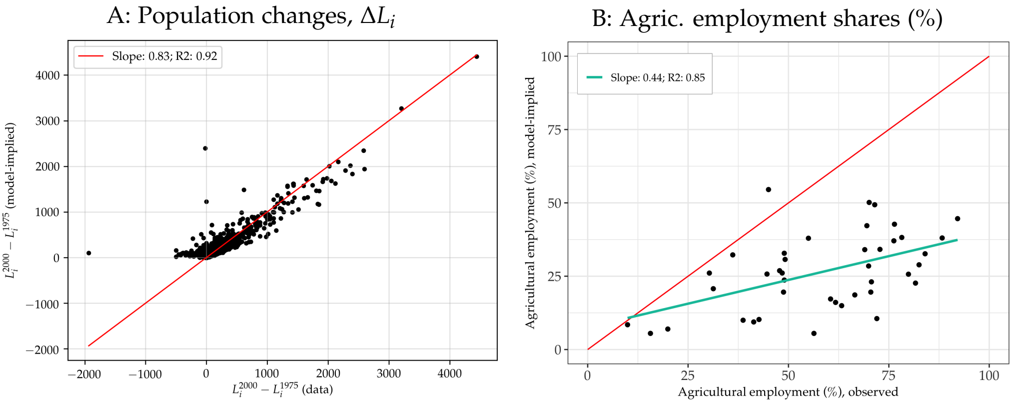
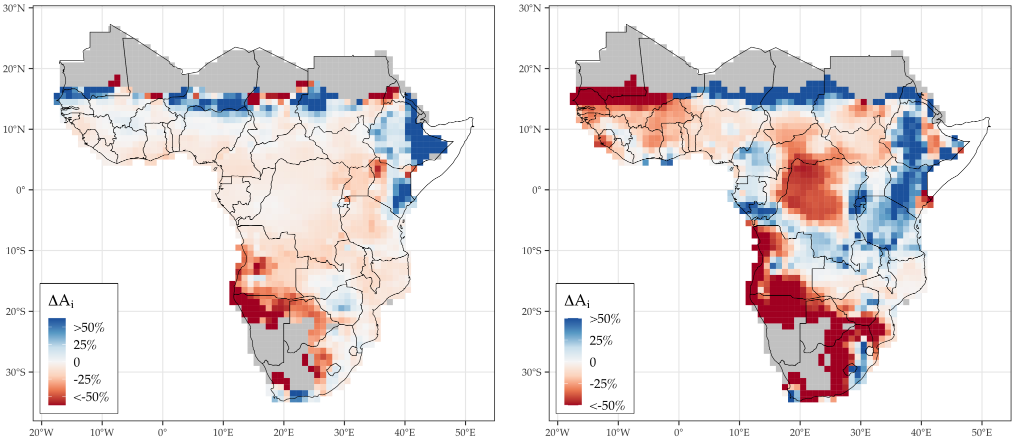


Figure 15: Change in agricultural suitabilities in SSA. back

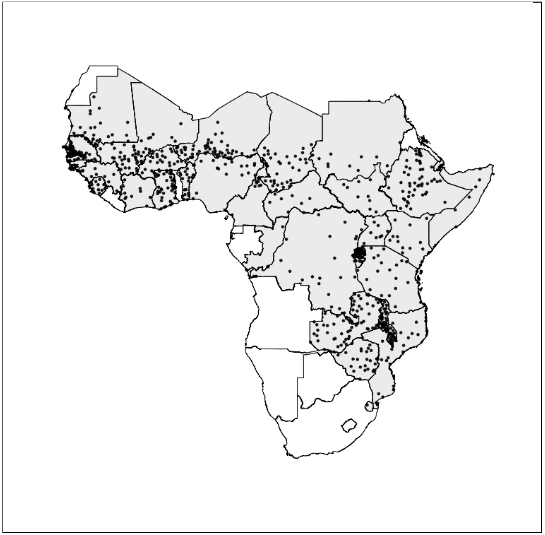
A: Change in average suitability to agriculture (1975–2000).

B: Change in average suitability to agriculture (2000–2080).



