# Climate Change, Income Inequality, and Migration in a Spatial Economy

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# Motivation

**Migration is commonly viewed as an important adaptation strategy to climate change**

- *"When people decide [...] to move due to environmental and climatic changes [...] their mobility is an adaptation strategy that allows them to minimize harm for themselves and/or improve their overall lives."* Source: International Organization for Migration (IOM)
- *Most migration is intra-national*

Magnitudes

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**Strong evidence that migration behavior varies across the income distribution**

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**Climate change may increase the incentives to migrate, while simultaneously constraining the ability to do so**

# What I do

**Key questions**

- How does income shape the migration response of individuals to climate change?
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- Calibrate to Brazilian data
- Simulate the effects of rising temperatures in Brazil

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**Evaluate counterfactual policy**

- How high would the welfare losses of climate change be if low-income households received a targeted migration subsidy?

# Preview of findings

**Welfare losses from climate change are highly regressive**

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**Migration plays a limited role as an adaptation strategy at baseline costs**

- A sizable share of low-income workers cannot afford to migrate

**A counterfactual migration subsidy is equitable and fiscally sustainable**

- It raises welfare among low-income workers
- It mitigates the welfare losses from climate change
- It reallocates labor toward more productive regions, increasing aggregate output, making it partly self-financing

# Related literature

*Embed monetary migration costs into a dynamic GE model*
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**Migration in spatial models:** **Burzyński, Deuster, Docquier, de Melo, 2022; Caliendo, Dvorkin, and Parro, 2019; Conte, 2022; Conte, Desmet, Nagy, and Rossi-Hansberg, 2021; Cruz and Rossi-Hansberg, 2024; Cruz, 2024; Desmet and Rossi-Hansberg, 2015; Jedwab, Haslop, Zarate, and Rodriguez Castelan, 2023; Morten and Oliveira, 2024** **Exceptions: Kennan & Walker, 2011; Bryan, Chowdhury, and Mobarak, 2014; Aron-Dine, 2024; Kleemans, 2015**

- Migration costs enter as utility (taste) shifters.
- Unconstrained optimal choices.

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**Income and migration:** Cattaneo & Peri, 2016; Bryan, Chowdhury, and Mobarak, 2014; Cai, 2020; Gazeaud, Mvukiyehe, and Sterck, 2023; Bastian & Black, 2022

- Liquidity constraints limit migration among low-income workers.
- Gap between incentives to migrate and realized migration.

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**Income and migration:**

- Liquidity constraints limit migration among low-income workers.
- Gap between incentives to migrate and realized migration.

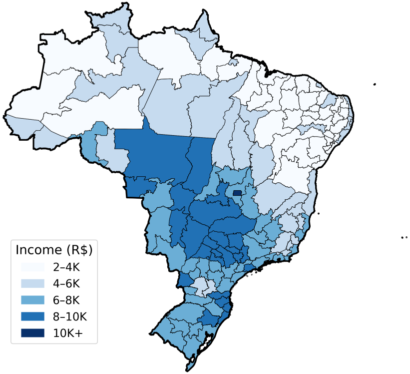
**I resolve this tension**

- I introduce liquidity constraints into a dynamic spatial GE model to study climate change impacts.
- I model costs as **monetary and non-monetary** $\Rightarrow$ migration choices are **constrained**.
- Poor households may want to migrate but cannot finance it $\Rightarrow$ **policy implications differ** (subsidies vs. taxes).

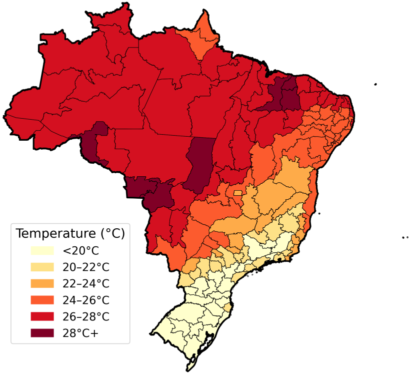
# Setting

# Setting: Brazil

**Large middle-income country (∼210 million) with pronounced spatial inequality**
**∼10 million employed in agriculture; strong north–south climate gradient (∼10 °C)**



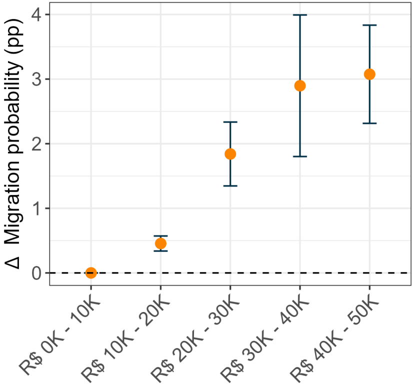

(a) Average annual income of workers in crop cultivation (Data: 2010 Census) Details




(b) Average annual near-surface temperature (Data: CMIP6) Details

# Setting

**High-income workers are more likely to move**

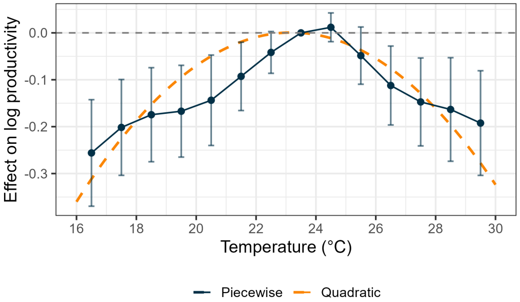



*Data: 2010 Census. Sample: Individuals aged 25–64 with positive income. Reference group: R$ 0K-10K. Specification includes mesoregion fixed-effects.*

▸ Data ▸ Specification

# Setting

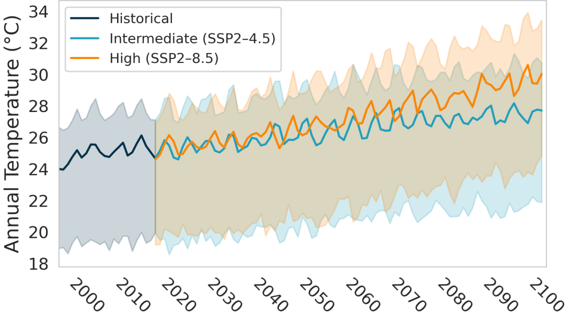
**Agricultural productivity peaks at 23.5°C**




*Data: PAM (1994-2014). Unit of observation: Mesoregion observed over time. Normalized to 0 at optimum. Specifications include mesoregion cubic time trends.*

▸ Data ▸ Specification

# Intuition




- Rising temperatures imply losses in regions above the productivity peak (North) and gains elsewhere (South)
- Creates incentives for agricultural workers in the North to migrate South $\rightarrow$ but less mobile than high-income workers!

