# Agriculture, Trade, and the Spatial Efficiency of Global Water Use

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October 2024

# Water-intensive production in water-scarce regions

SCIENCE

**In The Midst Of Drought, California Farmers Used More Water For Almonds**

**Mallory Pickett** Former Contributor

*I write about science and technology.*

Sep 28, 2016, 05:20pm EDT

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- **$\sim$12 liters of water used to grow one almond**

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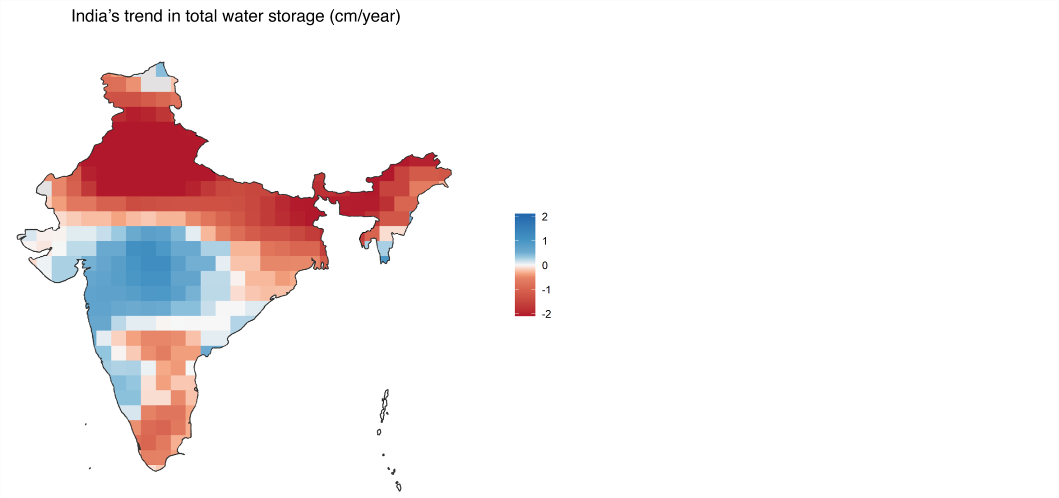

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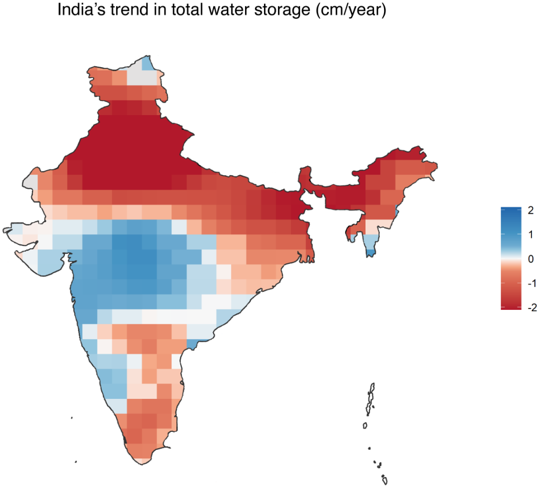


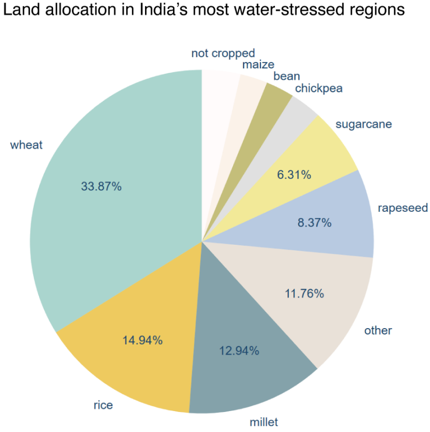

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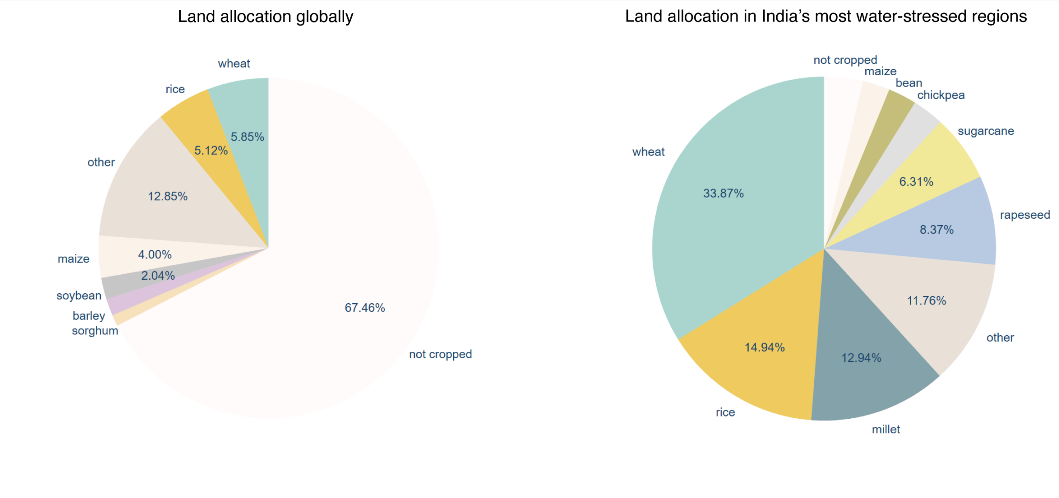

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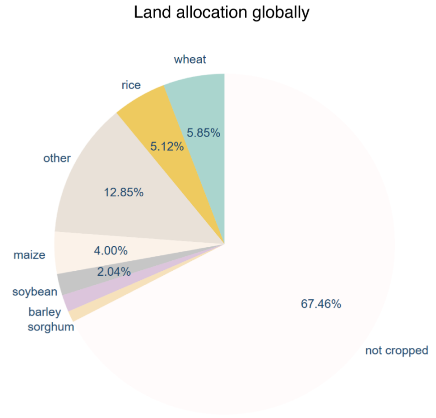


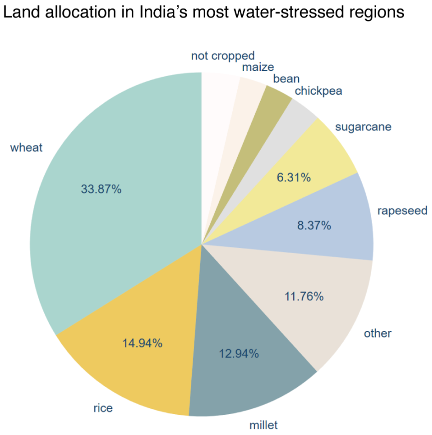


India is the world's **leading exporter of rice**

# Crop trade depletes global groundwater

Published online 6 April 2017

**The import and export of crops drawing on groundwater is threatening food and water security in the Middle East and elsewhere.**

Nadia El-Awady

News & Events Multimedia

# NASA-University Study Finds 11 Percent of Disappearing Groundwater Used to Grow Internationally Traded Food

ENVIRONMENTAL RESEARCH
LETTERS

LETTER • OPEN ACCESS

## Global unsustainable virtual water flows in agricultural trade

Lorenzo Rosa[1], Davide Danilo Chiarelli[2], Chengyi Tu[1,3], Maria Cristina Rulli[2] and Paolo D'Odorico[1]

Published 22 October 2019 • © 2019 The Author(s). Pu
Environmental Research Letters, Volume 14, Number 11

*"The globalization of water through trade contributes to running rivers dry, an environmental externality commonly overlooked by trade policies"*
*--Rosa et al. (2019)*

LETTER

doi:10.1038/nature21403

700 | NATURE | VOL 543 | 30 MARCH 2017

## Groundwater depletion embedded in international food trade

Carole Dalin[1], Yoshihide Wada[2,3,4,5], Thomas Kastner[6,7] & Michael J. Puma[3,4,8]

# Research question

How do global agricultural **trade patterns** and **policies** affect . . .