Newly Collected Price Data

back



Crop price data from WFP-VAM project (FAO):

- $\sim$ 40 countries and 900 markets (coordinates)
- 4 crops: maize, millet, sorghum, rice
- Covers 2000–2018

No origin-destination structure: use price dispersion to pin down δ (SMM)

Figure 16: Climate migration in SSA – baseline results for 2080. back

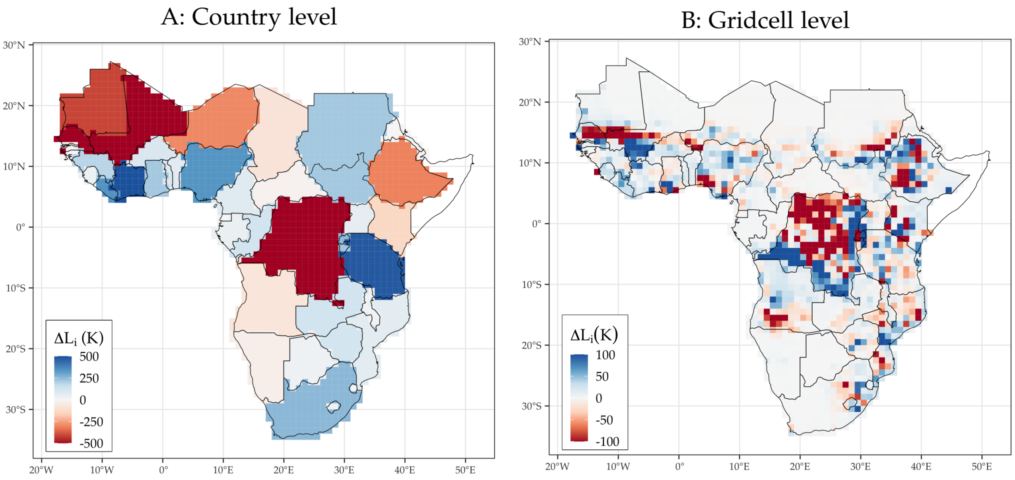


Figure 17: Climate change impact on non-agricultural employment. back

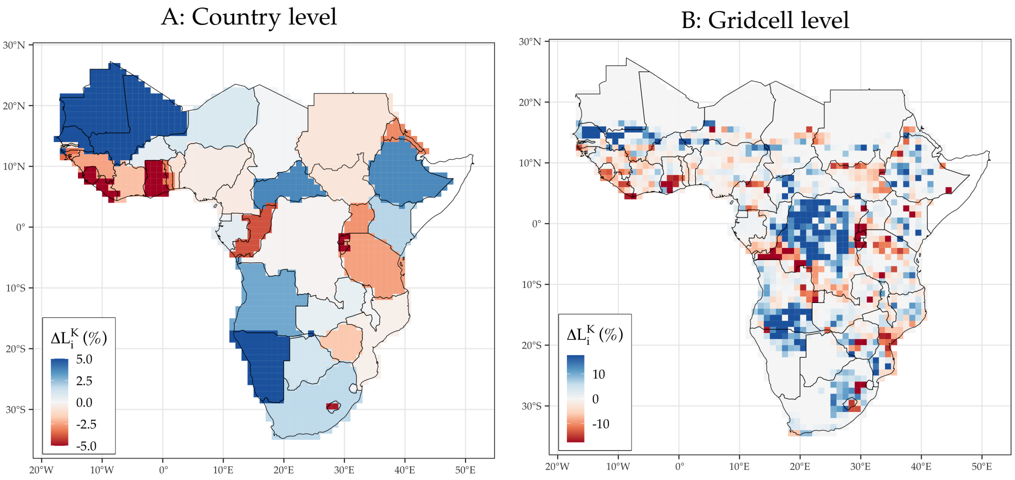


Figure 18: Climate change impact on real GDP per capita. back

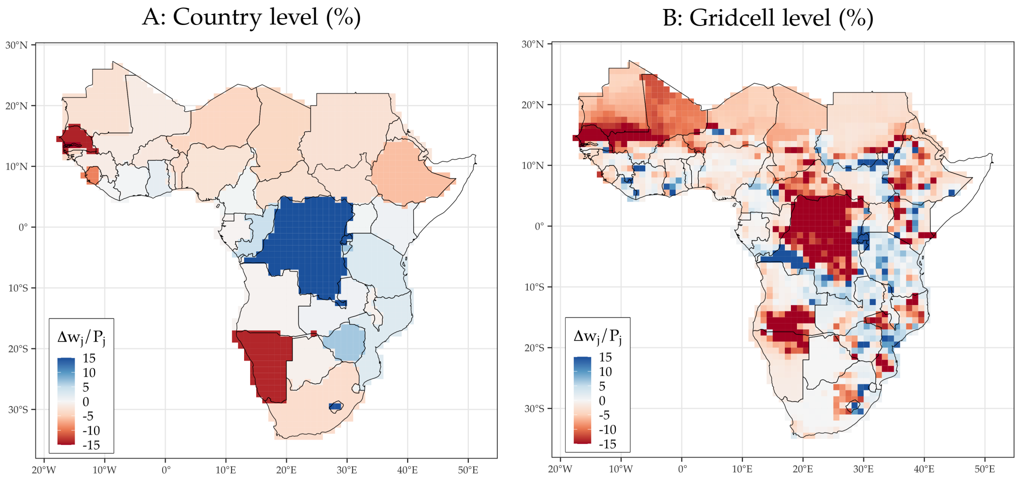
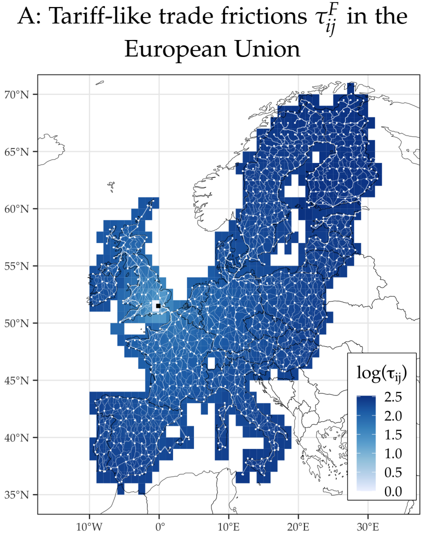
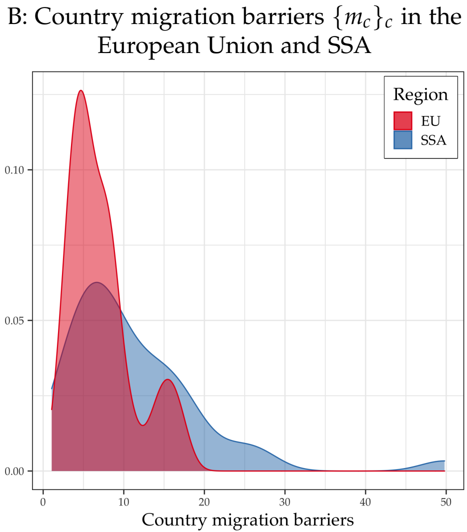


Figure 19: Estimated trade and migration frictions in the European Union back





Notes: Panel A presents trade frictions in the EU as done for SSA in Figure 12 (in this context, trade frictions are relative to Barcelona (Spain), represented by the black dot). Panel B plots the distribution of country migration barriers $\{m_c\}_c$ in SSA and the EU.

Robustness Checks and Additional Experiments back

	(1) Climate migration (million individuals)	(2) Δ GDP per capita (%)	(3) Δ Non–agricultural employment (%)
Benchmark results	4.02	-1.18	-0.85
Panel A: Robustness to frictions			
Higher trade frictions	17.41	-7.05	-3.19
Lower trade frictions	2.01	0.10	0.50
Higher migration frictions	0.37	-1.78	-1.11
Lower migration frictions	24.47	1.06	-0.33
Panel B: Robustness to assumptions and CΔ scenario			
Homothetic preferences	3.52	4.38	-1.94
Endogenous fertility	2.52	2.72	1.77
RCP 4.5 scenario	1.34	1.86	1.28

Notes: Panel A presents the aggregate effect of climate change for different levels of trade and migration frictions, driven by the parameters δ and ϕ, respectively. Panel B presents the results of the benchmark simulation when (separately) assuming homothetic preferences between agriculture and non-agriculture, endogenous fertility, and a less severe climate change scenario.