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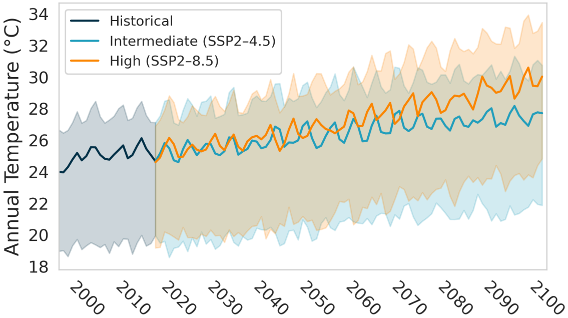


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**What does this mean for welfare & the distribution of losses across the income distribution? $\rightarrow$ introduce model next**

# Model

# Overview

## Model parts

**1. Static trade model**
pins down prices & incomes

**2. Dynamic migration model**
pins down migration flows

### Preferences

- Cobb–Douglas between agriculture and non-agriculture
- CES across regional agricultural varieties (Armington)

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**Production**

- Agriculture: land + labor, heterogeneous land quality
- Non-agriculture: labor only, heterogeneous job productivity

▸ Details

# Sectoral allocation

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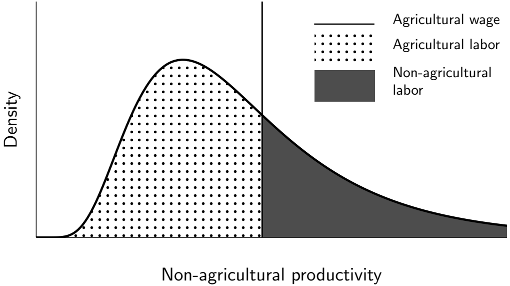
## Sectoral choice

- Workers draw a non-agricultural job offer
- Jobs differ in their productivity
- Agricultural wage acts as reservation wage
- Roy-style selection (Lucas–Luttmer cutoff)

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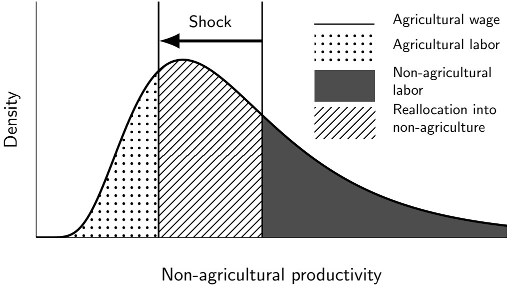


Details

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**Workers**

- Start in region $j$ with income $y$
- Make forward-looking migration decisions in every period

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**Preferences and costs**

- Logarithmic utility
- Migration cost = monetary $\chi^{j,i}$ + psychic $\kappa^{j}$

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**No savings**

- Migration must be financed from current income

Details

# Migration costs

## Model parts

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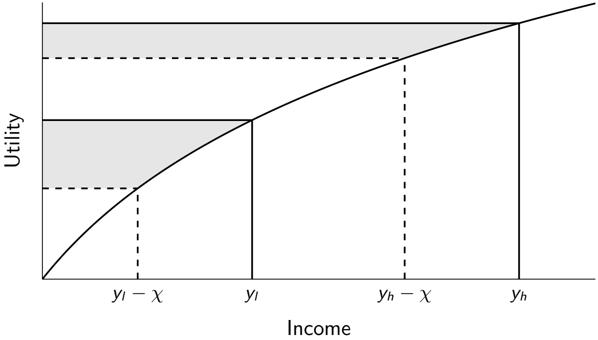
**Corollary:** A fixed cash cost implies a larger utility loss at low incomes.




▸ Details

# Utility-equivalent costs

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## Utility-equivalent monetary cost

$$\tilde{\tau}^{j,i}(y) = \log\left(\frac{y}{y - \chi^{j,i}}\right)$$

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**Composite cost**

$$\tau^{j,i}(y) = \tilde{\tau}^{j,i}(y) + \mathbf{1}(i \neq j)\kappa^{j}$$

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**Feasibility**

– If $y \leq \chi^{j,i}$, migration to $i$ is infeasible

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The utility cost of migrating is endogenous to income!
$\Rightarrow$ Absent in current workhorse models

Details

# Income persistence

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To keep the model easy & tractable (rework in progress)

**Income realization**

- Each worker has a rank $r \in (0, 1)$ in the local job ladder
- Rank determines income given local wages

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**Persistence (Calvo-style)**

- With prob. $\rho$: keep rank next period
- With prob. $1 - \rho$: redraw rank

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**Interpretation**

- Income, sector, and mobility are persistent

# Dynamic problem — Structure

## Model parts

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**Dynamic migration problem of a worker in region $j$ at time $t$ with rank $r$**

$$v_t^j(r) = \underbrace{U\left(C_t^j\left(y_t^j(r)\right)\right)}_{\text{baseline utility}} + \max_{i \in \mathcal{S}} \left\{ \underbrace{-\tau^{j,i}\left(y_t^j(r)\right) + \nu \upsilon_t^i}_{\text{current migration payoff}} + \underbrace{\beta E_t\left[v_{t+1}^i(\cdot)\right]}_{\text{continuation value}} \right\}$$

Migration trades off current utility and costs against discounted future payoffs.