- long-run water availability,
- agricultural production,
- and welfare

**across space** and **over time**?

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- Compile **globally comprehensive geospatial dataset** on water and agriculture

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- Establish a **series of facts** about the allocation of water in global agricultural production:
  - **1–2.** Vast heterogeneity in water availability and use (ag. dominates) $\rightarrow$ **factor-content trade**
  - **3–4.** Pervasive distortions on input (**open access**) & output (**tax/sub./tariff**) sides of ag. market
  - **5.** Water-intensive crops **concentrate** in water-abundant locations, but some **unsustainably**

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  - intensive + extensive margins of ag., Ricardian + H–O trade, regional water budget
  - in GE: ag./trade policy $\rightarrow$ ag./trade spatial allocation $\leftrightarrow$ long-run regional water availability

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- Use **model simulations** to characterize trade and welfare outcomes
  - How does global ag. trade affect long-run water availability and welfare?
  - Do specific ag./trade policies *exacerbate* or *mitigate* regional water depletion?

# Preview of results

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   → prevents water depletion over time, raising welfare in the long run

2. **Water-scarce regions benefit the most from trade**

   → import water-intensive goods, avoiding severe water depletion

3. **Liberalizing trade can be harmful** in specific contexts and regions:
   - California and India avoid extreme depletion under autarky
   - historic Uruguay Round of trade liberalization *increased* water depletion and lowered welfare

# Related literature

- Copeland, Shapiro, and Taylor (2022) review literature on globalization and the environment, but **little work on natural resources** [*lately:* Farrokhi et al. (2023)]
- Anderson, Rausser, and Swinnen (2013) review literature on ag. policy distortions, but **no investigation of environmental effects** [*exception:* Berrittella et al. (2008) using GTAP]
- **Reduced-form** empirics and **PE** analysis:
  - water markets: Bruno and Jessoe (2021), Ayres, Meng, and Plantinga (2021), Rafey (2023)
  - water + ag./trade policy: Debaere (2014), Carleton (2021), Sekhri (2022)
- Simple **two-country/SOE** models: Chichilnisky (1994) and Brander and Taylor (1997)
  - lack of property rights can give *comparative advantage* in extractive good
  - opening to trade → potentially long-run welfare losses
- Closest quantitative trade model: Costinot, Donaldson, and Smith (2016) on effect of climate change on agricultural comparative advantage, but **no dynamics** and **no water**

# Facts

# Facts 1–2: Vast spatial heterogeneity in water availability and use

Thru lens of basic **water budget**: $\boxed{\Delta \text{Depth}_{qt} = \rho_q(\text{Consume}_{qt} - \text{Recharge}_{qt}) \text{ given Depth}_{q0}}$

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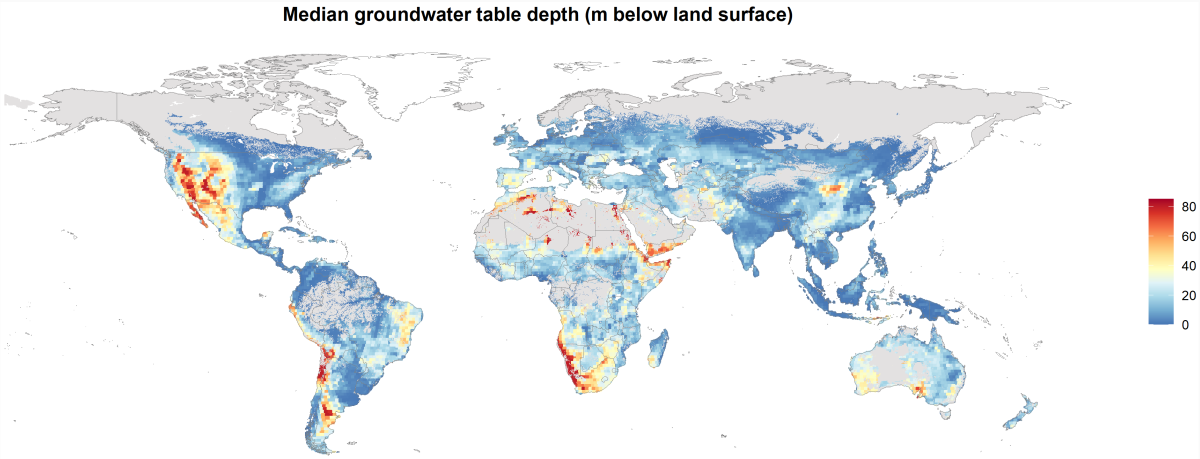


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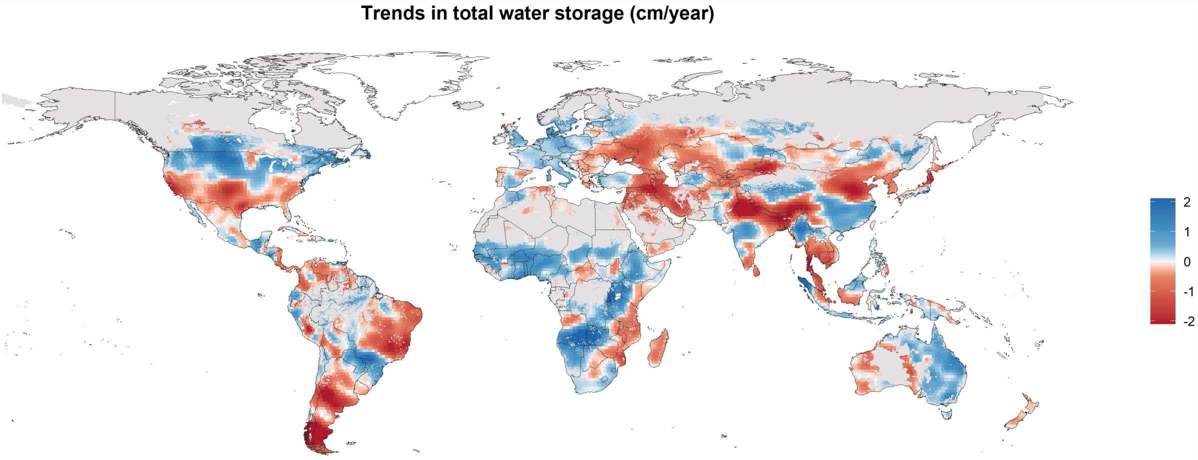


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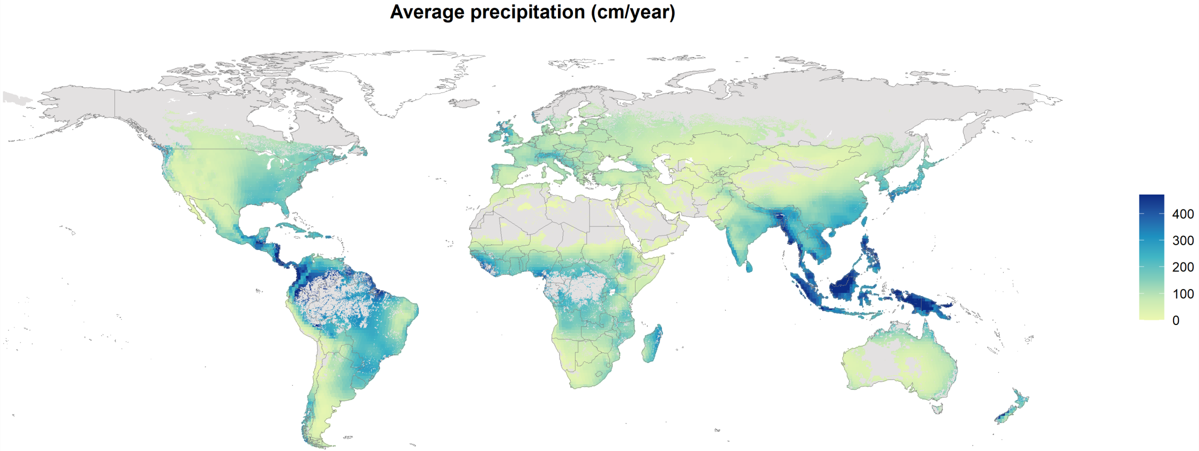