Theory Appendix

Model: Technology and Market Structure back

- Representative firm, linear technology, labor as unique input;

- TFP: product of sector-specific efficiency (b) and natural advantage (A) shifter:

$$q_i^k = b_i^k \times A_i^k \times L_i^k \quad \forall i, j, k$$

- Free mobility of workers across sectors $\rightarrow w_i^k = w_i \; \forall i, k$;

- Production is consumed locally and/or shipped (traded), perfect competition and full information in trade;

- If $q_{ij}^k > 0$, prices equals marginal (production + shipping) costs:

$$p_{ij}^k = (w_i / b_i^k A_i^k) \times \tau_{ij},$$

Model: Preferences back

- Continuum of workers $\forall i$; worker v born in i choosing to live in j enjoys:

$$U_{ij}(v) = C_j \times \bar{m}_{ij}^{-1} \times \varepsilon_j(v);$$

- C_j: utility from consumption of goods in j;

- $\bar{m}_{ij} \equiv$ migration cost between i and j:
  - $\bar{m}_{ij} = m_{ij} = \text{dist}(i,j)^{\phi}$ if $j \in c(i)$,
  - $\bar{m}_{ij} = m_{ij} \times m_{c(j)}$ otherwise, and
  - $c(i)$: country where location i belongs to.

- $\varepsilon_j(v)$: v's taste for living in j, drawn i.i.d. from G_j.

Model: Consumption Choice back

- Consumption: choose sector k varieties from $\forall i \in S$

$$C_j^k = \left(\sum_{j \in \mathcal{S}} \left(q_{ij}^k \right)^{\frac{\eta_k - 1}{\eta_k}} \right)^{\frac{\eta_k}{\eta_k - 1}} ;$$

- q_{ji}^k: per capita consumption of j's varieties of good from sector k in i;

- Crops: $K - 1$ sectors aggregated up into a CES $''a''$ composite

$$C_j^a = \left(\sum_{k \neq K} \left(C_j^k \right)^{\frac{\gamma - 1}{\gamma}} \right)^{\frac{\gamma}{\gamma - 1}}$$

Model: Consumption Choice back

- Budget constraint: $\sum_{j\in S}\sum_{k\in\mathcal{K}} p_{ji}^k q_{ji}^k = w_i$, max. w.r.t. $q_{ji}^k \rightarrow$

$$\lambda_{ji}^k = \frac{p_{ji}^k q_{ji}^k}{\sum_{j\in S} p_{ji}^k q_{ji}^k} = \left(p_{ji}^k / P_i^k\right)^{1-\eta_k},$$

$$P_i^k = \left(\sum_{j\in\mathcal{S}} \left(p_{ji}^k\right)^{1-\eta_k}\right)^{\frac{1}{1-\eta_k}}$$

- Analogous results for C_i^k's shares *within agriculture*:

$$\Xi_j^k = \left(P_j^k / P_j^a\right)^{1-\gamma},$$

$$P_j^a = \left(\sum_{k\neq K} \left(P_j^k\right)^{1-\gamma}\right)^{\frac{1}{1-\gamma}}.$$

Model: Consumption Choice back

- Non–/agriculture choice (K, a): non–homothetic CES as in Comin et al. (2021);

- C_j implicitly determined in

$$\sum_{k \in \{a,K\}} \left(\Omega^k\right)^{1/\sigma} \left(C_j\right)^{\epsilon_k/\sigma} \left(C_j^k\right)^{(\sigma-1)/\sigma} = 1$$

- $C_j \equiv w_j / P_j$ and $\mu_j^k \equiv P_j^k C_j^k / w_j$ such that:

$$\mu_j^k = \Omega^k \times \left(P_j^k / P_j\right)^{1-\sigma} \times \left(w_j / P_j\right)^{\epsilon_k - (1-\sigma)} \quad \forall k \in \{a, K\},$$

$$P_j = \left(\sum_{k \in \{a,K\}} \left(\Omega^k \left(P_j^k\right)^{1-\sigma}\right)^{\frac{1-\sigma}{\varepsilon_k}} \times \left(\mu_j^k w_j^{1-\sigma}\right)^{\frac{\varepsilon_k - (1-\sigma)}{\varepsilon_k}} \right)^{\frac{1}{1-\sigma}}$$

Model: Consumption Choice

back

- Bilateral demand in j from sector k goods from i is X^k_{ji}:

$$X^k_{ij} = \lambda^k_{ij}\Xi^k_j \mu^k_i w_j L_j \quad \forall k \neq K, \text{ and}$$
$$X^K_{ij} = \lambda^K_{ij}\mu^K_j w_j L_j.$$