**Notation:** $y_t^j(r)$ = income associated with rank $r$, $\tau^{j,i}(y)$ = migration cost, $\upsilon_t^i$ = location preference shock, $\nu$ = taste-shock dispersion, $\beta$ = discount factor

▸ Expected lifetime utility

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$$\left. + \underbrace{\beta\left[\underbrace{\rho E_t\left[v_{t+1}^i(r)\right]}_{\text{rank persistence}} + \underbrace{(1-\rho)E_t\left[v_{t+1}^i(r')\right]}_{\text{rank redraw}}\right]}_{\text{continuation value}} \right\}$$

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Expected lifetime utility

# Migration choices

## Model parts

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## Migration choice probabilities

$$\mu_t^{j,i}(r) = \frac{\exp\left(\left[\beta V_{t+1}^i(r) - \tau^{j,i}\left(y_t^j(r)\right)\right]/\nu\right)}{\sum_{k\in\mathcal{S}} \exp\left(\left[\beta V_{t+1}^k(r) - \tau^{j,k}\left(y_t^j(r)\right)\right]/\nu\right)}$$

## Continuation value:

$$V_{t+1}^i(r) \equiv \rho\, E_t\left[v_{t+1}^i(r)\right] + (1-\rho)\, E_t\left[v_{t+1}^i(r')\right]$$

**Notation:** $\mu_t^{j,i}(r)$ = probability that a worker of rank $r$ in $j$ chooses $i$, $\tau^{j,i}(y)$ = migration cost, $\nu$ = logit scale parameter, $r'$ = newly drawn rank.

Details

# Equilibrium

**Dynamic spatial general equilibrium**

An equilibrium is a sequence

$$\left\{ L_t^i,\ p_t^{j;a},\ p_t^0,\ w_t^{i;a},\ \mu_t^{j,i} \right\}_{t=1}^{T}, \qquad i,j \in \mathcal{S},$$

such that:

- For each period $t$, prices and wages constitute a temporary equilibrium given regional labor allocations $\{L_t^i\}_{i\in\mathcal{S}}$;
- Given the resulting sequence of temporary equilibria, workers choose migration optimally;
- Regional labor stocks evolve according to

$$L_{t+1}^i = \sum_{j\in\mathcal{S}} \mu_t^{j,i} L_t^j.$$

Prices & wages adjust within periods; labor reallocates across periods.

▸ Income ⟶ Value    ▸ Solution algorithm

# Calibration

# Calibration

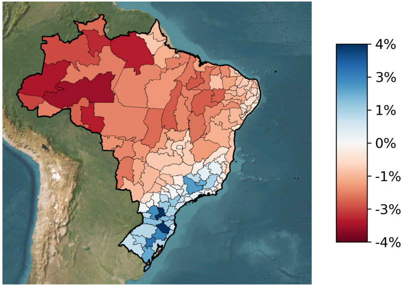
**The calibration proceeds in three stages:**

1. **Baseline economy (2010):** Model inversion of the static trade model to match observed 2010 data.
   ▸ Model inversion
2. **Counterfactual fundamental productivity:** Map projected temperature changes into regional productivity paths using the estimated temperature–productivity relationship.
   ▸ Climate change
3. **Dynamic part and migration costs:** Calibrate intertemporal parameters and mobility frictions to match observed migration patterns.

Together, these steps ensure consistency between the 2010 benchmark, the climate-induced productivity shocks, and agents' dynamic migration responses.

# Results

# Results I: Welfare effects by income & region



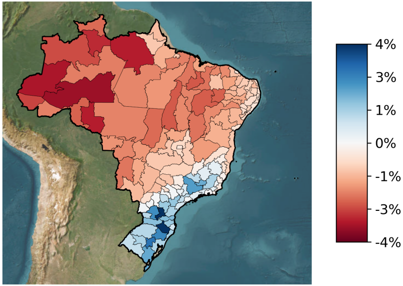

(a) Lowest income percentile


(b) Highest income percentile

**Two patterns:**

- **Strong spatial heterogeneity:** hot regions lose, cooler regions gain
- **Highly regressive effects in hot regions:** losses are concentrated among low-income households

# Results I: Welfare effects by income & region

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**Interpretation:**

- Low-income households in the North would require a **3-4% permanent increase in consumption** (2010–2100) to offset climate-change losses.

▸ Welfare measure ▸ Additional results

# Results II: Migration as adaptation?

| Income group | Share unable to migrate ($\chi \geq y$) | Mean migration probability |
|---|---|---|
| Low income ($\leq$10k) | 52.43% | 5.41% |
| Middle income (10-20k) | 6.48% | 6.39% |
| High income ($>$20k) | 0.38% | 11.77% |

**Migration plays a limited role as an adaptation strategy to climate change.**

- Over 50% of low-income households cannot afford **any** migration.
- Average migration rates are 5.41% per period; about half those of high-income households.

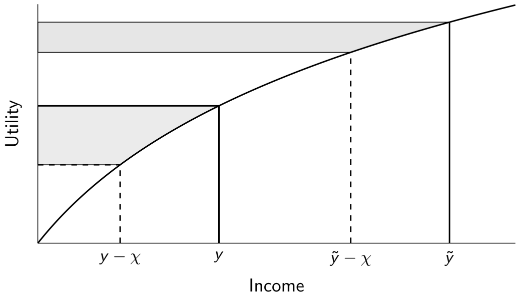
# Counterfactual policy: Targeted migration subsidy

**Reminder**

- A fixed cash cost implies a larger utility loss at low incomes.

**Counterfactual subsidy**

- Poor households receive a subsidy so their migration burden matches richer households.