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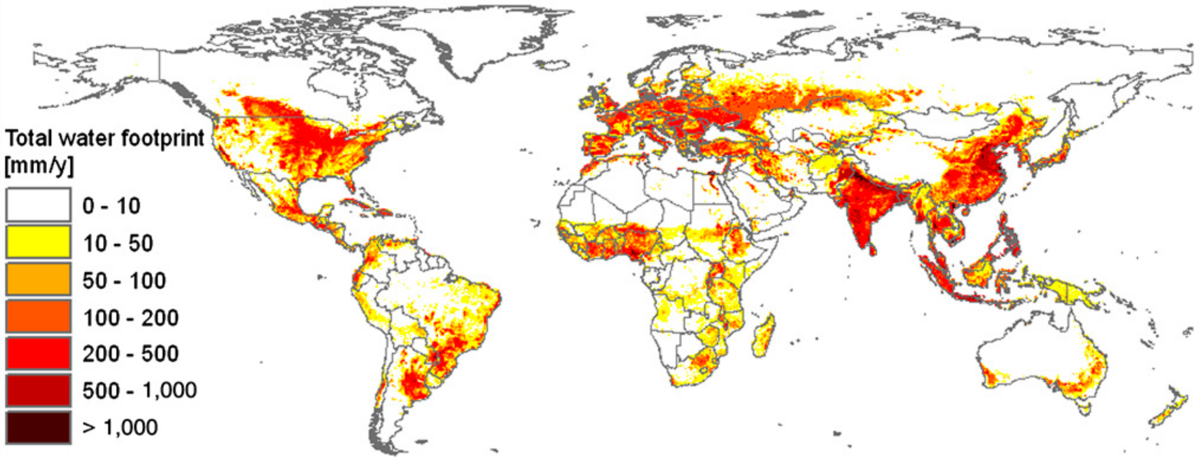


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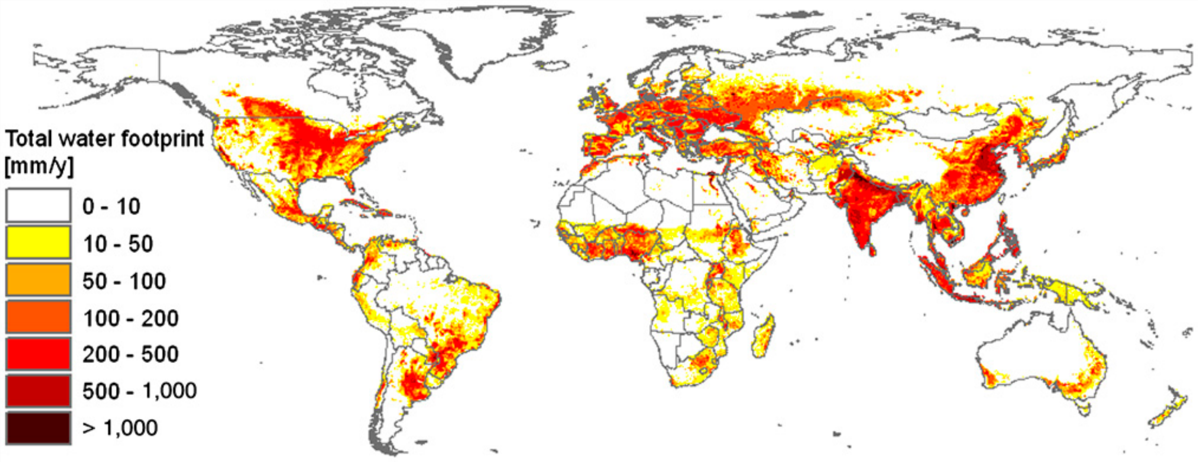


It's all about agriculture: $\sum_q$ **Consume**$_{\mathbf{qt}} \approx$ **90% agricultural input use** (d'Odorico et al., 2019)

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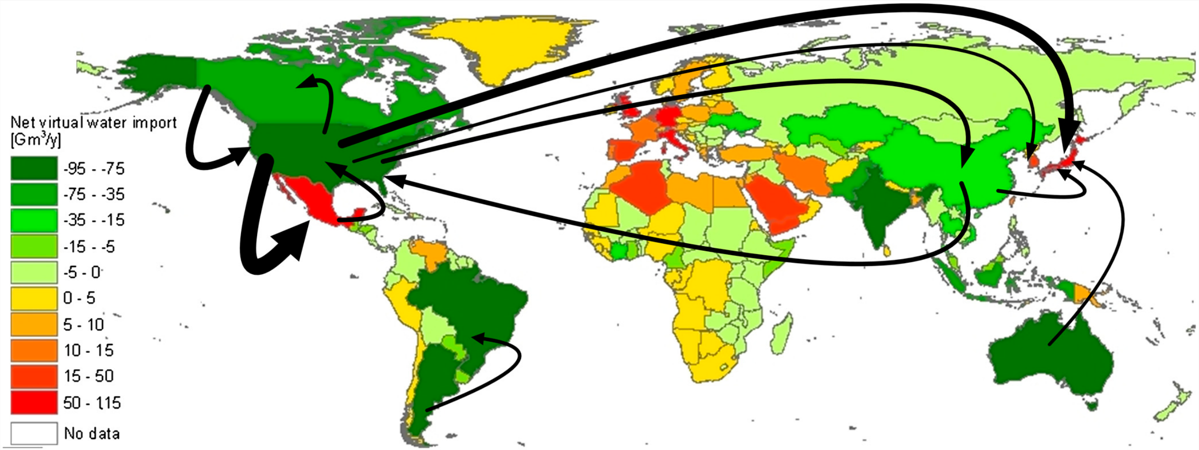
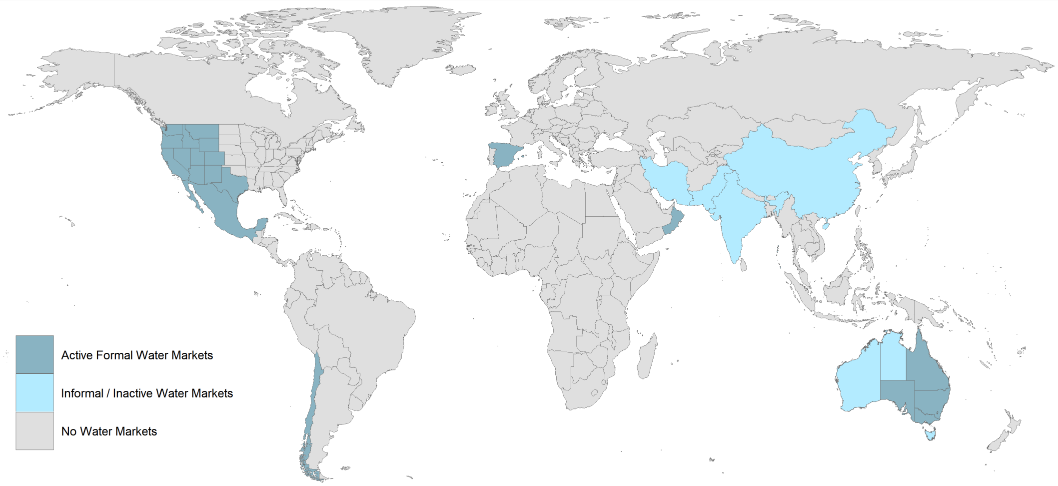



Ag. trade embeds **20–25%** of $\sum_q \textbf{Consume}_{\textbf{qt}}$ (Hoekstra and Mekonnen, 2012; Carr et al., 2013)

# Facts 3–4: Pervasive distortions on input & output sides of ag. market




$>$**93%** of global agricultural production occurs in regions with **no formal water markets**

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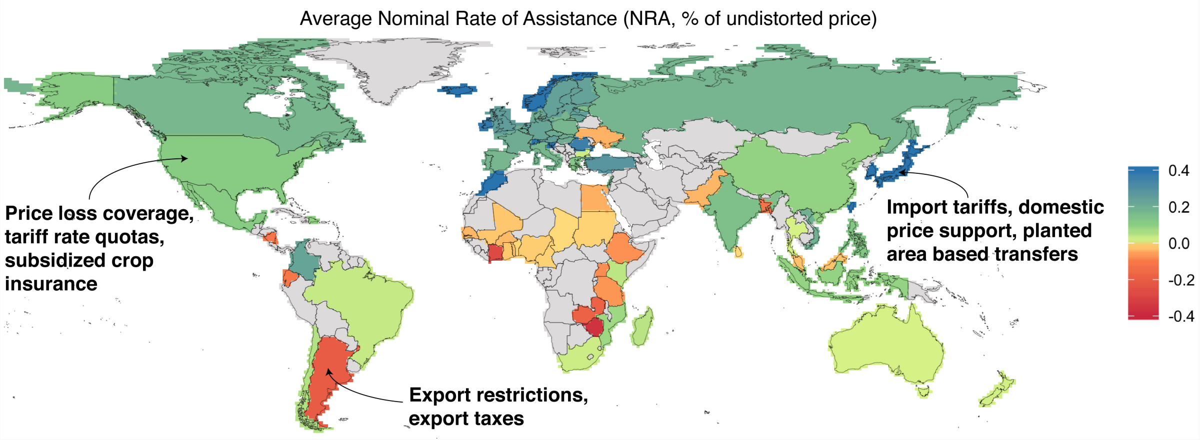