- Bilateral trade flows from i to j:

$$X_{ij} = \sum_{k \in \mathcal{K}} X^k_{ij} = \sum_{k \neq K} \lambda^k_{ij}\Xi^k_j \mu^k_i w_j L_j + \lambda^K_{ij}\mu^K_j w_j L_j.$$

Model: Location Choice back

- Choice of worker v born in i:

$$\max_j \quad U_{ij}(v) = (w_j/P_j) \times \bar{m}_{ij}^{-1} \times \varepsilon_j(v)$$

- Assumption: $\varepsilon_j \sim G_j(z) = e^{-z^{-\theta} \times u_j L_j^{-\alpha}}$
  - u_j: amenity level of location j;
  - θ: dispersion parameter, decreasing with workers' heterogeneity;
  - α: degree of "disutility" w.r.t. population density.

- Implication (Redding, 2016, among others):

$$\Pi_{ij} = \frac{(w_j/P_j)^{\theta} \bar{m}_{ij}^{-\theta} u_j L_j^{-\alpha}}{\sum_{s \in S} (w_s/P_s)^{\theta} \bar{m}_{is}^{-\theta} u_s L_s^{-\alpha}}$$

Model: Spatial Equilibrium back

Given a geography $\mathcal{G}(S) = \{\mathcal{L}, \mathcal{A}, \mathcal{U}, \mathcal{T}, \mathcal{M}\}$ and parameters $\{\theta, \alpha, \sigma, \gamma_a, \{\eta_k\}_k, \{b_i^k\}_{i,k}\}$, a spatial equilibrium is a vector of wages and labor allocations $\{w_j, L_j\}_{j\in S}$ such that

1. Prices solve firms' and workers consumption choice problems;
2. Labor allocations solve workers' location choice problem (labor market clearing);
3. Markets for goods clear; i.e. total GDP equals total sales and total expenditure:

$$w_j L_j = \sum_{i\in\mathcal{S}} X_{ij} = \sum_{i\in\mathcal{S}} X_{ji} \quad \forall j.$$

$\rightarrow$ following system of $6 \times N$ equations and unkowns:

Model: Spatial Equilibrium back

$$
\begin{aligned}
w_j L_j = & \sum_{i \in S} \sum_{k \neq K} \left(\frac{w_i \tau_{ij}}{b_i^k A_i^k P_j^k} \right)^{1-\eta_k} \left(\frac{P_j^k}{P_j^a} \right)^{1-\gamma_a} \Omega^a \left(\frac{P_j^a}{P_j} \right)^{1-\sigma} \left(\frac{w_j}{P_j} \right)^{\epsilon_a - (1-\sigma)} w_j L_j \; + \\
& + \sum_{i \in S} \left(\frac{w_i \tau_{ij}}{b_i^K A_i^K P_j^K} \right)^{1-\eta_K} \Omega^K \left(\frac{P_j^K}{P_j} \right)^{1-\sigma} \left(\frac{w_j}{P_j} \right)^{\epsilon_K - (1-\sigma)} w_j L_j
\end{aligned} \tag{11}
$$

$$
P_j^k = \left(\sum_{i \in S} (w_i \tau_{ij} / b_i^k A_i^k)^{1-\sigma} \right)^{\frac{1}{1-\sigma}} \tag{12}
$$

$$
P_j^a = \left(\sum_{k \neq K} \left(P_j^k \right)^{1-\gamma_a} \right)^{\frac{1}{1-\gamma_a}} \tag{13}
$$

$$
P_j = \left(\sum_{k \in \{a,K\}} \left(\Omega^k \left(P_j^k \right)^{1-\sigma} \right)^{\frac{1-\sigma}{\varepsilon_k}} \left(\mu_j^k w_j^{1-\sigma} \right)^{\frac{\varepsilon_k - (1-\sigma)}{\varepsilon_k}} \right)^{\frac{1}{1-\sigma}} \tag{14}
$$

$$
\mu_j^k = \Omega^k \left(P_j^k / P_j \right)^{1-\sigma} \left(w_j / P_j \right)^{\epsilon_k - (1-\sigma)} \tag{15}
$$

$$
L_j = \sum_{i \in S} \frac{(w_j / P_j)^{\theta} \bar{m}_{ij}^{-\theta} u_j L_j^{-\alpha}}{\sum (w_s / P_s)^{\theta} \bar{m}_{is}^{-\theta} u_s L_s^{-\alpha}} \times L_i^0 \tag{16}
$$