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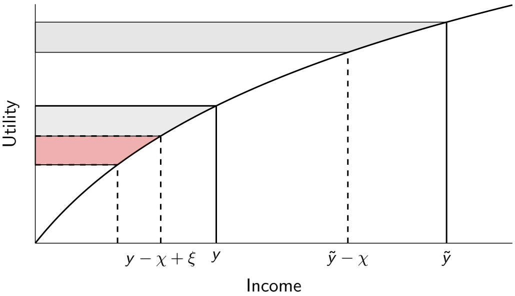



**Subsidy rule:**

$$U(y) - U(y - \chi + \xi) = U(\tilde{y}) - U(\tilde{y} - \chi)$$

Derivation

# Counterfactual policy I: Impact of the subsidy

| | R$ 0–10k | R$ 10–20k | R$ >20k | All households |
|---|---|---|---|---|
| Subsidized vs. Baseline (CEV, %) | 24.09 | 5.49 | 1.33 | 8.22 |
| Share of climate losses removed (%) | 4.16 | 4.10 | 1.01 | 2.92 |

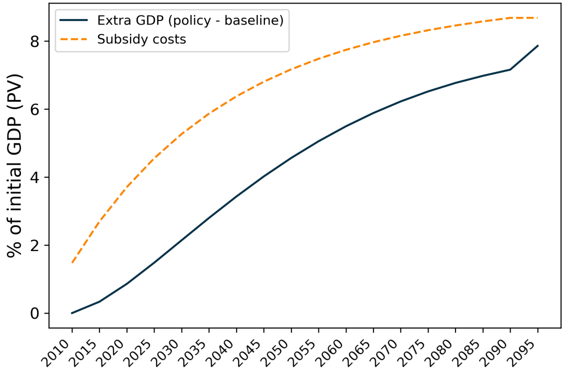
**The subsidy yields large welfare gains for low-income workers, especially in the Northeast**

→ Driven by migration toward more productive regions

**The subsidy modestly reduces the welfare impact of climate change**

▸ Mobility effects ▸ Additional results

# Counterfactual policy II: Fiscal costs and dynamic payoffs




- Discounted present value of subsidy payments: **8.7%** of 2010 GDP
  Details
- Discounted present value of GDP gains: **7.9%**
  → Coverage ratio of about **90%**
- Fiscal costs accrue gradually, while GDP gains materialize over time

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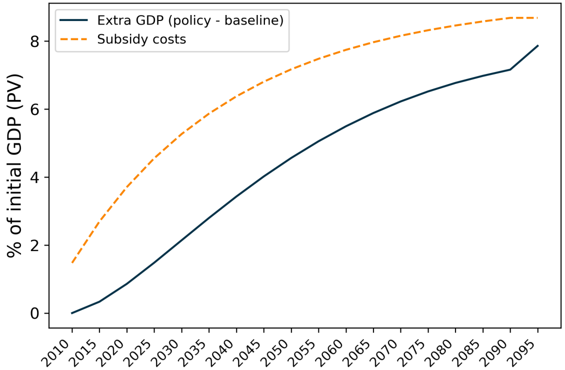


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**Mechanism:**

Subsidized migration reallocates labor toward higher-productivity regions:

→ Output per worker increases by **6.4%** in agriculture

→ Aggregate output increases by **10%**

# Conclusion

**What I do:**

- Embed **monetary migration costs and liquidity constraints** into a dynamic spatial general equilibrium model to match empirical evidence on income gradients in migration.

**Main insight:**

- Observed migration flows reflect **binding constraints**, not globally optimal location choices.
- Liquidity constraints make climate change **more regressive** and hinder spatial adjustment.

**Implications:**

- Policy implications differ from canonical models: **subsidies vs. taxation**.
- Treating migration costs as monetary makes spatial frictions **directly actionable**.

# Appendix

# Appendix — Migration by type

**Brazil illustrates the scale of internal mobility. Between 2005 and 2010:**

- **13 million** people moved across municipalities (Census)
- **4.6 million** moved across states (Census)
- **0.6 million** migrated internationally (Carvalho, Campos, Rigotti, & Pinho (2018))

Back

# Appendix — Census Data

**Source: 2010 Brazilian Census (IBGE)**

**Sample:**

- Individuals aged 25–64 with positive income
- $\approx$ 6.2 million observations (weighted $\approx$ 60 million)
- Aggregated to 137 mesoregions

**Key variables:**

- Place of residence in 2005 and 2010 $\Rightarrow$ migration flows
- Income and employment characteristics

**Migration summary:**

- 95.6% stay in same mesoregion
- 1.8% move within state
- 2.6% move to another state

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# Appendix — Climate & Agricultural Data

**Climate data:**

- CMIP6 (CMCC-ESM2) – monthly temperature on 1° grid
- Aggregated to mesoregions (1994–2100)
- Used for both historical trends and future projections

**Agricultural data:**

- IBGE PAM (1994–2014) – municipal crop production (60+ crops)
- Aggregated to mesoregions
- *Measured* productivity = value per hectare (constant prices)
- Adjusted for land-use intensity to derive estimate of *fundamental* agricultural productivity

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# Appendix – Specification

*Who migrates?*

- Predict each worker's *counterfactual income* in 2005 location (had they not moved)
- Regress migration outcomes on predicted earnings capacity
- *Identification:* variation in predicted income comes from observable characteristics, not migration decisions

$$Y_{ijt} = \sum_{b=2}^{5} \beta_b \mathbf{1}\{\text{Pred. Inc.}_{ijt} \in b\} + \mu_j + \varepsilon_{ijt}$$

where $i$ indexes individuals, $j$ indexes the 2005 mesoregion of residence, and $t$ indexes the 2010 cross-section (with outcomes measured over 2005-2010). $Y_{ijt}$ is the individual outcome, $\mu_j$ are mesoregion fixed effects, and income bin $b = 1$ (R$0-10,000) is the omitted category.

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# Appendix – Specification

*How does temperature affect agricultural productivity?*

- **Estimate Temperature-Productivity Curve**
- Identify region–year variation from historical climate data

$$\ln A_{it} = \sum_{b \in \mathcal{B} \setminus b^\star} \beta_b \mathbf{1}\{TG_{it} \in b\} + \mu_i + \sum_{p=1}^{3} \tau_{ip} t^p + \varepsilon_{it} \qquad \text{(piecewise)}$$

$$\ln A_{it} = \beta_1 TG_{it} + \beta_2 TG_{it}^2 + \mu_i + \sum_{p=1}^{3} \tau_{ip} t^p + \varepsilon_{it} \qquad \text{(quadratic)}$$

where $TG_{it}$ denotes the annual mean temperature of mesoregion $i$ in year $t$, $\mu_i$ are mesoregion fixed effects, and $\{\tau_{ip}\}_{p=1}^{3}$ allows for region-specific linear, quadratic, and cubic time trends. The piecewise specification uses 1°C bins, with $[23, 24)$ as the omitted category.