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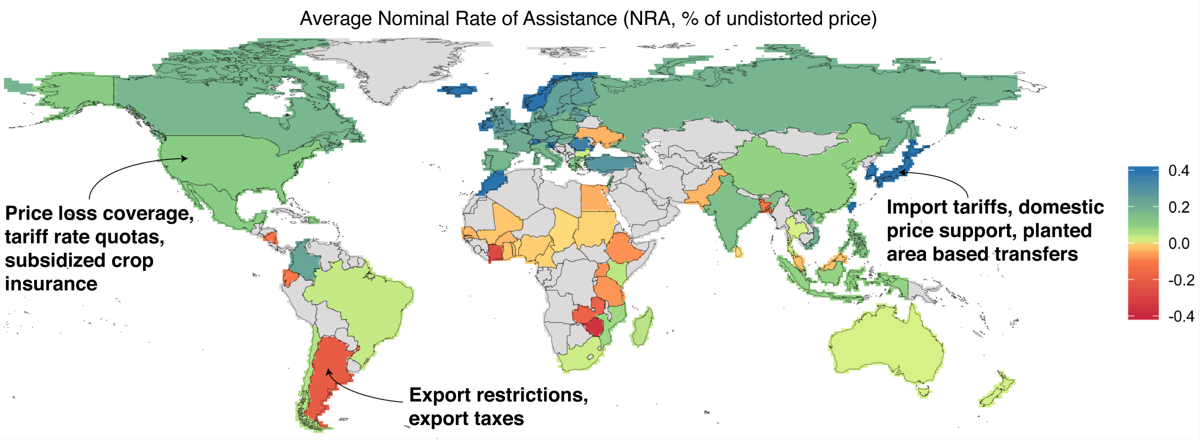


10pp inc. in net ag. subsidy → $\Delta\text{Depth}_{qt}$ from 50$^{\text{th}}$ to 75$^{\text{th}}$ pctl (Carleton, 2021)

# Fact 5: Water-intensive crops locate primarily in water-abundant regions...

$$\text{Water Intensity of Arable Land}\,(\text{m}^3/\text{ha}) = \frac{\sum_{k\in\mathcal{K}} \text{hectares}^k \times \left(\frac{\text{water (m}^3)}{\text{hectare}}\right)^k}{\sum_{k\in\mathcal{K}} \text{hectares}^k + \text{pasture}}$$

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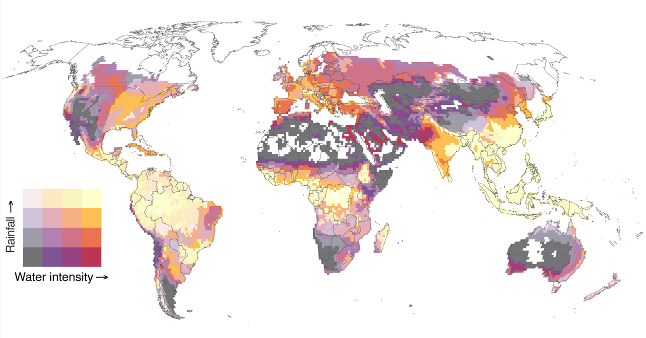


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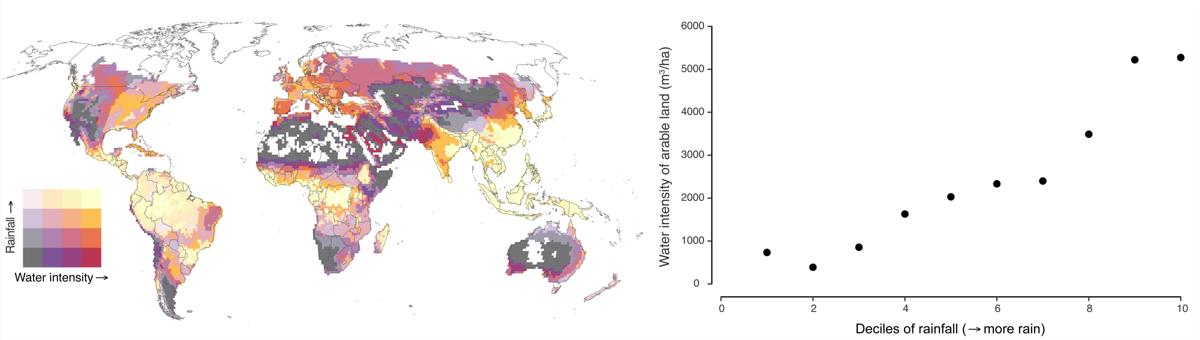


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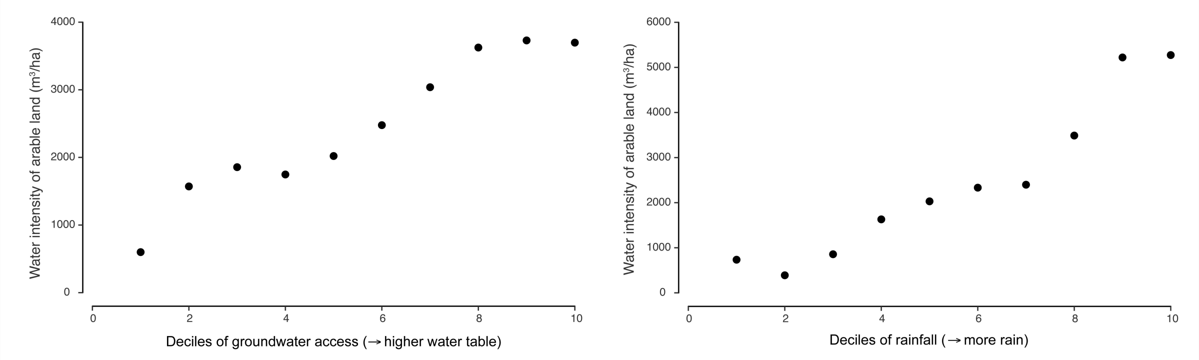


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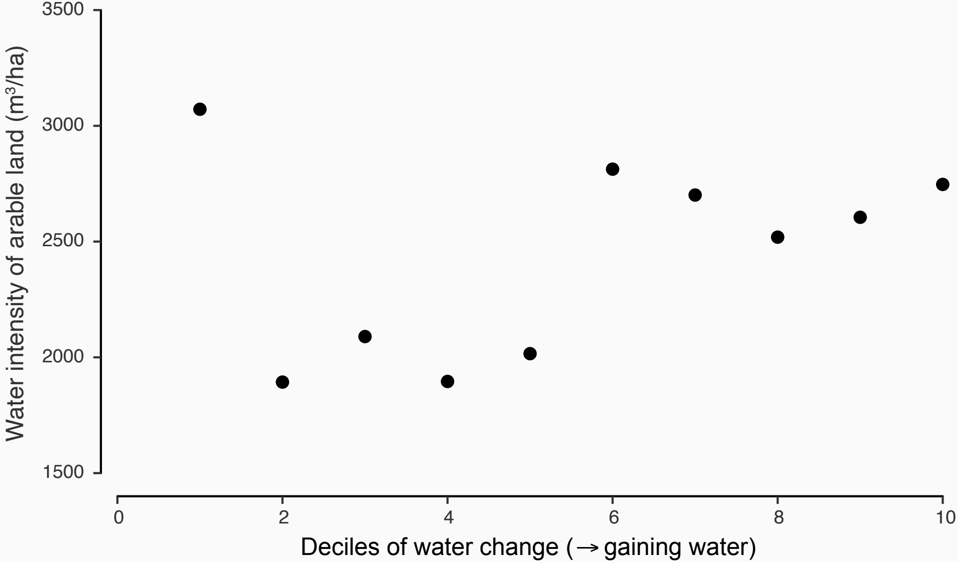