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# Appendix — Static trade model

## Preferences

Details

- Cobb–Douglas over agriculture and non-agriculture
- CES aggregation of agricultural varieties (Armington)
- Non-agriculture freely traded (numeraire)

## Production

Plot-level production | Land quality | Selection | Non-ag

- Agriculture: land and labor with heterogeneous plots
- Land selection from productivity and operating costs
- Non-agriculture: heterogeneous jobs, linear technology

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# Appendix — Static trade model: Preferences

**Final consumption (region $i$, period $t$)**

$$C_t^i = \frac{(C_t^{i;a})^{\gamma}(C_t^{i;n})^{1-\gamma}}{\gamma^{\gamma}(1-\gamma)^{1-\gamma}}$$

$C_t^{i;a}$: agricultural composite, $C_t^{i;n}$: non-agricultural good, $\gamma \in (0,1)$: Cobb–Douglas parameter

**Agricultural composite (Armington)**

$$C_t^{i;a} = \left(\sum_{j\in\mathcal{S}} (\psi^j)^{1/\epsilon} (c_t^{j,i;a})^{\frac{\epsilon-1}{\epsilon}}\right)^{\frac{\epsilon}{\epsilon-1}}$$

$c_t^{j,i;a}$: variety from origin $j$, $\psi^j$: taste/quality weight, $\epsilon > 1$: elasticity of substitution

Non-agriculture is freely traded and used as the numeraire. Iceberg trade costs apply to agricultural varieties only.

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# Appendix — Static trade model: Production (Agriculture)

**Plot-level production**

$$q_t^i(\omega) = [L_t^i(\omega)]^\alpha [z_t^i(\omega) X_t^i(\omega)]^{1-\alpha}$$

$L_t^i(\omega)$: labor, $X_t^i(\omega)$: land, $z_t^i(\omega)$: land productivity, $\alpha \in (0,1)$: labor share

**Plot-level profits**

$$\pi_t^i(\omega) = p_t^{i;a} q_t^i(\omega) - w_t^{i;a} L_t^i(\omega) - p_t^0 z^{i0}(\omega) X_t^i(\omega)$$

$p_t^{i;a}$: agricultural price, $w_t^{i;a}$: agricultural wage, $z^{i0}(\omega)$: operating cost

Agricultural firms take prices and wages as given.

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# Appendix — Static trade model: Land heterogeneity

*As in Costinot, Donaldson, Smith (2016, JPE)*

**Plot characteristics**

$$(z_t^i(\omega), z^{i0}(\omega)) \sim \textbf{nested Fréchet}$$

**Joint distribution**

$$\Pr(z \leq \bar{z}, z^0 \leq \bar{z}^0) = \exp\left\{-o\left[\left(\frac{\bar{z}}{A_t^i}\right)^{-\theta} + \left(\frac{\bar{z}^0}{F^{i0}}\right)^{-\theta}\right]\right\}$$

$A_t^i$: mean productivity, $F^{i0}$: mean operating cost, $\theta > 1$: dispersion

Higher-productivity, lower-cost plots are more likely to be cultivated.

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# Appendix — Static trade model: Production (Land selection)

**Effective profitability**

$$\Omega_t^i = \left[\alpha^\alpha (1-\alpha)^{1-\alpha} p_t^{i;a} (w_t^{i;a})^{-\alpha}\right]^{\frac{1}{1-\alpha}}$$

**Selection condition**

$$z_t^i(\omega)\Omega_t^i \geq p_t^0 z^{i0}(\omega)$$

**Share of land cultivated**

$$\zeta_t^i = \frac{(A_t^i \Omega_t^i)^\theta}{(A_t^i \Omega_t^i)^\theta + (F^{i0} p_t^0)^\theta}$$

Selection implies endogenous average productivity and shrinking cultivated land under adverse shocks.

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# Appendix — Static trade model: Production (Non-agriculture)

**Job-level production**

$$q_t^{i;n}(\eta) = A^{i;n}(\eta) L_t^{i;n}(\eta)$$

**Job productivity distribution**

$$\ln A^{i;n}(\eta) \sim \mathcal{N}(\mu^i, (\sigma^i)^2)$$

**Wages**

$$w_t^{i;n}(\eta) = A^{i;n}(\eta)$$

Non-agricultural output is freely traded and used as the numeraire.

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# Appendix — Sectoral allocation

**Roy-style sectoral choice** ▸ Cutoff

- Workers draw non-agricultural productivity
- Agricultural wage acts as reservation wage
- Sector choice follows a Lucas–Luttmer cutoff

**Role of climate change** ▸ Climate channel

- Climate affects agricultural productivity
- Agricultural wage shifts endogenously
- Income distribution and inequality respond

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# Appendix — Sectoral allocation: Non-agriculture

### Job-level production

$$q_t^{i;n}(\eta) = A^{i;n}(\eta)\, L_t^{i;n}(\eta), \qquad L_t^{i;n}(\eta) \in \{0,1\}$$

$A^{i;n}(\eta)$: job-specific productivity, each job can employ at most one worker

### Homogeneous output, heterogeneous jobs

$$Q_t^{i;n} = \int q_t^{i;n}(\eta)\, d\eta$$

All jobs produce the same good, but at different productivity levels

### Wages

$$w_t^{i;n}(\eta) = A^{i;n}(\eta)$$

Perfect competition implies wages equal job-specific marginal product

### Productivity distribution

$$\ln A^{i;n}(\eta) \sim \mathcal{N}(\mu^i, (\sigma^i)^2)$$

$\mu^i$: mean log productivity, $\sigma^i$: dispersion of job productivity

Each worker is randomly matched to one job; unfilled jobs produce zero output.

# Appendix — Sectoral allocation: Cutoff rule

**Agricultural reservation wage**

$$y^{i;a} = w_t^{i;a}$$

$w_t^{i;a}$: market-clearing agricultural wage

**Sectoral choice**

$$\textbf{Work in non-agriculture if } A^{i;n}(\eta) \geq w_t^{i;a}$$

Otherwise, the worker supplies labor to agriculture

**Agricultural employment share**

$$\lambda_t^i = \Pr\left(A^{i;n}(\eta) < w_t^{i;a}\right) = \Phi\left(\frac{\ln w_t^{i;a} - \mu^i}{\sigma^i}\right)$$

This is a Roy-style selection mechanism with a single reservation wage.

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# Appendix — Sectoral allocation: Climate channel

**Climate shock**

$$A_t^i \downarrow$$

Climate change reduces agricultural land productivity

**General equilibrium response**

$$A_t^i \downarrow \Rightarrow \; w_t^{i;a} \downarrow$$

Lower agricultural productivity reduces the reservation wage

**Implication for sectoral choice**

$$\lambda_t^i = \Pr\big(A^{i;n}(\eta) < w_t^{i;a}\big) \downarrow$$

More workers accept low-productivity non-agricultural jobs

**Distributional consequences**

- Lower average income
- Higher within-region inequality
- Thicker lower tail of non-agricultural earnings

Climate change affects sectoral allocation + income (inequality) through the endogenous agricultural wage.

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# Appendix — Dynamic migration model: Setup

**Timing**

- Income $y_t^j$ realized at start of period
- Migration chosen at end of period
- Households consume $y_t^j - \chi^{j,i}$ if they move

**Preferences**

$$U(C) = \log C$$

Implies income-dependent utility cost of monetary migration expenses

**Migration costs**

$$\tau^{j,i}(y) = \log\left(\frac{y}{y - \chi^{j,i}}\right) + \mathbf{1}(i \neq j)\kappa^j$$

Migration infeasible if $y \leq \chi^{j,i}$

**No savings**

Why?

- Households cannot borrow against future income
- Low income increases the effective burden of moving

This mechanism is absent in income-invariant migration cost models.

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# Appendix — Why no savings? Liquidity constraints

./job_market_presentations/fraction_below_threshold.png

**Threshold: R$510/month $\times$ 12 = R$6,120/year (2010 minimum wage)**

**About US$7 per day (2010 exchange rates)**

**8.4% of the population lived below the US$3/day (PPP) poverty line in 2010**

A substantial share of households live close to subsistence and face tight liquidity constraints. For these households, financing large, one-time migration costs out of savings is implausible.

# Appendix — Utility-equivalent migration costs

**Consumption with and without migration**

$$C_t^j(y) = y/P_t^j, \qquad C_t^{j,i}(y) = \left(y - \chi^{j,i}\right)/P_t^j$$

**Log preferences**

$$U(C) = \log C$$

**Utility-equivalent monetary cost**

$$\tilde{\tau}^{j,i}(y) \;\equiv\; U\big(C_t^j(y)\big) - U\big(C_t^{j,i}(y)\big) = \log\left(\frac{y}{y - \chi^{j,i}}\right)$$

**Regressivity**

$$\frac{\partial \tilde{\tau}^{j,i}(y)}{\partial y} = -\frac{\chi^{j,i}}{y\left(y - \chi^{j,i}\right)} \;<\; 0$$

A fixed monetary cost implies a larger utility loss at lower incomes.

**Feasibility**

- If $y \leq \chi^{j,i}$, then $\tilde{\tau}^{j,i}(y) = +\infty$
- Migration is infeasible for liquidity-constrained households

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# Appendix – Expected lifetime utility

The dynamic discrete choice problem admits the standard logit closed-form expression for expected lifetime utility (McFadden, 1974). Let $V_t^j(r) \equiv \mathbb{E}[v_t^j(r)]$ and $\bar{V}_t^i \equiv \int_0^1 V_t^i(r')\, dr'$. Then, the expected lifetime utility of a worker with rank $r$ in the non-agricultural productivity distribution (associated with income $y_r$) currently located in region $j$ is:

$$V_t^j(r) = U\big(C_t^j(y_r)\big) \; + \; \nu \log \sum_{i \in \mathcal{S}} \exp\big(\beta\big[\rho\, V_{t+1}^i(r) + (1-\rho)\, \bar{V}_{t+1}^i\big] - \tau^{j,i}(y_r)\big)^{1/\nu}. \qquad (1)$$

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# Appendix — Logit migration probabilities

**Choice problem**

A worker of rank $r$ in region $j$ chooses destination $i$ to maximize

$$\beta V_{t+1}^{i}(r) \; - \; \tau^{j,i}\big(y_t^j(r)\big) \; + \; \nu\, \upsilon_t^i,$$

where $\upsilon_t^i$ are i.i.d. preference shocks.

**Assumption (Extreme Value tastes)**

$$\upsilon_t^i \;\sim\; \text{i.i.d. Type-I Extreme Value (Gumbel)}$$

**Result (McFadden, 1974)**

Under this assumption, choice probabilities take a logit form:

$$\mu_t^{j,i}(r) = \frac{\exp\Big(\big[\beta V_{t+1}^{i}(r) - \tau^{j,i}(y_t^j(r))\big]/\nu\Big)}{\sum_{k\in\mathcal{S}} \exp\Big(\big[\beta V_{t+1}^{k}(r) - \tau^{j,k}(y_t^j(r))\big]/\nu\Big)}.$$

The parameter $\nu$ governs choice dispersion: as $\nu \to 0$, choices become deterministic; as $\nu \to \infty$, probabilities flatten across feasible destinations.