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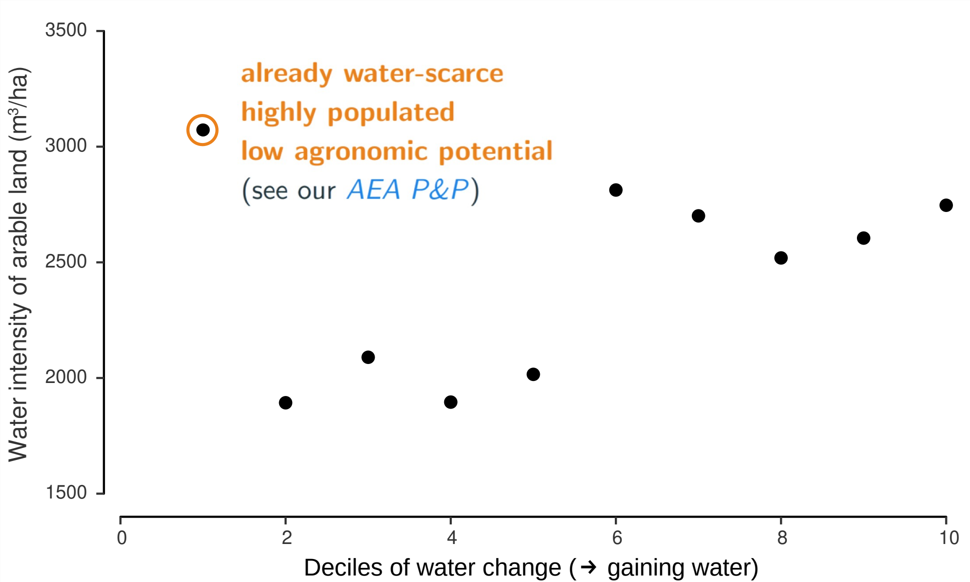

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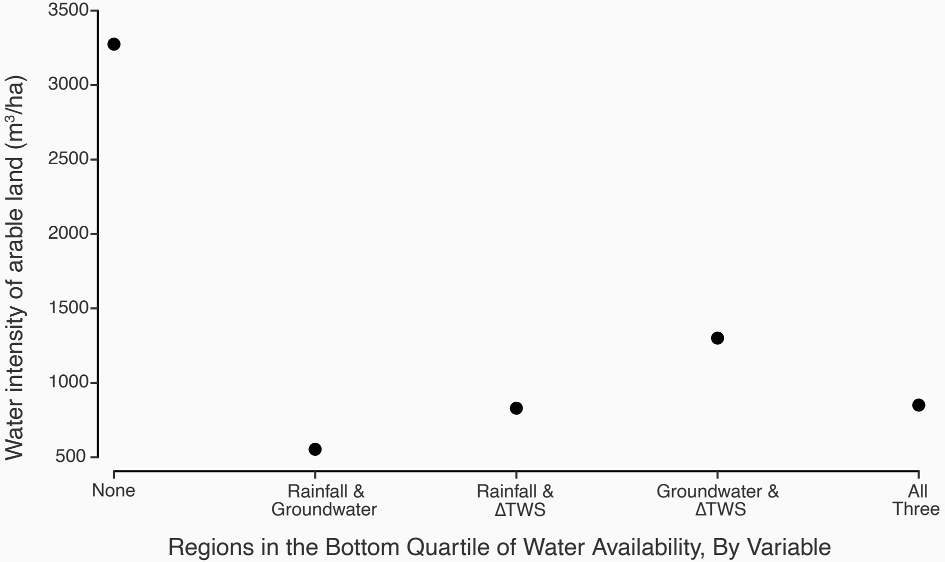
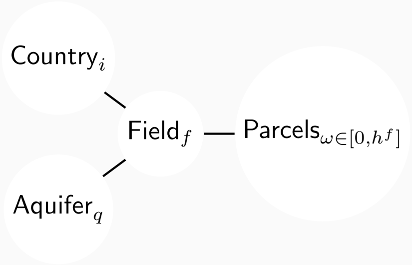


# Model

# Basic environment

- **Time and space:** discrete time $t$, geography split into ...




- **Two sectors:** homog. outside good + crops $k$ distinguished by exporter $j$, all traded
- Atomistic **laborers**: earn wage $w_i$ in outside sector OR farm chosen $k$ on assigned parcel $\omega$
- **Water**: drawn from $q$ to farm $f \in \mathcal{F}_q$, w/ each $q$ an **open access renewable resource**

# Preferences of each country's representative consumer

For each country $i$, the representative consumer lives **hand-to-mouth** with **quasilinear** utility over the outside good and a **nested CES** bundle of exporter-specific crop varieties:

$$U_{it} = C^o_{it} + \zeta_i \ln C_{it} \quad \text{with} \quad C_{it} = \left[ \sum_{k \in \mathcal{K}} \left(\zeta^k_i\right)^{1/\kappa} \left(C^k_{it}\right)^{\frac{\kappa-1}{\kappa}} \right]^{\frac{\kappa}{\kappa-1}}$$

$$C^k_{it} = \left[ \sum_{j \in \mathcal{I}} \left(\zeta^k_{ji}\right)^{1/\sigma} \left(C^k_{jit}\right)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}}$$

# Technology I: Agriculture

Consider the farmer of parcel $\omega$ on field $f \in \mathcal{F}_{iq}$, who combines ...

- $H_t^{fk}(\omega)$ units of labor (endowment = 1)
- $L_t^{fk}(\omega)$ units of land (endowment = 1)
- $G_t^{fk}(\omega)$ units of groundwater

to produce

$$Q_t^{fk}(\omega) = A^{fk}(\omega)\left[H_t^{fk}(\omega)\right]^{\alpha}\left[\min\left\{L_t^{fk}(\omega), \frac{G_t^{fk}(\omega)}{\phi^k}\right\}\right]^{1-\alpha},$$

of crop $k$, where

- $\phi^k$ is **water intensity** of crop $k$
- $A^{fk}(\omega)$ is **idiosyncratic crop-specific TFP** drawn i.i.d from Fréchet:

$$\mathbb{P}\left\{A^{fk}(\omega) \leq a\right\} = \exp\left\{-\gamma\left(\frac{a}{A^{fk}}\right)^{-\theta}\right\} \quad \text{with} \quad \mathbb{E}[A^{fk}(\omega)] = A^{fk}$$

# Technology II: Water extraction

- A farmer must use some of his labor to pump up groundwater for cultivation:

$$G_t^{fk}(\omega) = A_{q(f)}^w(D_{q(f)t}) \left[1 - H_t^{fk}(\omega)\right]$$

where $D_{qt}$ is the **depth** of groundwater in aquifer $q$ at time $t$, with $A_q^w(D) = \Upsilon_q D^{-\upsilon}$.

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- **Implications for crop output:** Can show that

$$\max_H Q_t^{fk}(\omega) = \boldsymbol{A^{fk}(\omega) M(\phi^k, D_{qt})}$$

where $M(\phi^k, D_q)$ is *continuous* and *decreasing* in both $\phi^k$ and $D_q$.

# Technology III: Outside good

- Produced under constant returns to scale using **labor only**
- **Idiosyncratic productivity** in outside sector $A_i^o(\omega)$ of laborer assigned to $\omega$ is drawn i.i.d. from Fréchet with **same shape parameter** $\theta$:

$$\mathbb{P}\left\{A_i^o(\omega) \leq a^o\right\} = \exp\left\{-\gamma\left(\frac{a^o}{A_i^o}\right)^{-\theta}\right\}, \quad \text{with} \quad \mathbb{E}[A_i^o(\omega)] = A_i^o$$

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- **Implication**: Laborer's choice between sectors *and* crops becomes one discrete choice problem that can be solved in closed form

# Tying components together: Market structure and groundwater evolution

- All markets are **perfectly competitive**
- **Trade**:
  - outside good is **freely traded** and is the numeraire
  - trade in crops is subject to **iceberg costs**: $p^k_{jit} = \delta^k_{ji} p^k_{jt}$
  - **NRA** $\tau^k_{jt}$ summarizes effect of taxes/subsidies/tariffs/quotas/...