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# Temporary equilibrium — Labor markets

**Given regional labor allocations $\{L_t^i\}_{i\in\mathcal{S}}$:**
Agricultural wages clear labor markets within each region. Workers sort between agriculture and non-agriculture.

$$w_t^{i;a} = p_t^{i;a}\alpha\left(\frac{A_t^i(\zeta_t^i)^{-1/\theta}X_t^{i;a}}{L_t^{i;a}}\right)^{1-\alpha},$$

$$\lambda_t^i = \Pr\big(A^{i;n}(\eta) < w_t^{i;a}\big) = \Phi\left(\frac{\ln w_t^{i;a} - \mu^i}{\sigma^i}\right),$$

$$L_t^{i;a} = \lambda_t^i L_t^i, \qquad L_t^{i;n} = (1-\lambda_t^i)L_t^i.$$

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# Temporary equilibrium — Land allocation

**Given prices and wages:**
Land is allocated to agriculture according to profitability. Only plots with non-negative profits are cultivated.

$$\Omega_t^i = \left[\alpha^\alpha (1-\alpha)^{1-\alpha} p_t^{i;a} (w_t^{i;a})^{-\alpha}\right]^{\frac{1}{1-\alpha}},$$

$$\zeta_t^i = \frac{(A_t^i \Omega_t^i)^\theta}{(A_t^i \Omega_t^i)^\theta + (F^{i0} p_t^0)^\theta},$$

$$X_t^{i;a} = \zeta_t^i X^i.$$

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# Temporary equilibrium — Goods markets

**Output definitions**

$$Q_t^{i;a} = (L_t^{i;a})^\alpha \left[A_t^i(\zeta_t^i)^{-1/\theta} X_t^{i;a}\right]^{1-\alpha},$$
$$Q_t^{i;n} = w_t^{i;n}(1-\lambda_t^i)L_t^i.$$

**Regional income**

With profits and land-clearing costs rebated locally, total income equals the value of production:

$$Y_t^i \equiv p_t^{i;a} Q_t^{i;a} + p_t^0 Q_t^{i;n}.$$

**Goods market clearing**

Prices adjust such that:

$$p_t^{j;a} Q_t^{j;a} = \gamma \sum_{i \in \mathcal{S}} \pi_t^{j,i;a} Y_t^i,$$
$$\sum_{j \in \mathcal{S}} p_t^0 Q_t^{j;n} = (1-\gamma) \sum_{i \in \mathcal{S}} Y_t^i,$$

with $\pi_t^{j,i;a} = \frac{\psi^j (p_t^{j;a}\delta^{j,i})^{1-\epsilon}}{\sum_{k\in\mathcal{S}} \psi^k (p_t^{k;a}\delta^{k,i})^{1-\epsilon}}$.

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# Appendix — Income distributions and value functions

**From income distributions to value functions**

The temporary equilibrium in period $t$ delivers, for each region $j$:

- **an income distribution $f_t^j(y)$,**
- **a regional consumption price index $P_t^j$.**

Households are indexed by their rank $r \in (0,1)$ in the local income distribution. Income is given by the quantile function:

$$y_t^j(r) = F_t^{j,-1}(r).$$

Per-period utility for a household of rank $r$ in region $j$ is:

$$U_t^j(r) = \log\left(\frac{y_t^j(r)}{P_t^j}\right).$$

This object enters the dynamic migration problem as the current-period payoff. Continuation values depend on future temporary equilibria and income persistence.

Back to equilibrium

# Appendix — Solving the model

## Solution algorithm

The model is solved by iterating between a static and a dynamic block:

1. **Static block (temporary equilibrium). Given $\{L_t^i\}$, solve for prices, wages, land use, trade shares, and income distributions in each period.**
2. **Dynamic block (migration). Given the sequence of temporary equilibria, solve the finite-horizon dynamic migration problem backward and compute migration probabilities $\{\mu_t^{j,i}\}$.**
3. **Labor update. Update regional labor stocks using**

$$L_{t+1}^i = \sum_{j \in \mathcal{S}} \mu_t^{j,i} L_t^j.$$

4. **Iteration. Repeat until the full path $\{L_t^i\}_{t=1}^T$ converges.**

This procedure yields prices, wages, migration flows, and labor allocations that are mutually consistent across space and time.

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# Appendix – Model inversion

Calibrate the static model to match 2010 regional moments. E.g., total labor, average wages, employment share in agriculture, average agricultural wage, non-agricultural average wages, land endowments, fraction of land used in agriculture.

| Object | Interpretation | Target / Source | Value |
|---|---|---|---|
| $\epsilon, \theta$ | Trade elasticities, heterogeneity in land quality | Literature | 9, 2 |
| $\alpha$ | Labor share in agriculture | Agricultural wage bill / value of production | 0.1579 |
| $\gamma$ | Agricultural expenditure share | Agricultural spending / income | 0.119 |
| *Varying by region:* | | | |
| $\mu^i$ | Location parameter (non-agricultural productivity) | $w_0^{i;a}, w_0^{i;n}, \lambda_0^i$ | 9.36 (0.43) |
| $\sigma^i$ | Scale parameter (non-agricultural productivity) | $w_0^{i;a}, w_0^{i;n}, \lambda_0^i$ | 0.64 (0.18) |
| $A_0^i$ | Fundamental land productivity | Corrected measured productivity | 660.12 (524.03) |
| $p_0^{i;a}$ | Agricultural producer price | Inverted from wage equation | 17.08 (21.34) |
| $F^{i0}$ | Fixed cost of land clearing | Land share condition | 7109.07 (22908.90) |
| $\psi^j$ | Regional preference shifter | Agricultural goods market clearing | 0.01 (0.08) |
| $\delta^{j,i}$ | Trade costs | Distance data | 1.78 (0.12) |

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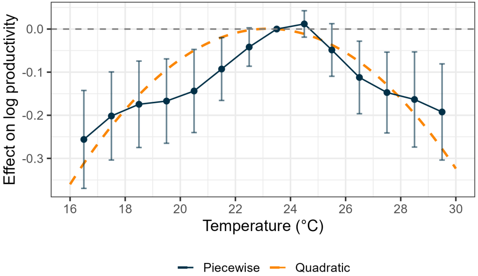
# Appendix – Counterfactual agricultural productivity

**Mapping temperature projections into productivity**

$$\ln A_t^i = \ln A_0^i + \left(\widehat{g}(TG_{it}) - \widehat{g}(TG_{i0})\right), \qquad \widehat{g}(TG) = \hat{\beta}_1 TG + \hat{\beta}_2 TG^2$$

Each region $i$ is anchored to its own 2010 temperature $TG_{i0}$; climate change shifts productivity by moving regions along the estimated nonlinear temperature–productivity relationship.