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- **Groundwater evolution**: The depth $D_{qt}$ follows the law of motion

$$D_{qt+1} = D_{qt} + \rho_q[(1-\psi)X_{qt} - R_q], \qquad \psi \in (0,1)$$

where

  - $X_{qt}$ is the **total extracted** from aquifer $q$ in period $t$
  - $R_q$ is the **natural recharge** of aquifer $q$
  - $\rho_q$ is the **specific yield** of aquifer $q$ (volume $\rightarrow$ depth)
  - $\psi$ is the rate of **return flow** per unit extracted

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  - **NRA** $\tau^k_{jt}$ summarizes effect of taxes/subsidies/tariffs/quotas/...
- **Groundwater evolution**: The depth $D_{qt}$ follows the law of motion

$$D_{qt+1} = D_{qt} + \rho_q[(1-\psi)X_{qt} - R_q], \qquad \psi \in (0,1)$$

where

- $X_{qt}$ is the **total extracted** from aquifer $q$ in period $t$
- $R_q$ is the **natural recharge** of aquifer $q$
- $\rho_q$ is the **specific yield** of aquifer $q$ (volume $\rightarrow$ depth)
- $\psi$ is the rate of **return flow** per unit extracted

*No dynamic choices, but the evolution of depths matters!*

# Equilibrium I: Utility maximization

Utility maximization by the representative household in each country requires that

$$C^k_{jit} = \zeta_i \frac{\zeta^k_i \left(P^k_{it}\right)^{1-\kappa}}{\sum_{\ell \in \mathcal{K}} \zeta^\ell_i \left(P^\ell_{it}\right)^{1-\kappa}} \frac{\zeta^k_{ji} \left(\delta^k_{ji} p^k_{jt}\right)^{-\sigma}}{\sum_{n \in \mathcal{I}} \zeta^k_{ni} \left(\delta^k_{ni} p^k_{nt}\right)^{1-\sigma}} \quad \text{for all } i, j \in \mathcal{I}, \;\; k \in \mathcal{K},$$

where

$$P^k_{it} = \left[\sum_{n \in \mathcal{I}} \zeta^k_{ni} \left(\delta^k_{ni} p^k_{nt}\right)^{1-\sigma}\right]^{\frac{1}{1-\sigma}}$$

denotes the CES price index associated with crop $k$ in country $i$ at time $t$.

# Equilibrium II: Profit maximization and labor choice

- Each laborer $\omega$ selects the activity (outside good or crop $k$) that achieves

$$\max\{A_i^o(\omega), r_t^{f1}(\omega), \ldots, r_t^{fK}(\omega)\}$$

where $r_t^{fk}(\omega) = \tau_{i(f)t}^k p_{i(f)t}^k A^{fk}(\omega) M(\phi^k, D_{q(f)t})$ is his **revenue** from producing crop $k$

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- By i.i.d. Fréchet with common shape parameter,

$$\pi_t^{fk} \equiv \mathbb{P}\left\{r_t^{fk}(\omega) = \max\{A_i^o(\omega), r_t^{f1}(\omega), \ldots, r_t^{fK}(\omega)\}\right\}$$

$$= \frac{\left(\tau_{i(f)t}^k p_{i(f)t}^k A^{fk} M(\phi^k, D_{q(f)t})\right)^\theta}{\left(A_{i(f)}^o\right)^\theta + \sum_{\ell \in \mathcal{K}} \left(\tau_{i(f)t}^\ell p_{i(f)t}^\ell A^{f\ell} M(\phi^\ell, D_{q(f)t})\right)^\theta}$$

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- **Total production**: adding across fields & incorporating selection

$$Q_{it}^k = \sum_{f \in \mathcal{F}_i} h^f A^{fk} M(\phi^k, D_{qt}) \left(\pi_t^{fk}\right)^{\frac{\theta - 1}{\theta}}$$

# Equilibrium III: Definition of competitive equilibrium

Given NRAs, $\{\tau_{it}^k\}$, and initial groundwater depths, $\{D_{q0}\}$, a competitive equilibrium is a **path** of consumption, $\{C_{jit}^k\}$, output, $\{Q_{it}^k\}$, prices, $\{p_{it}^k\}$, shares, $\{\pi_t^{fk}\}$, groundwater depths, $\{D_{qt}\}$, and groundwater extractions, $\{X_{qt}\}$, such that

- representative consumers maximize their utility;
- laborers select activities to maximize their returns;
- markets clear:

$$Q_{it}^k = \sum_{j \in \mathcal{I}} \delta_{ij}^k C_{ijt}^k \qquad \forall i, k, t$$

$$X_{qt} = \sum_{f \in \mathcal{F}_q} \sum_{k \in \mathcal{K}} h^f \pi_t^{fk} x^{fk} \qquad \forall q, t;$$

- depths obey their law of motion.

**Steady state:** $\{\bar{C}_{ji}^k, \bar{Q}_i^k, \bar{p}_i^k, \bar{\pi}^{fk}, \bar{D}_q, \bar{X}_q\}$ with $(1-\psi)\bar{X}_q = R_q$

# Quantification

# Data

For a sample of **52 countries** (>97% ag. value & pop.), **22 crops**, and **205 aquifers** . . .

- Field-level ($f$): from **GAEZ** and **SAGE** at 5-arc minute level (∼**1.9mil grid cells**)
  - crop-specific potential yields $A^{fk}$
  - crop-specific cropped area fractions $\pi^{fk}$
  - area $h^f$
- Country-level ($i$): from **FAOSTAT** and **World Bank**
  - crop-specific output $Q_{it}^k$
  - crop-specific NRA $\tau_{it}^k$ and prices $p_{it}^k$
  - total cultivated land $L_{it}$
- Bilateral country-level ($ij$): from **UN Comtrade**
  - bilateral trade flows $E_{ijt}^k \equiv p_{it}^k \delta_{ij}^k C_{ijt}^k$
- Aquifer-level ($q$): from **GRACE** and **Fan, Li, and Miguez-Macho (2013)**
  - initial depths $D_{q,0}$ (→ starting **out-of-S.S.**)
  - change in total water storage $\propto \Delta D_{q,t}$

# Parameters to be calibrated/estimated

| | | |
|---|---|---|
| ☐ | $\sigma$, $\kappa$ | demand elasticities |
| ☐ | $\{\zeta_j, \zeta_j^k, \zeta_{ij}^k\}$ | demand shifters |
| ☐ | $\{\delta_{ij}^k\}$ | bilateral crop-specific trade costs |
| ☐ | $1-\alpha$ | land share in crop production |
| ☐ | $\{\phi^k\}$ | crop-specific water intensity |
| ☐ | $\theta$ | technological heterogeneity |
| ☐ | $\{A_i^o\}$ | mean labor prod. in outside sector |
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| ☐ | $\{\Upsilon_q\}$ | scale of extraction productivity |
| ☐ | $\upsilon$ | elasticity of extraction productivity |

# Calibrating technological and hydrological parameters

| Parameter | | Value | Source |
|---|---|---|---|
| land share | $1-\alpha$ | 0.25 | Boppart et al. (2019) |
| return flow rate | $\psi$ | 0.25 | Dewandel et al. (2008) |
| extraction elasticity | $\upsilon$ | 1.0 | Burlig, Preonas, and Woerman (2021) |
| water intensity | $\{\phi^k\}$ | | convert from Mekonnen and Hoekstra (2011) |
| specific yield | $\{\rho_q\}$ | | s.y. by soil type (Loheide, Butler, and Gorelick, 2005) |
| | | | soil type (Hengl et al., 2017) |
| natural recharge | $\{R_q\}$ | | residual of avg. $\Delta$TWS from NASA's GRACE data |
| | | | & implied water use based on $\{\phi^k\}$ and obs. $\{\pi^{fk}\}$ |
| | | | from SAGE (Monfreda, Ramankutty, and Foley, 2008) |