$\Longrightarrow$

| Year | Median | Min | Max |
|---|---|---|---|
| 2030 | −1.5% | −8.3% | 13.1% |
| 2050 | −4.9% | −16.4% | 20.8% |
| 2100 | −24.2% | −55.3% | 38.5% |

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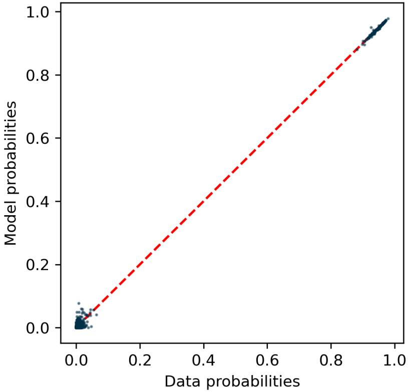
# Appendix – Migration costs

Figure: Migration probabilities: Model vs. data

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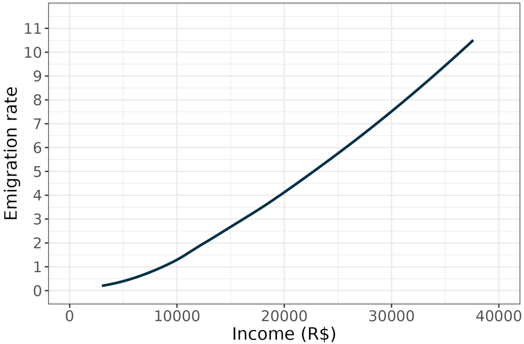
# Appendix – Migration costs

Figure: Migration probabilities by income (model)

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# Appendix – Welfare losses of climate change

**Welfare effects are evaluated by comparing the expected lifetime utility of 2010 households under two scenarios:**

- *No climate change:* regional productivity-level remains fixed at 2010 levels.
- *With climate change:* productivity evolves according to projected warming.

**Welfare differences are expressed in consumption-equivalent terms:**

- The constant, proportional, and permanent increase in consumption that would make households under climate change as well off as in the no-climate-change scenario.
- Interpreted as a **uniform percentage change in consumption** from 2010–2100 that equalizes lifetime utility across the two scenarios.

# Appendix – Welfare losses of climate change

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- Interpreted as a **uniform percentage change in consumption** from 2010–2100 that equalizes lifetime utility across the two scenarios.

**Role of discounting:**

- Welfare losses accrue gradually over time.
- The magnitude of the welfare gap is therefore highly sensitive to the **discount factor**.

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# Appendix – Welfare effects by region and income bin

| | R\$ 0–10k | R\$ 10–20k | R\$ >20k | All households |
|---|---|---|---|---|
| *Population-weighted means* | | | | |
| Norte | -0.87 | -0.36 | -0.34 | -0.55 |
| Nordeste | -0.57 | -0.24 | -0.23 | -0.40 |
| Centro-oeste | -0.68 | -0.21 | -0.17 | -0.24 |
| Sudeste | +0.09 | -0.03 | -0.03 | -0.02 |
| Sul | +0.77 | +0.15 | +0.13 | +0.24 |
| *Maximum losses* | | | | |
| Norte | -3.23 | -0.90 | -0.90 | -3.23 |
| Nordeste | -2.34 | -0.67 | -0.45 | -2.34 |
| Centro-oeste | -2.13 | -0.47 | -0.43 | -2.13 |
| Sudeste | -1.62 | -0.35 | -0.30 | -1.62 |
| Sul | -0.63 | -0.11 | -0.12 | -0.63 |

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# Appendix – Derivation of the subsidy rule

With log utility, the utility-equivalent migration cost is

$$\tau^{j,i}(y) = \log\left(\frac{y}{y - \chi^{j,i}}\right).$$

Equating utility costs across incomes $y < \bar{y}$ implies

$$\log\left(\frac{y}{y - (\chi^{j,i} - \xi^{j,i})}\right) = \log\left(\frac{\bar{y}}{\bar{y} - \chi^{j,i}}\right),$$

which yields

$$\xi^{j,i}(y \mid \bar{y}) = \chi^{j,i}\left(1 - \frac{y}{\bar{y}}\right).$$

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# Appendix – Mobility response to the migration subsidy

| Income group | Share unable to migrate ($\chi \geq y$) | Mean migration probability |
|---|---|---|
| Low income ($\leq$10k) | 52.43% $\rightarrow$ 3.90% | 5.41 $\rightarrow$ 11.09% |
| Middle income (10-20k) | 6.48% $\rightarrow$ 2.56% | 6.39 $\rightarrow$ 5.41% |
| High income ($>$20k) | 0.38% $\rightarrow$ 0.38% | 11.77 $\rightarrow$ 9.63% |

**The subsidy alleviates liquidity constraints**

$\rightarrow$ Roughly doubles per-period migration probabilities for low-income workers

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# Appendix – Mobility response to the migration subsidy

| | R\$ 0–10k | R\$ 10–20k | R\$ >20k | All households |
|---|---|---|---|---|
| *Climate change in both scenarios* | | | | |
| **Subsidized vs. Baseline (CEV, %)** | | | | |
| Norte | 14.11 | 6.05 | 2.94 | 8.30 |
| Nordeste | 36.41 | 13.70 | 4.94 | 23.44 |
| Centro-oeste | 9.37 | 4.87 | 1.29 | 3.68 |
| Sudeste | 11.40 | 2.66 | 0.56 | 2.68 |
| Sul | 11.17 | 4.33 | 1.09 | 4.19 |

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# Appendix – Costs

Table: Average fiscal incidence of the migration subsidy

| Income bin | Avg. transfer per capita (R$) | Share of GDP (%) |
|---|---|---|
| R$ 0–10k | 913.3 | 0.96 |
| R$ 10–20k | 173.1 | 0.32 |
| R$ >20k | 0.0 | 0.00 |
| **Total** | **271.5** | **1.27** |

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