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☑ calibrated: lit. & data

# Estimating the demand side: Go inside out, nest by nest

1. If zero trade flow, set $\zeta_{ij}^k(\delta_{ij}^k)^{1-\sigma} = 0$
2. If positive, run IV on

$$\ln(E_{ij}^k / E_j^k) = \mathsf{FE}_j^k + (1-\sigma)\ln\left(p_i^k\right) + \epsilon_{ij}^k$$

   under the normalization that the shocks sum to zero, with instrument

$$Z_i^k \equiv \ln\left(\frac{1}{F_i}\sum_{f\in\mathcal{F}_i} A_i^{fk}\right)$$

   $\Longrightarrow$ variation in $p_i^k$ independent of preferences and trade costs

3. That regression identifies $\sigma$, and we set $\ln[\zeta_{ij}^k(\delta_{ij}^k)^{1-\sigma}] \equiv \epsilon_{ij}^k$

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Absorb all extra variation in taste $\times$ trade cost parameters $\implies$ **exactly** match demand side

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☑ calibrated: lit. & data

☑ estimated: follow **CDS (2016)**

# Estimating the supply side

Estimate $\theta$, $\{A_i^o\}$, and $\{\Upsilon_q\}$ jointly via **nonlinear least squares** (NLS):

$$\min_{\theta,\{A_i^o\},\{\Upsilon_q\}} \sum_i \sum_k \left[\ln Q_i^k(\theta,\{A_i^o\},\{\Upsilon_q\}) - \ln Q_i^k\right]^2 \text{ s.t. } X_q = X_q(\theta,\{A_i^o\},\{\Upsilon_q\}), \quad \forall q$$

$$L_i = L_i(\theta,\{A_i^o\},\{\Upsilon_q\}), \quad \forall i$$

where *observed* extraction is

$$X_q := \sum_{f\in\mathcal{F}_q} \sum_{k\in\mathcal{K}} h^f \pi^{fk} \phi^k$$

**Intuition for identification**

- Share of non-cultivated land $\leftrightarrow$ non-agricultural labor productivity
- Water extracted $\leftrightarrow$ labor productivity of extraction
- Cross-parcel dispersion in productivity $\leftrightarrow$ cross-crop dispersion in output

# Parameters to be calibrated/estimated

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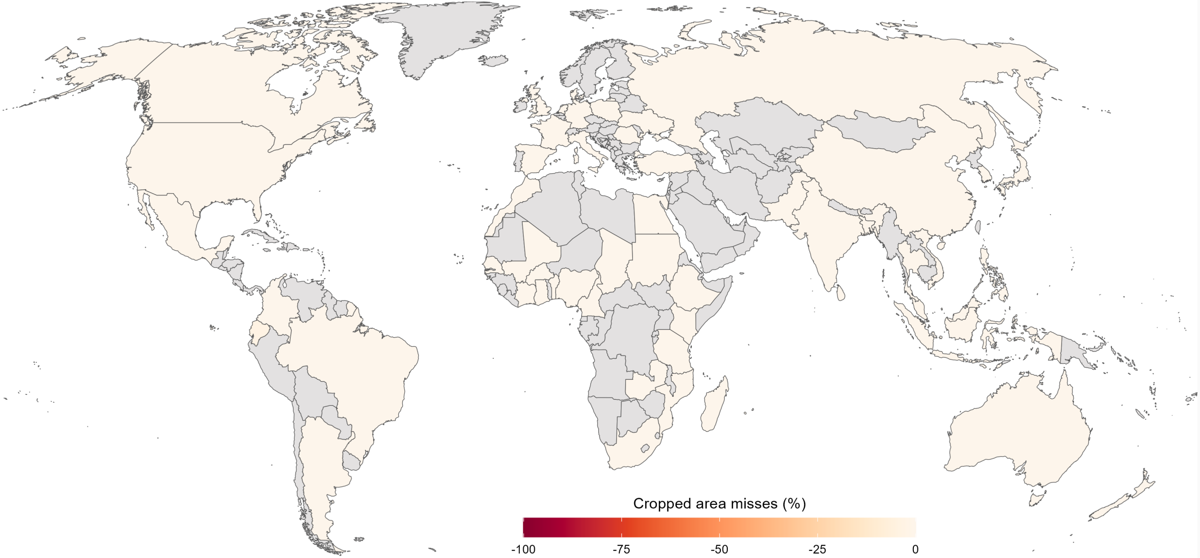
☑ calibrated: lit. & data

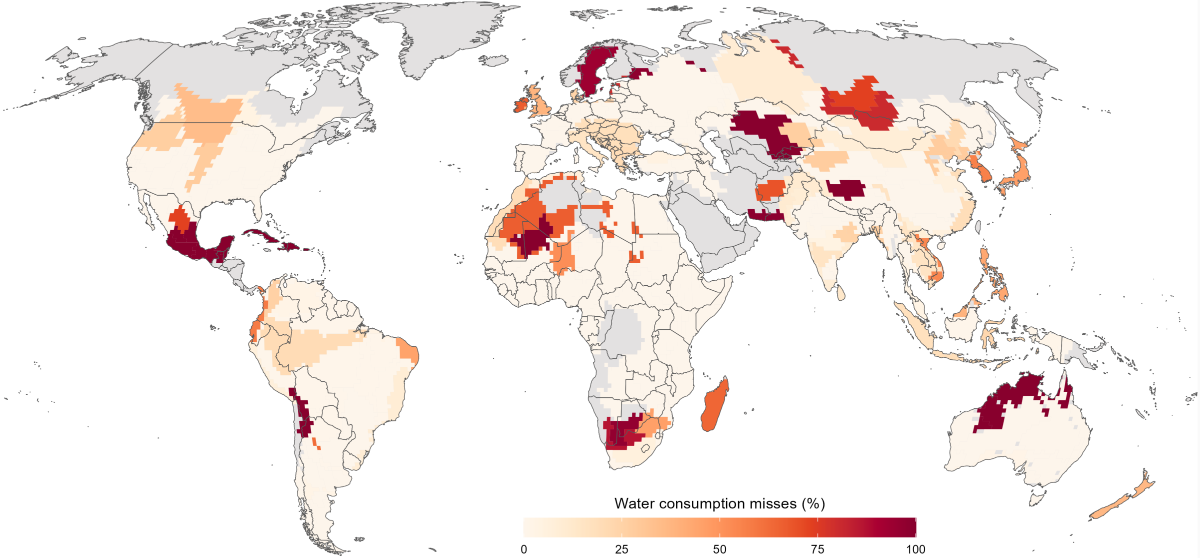
☑ estimated: follow **CDS (2016)**

☑ estimated: **NLS** (land & water use)

# Model fit: Cropped area



# Model fit: Agricultural water extraction



# Counterfactuals

# Menu of counterfactuals

1. **Eliminate trade in agriculture**—set $\delta_{ji}^{k} = \infty$ for all $i, j, k$ with $i \neq j$
   **Does existing trade in agriculture improve or worsen the allocation?**

# Menu of counterfactuals

1. **Eliminate trade in agriculture**—set $\delta_{ji}^k = \infty$ for all $i, j, k$ with $i \neq j$
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2. **Evaluate historical changes in output market interventions**—compare allocation with $\tau_i^k$ from pre-Uruguay round of WTO negotiations (∼1990) to $\tau_i^k$ from ∼2009
   **What are the impacts of a major historic global ag. market liberalization?**

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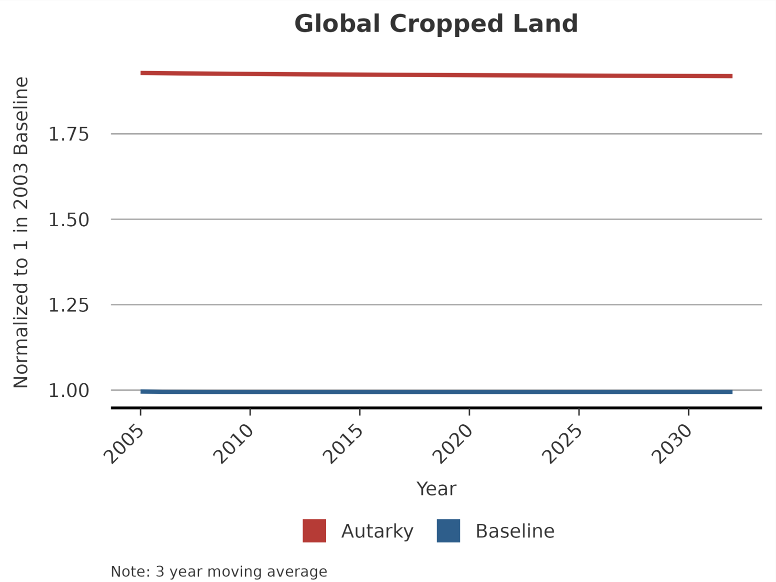
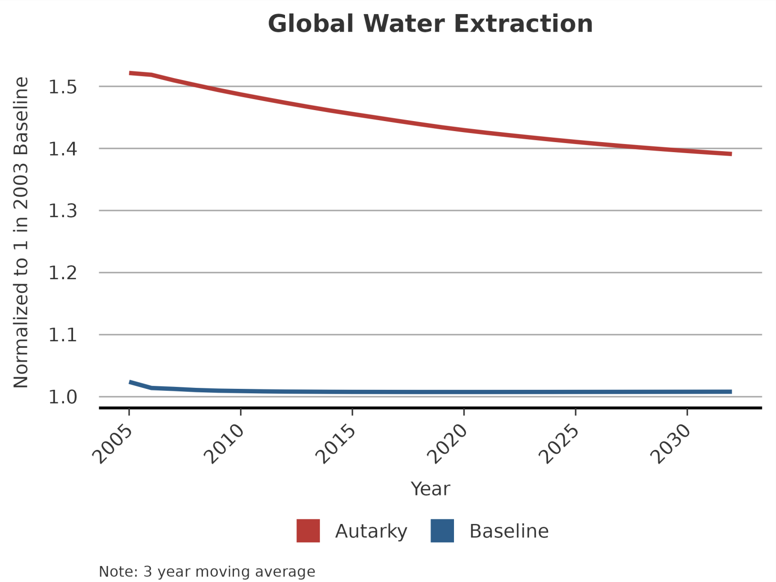
3. **Eliminate all output market distortions**—set $\tau_i^k = 1$ for all $i, k$
   **Do all observed agricultural market interventions exacerbate input market failures?**

4. **Unilateral country policy changes**—e.g. rice export ban in India, EU import restrictions from certain countries, etc.

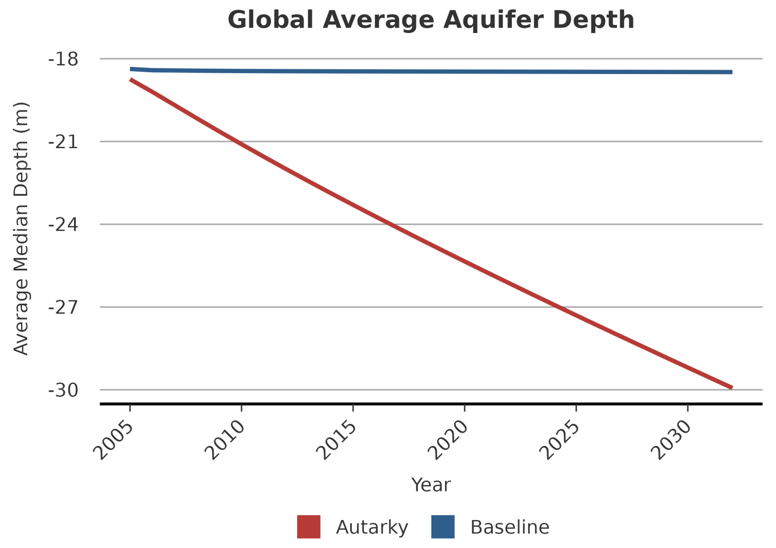
# Total global cropped area nearly doubles in autarky



# Total global water use also much higher in autarky

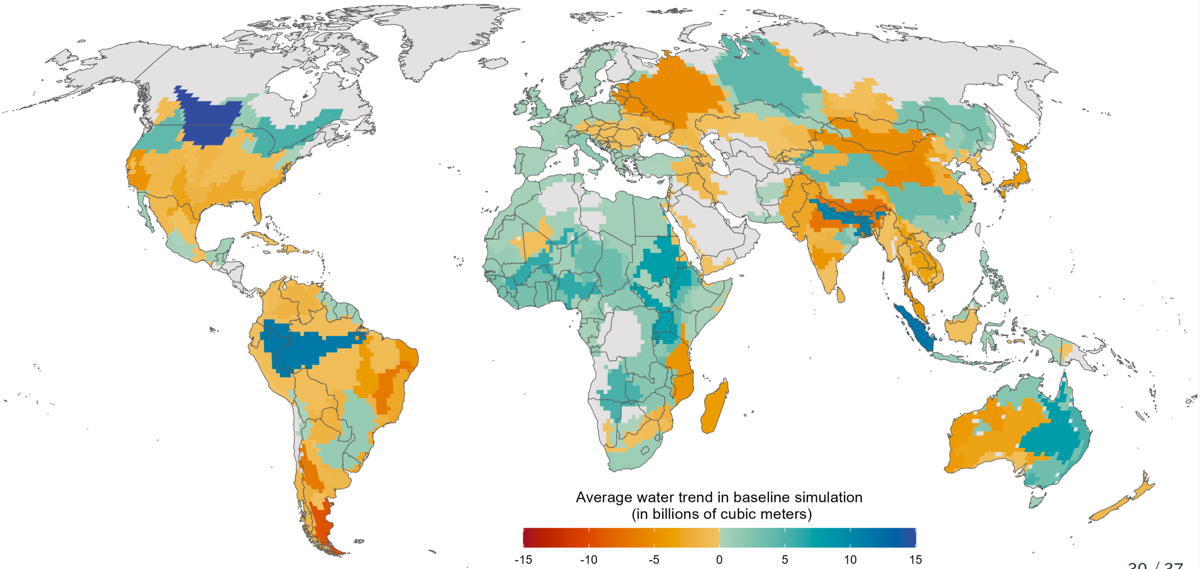


# Allowing trade prevents global aquifer depletion




Note: 3 year moving average

# Allowing trade prevents extreme regional depletion. . .



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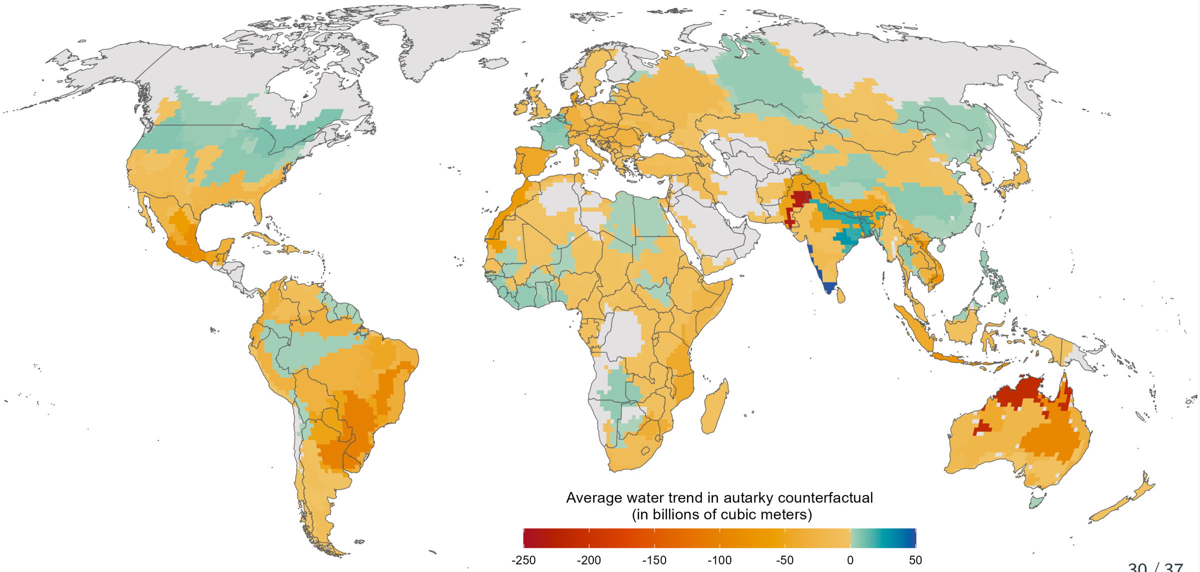
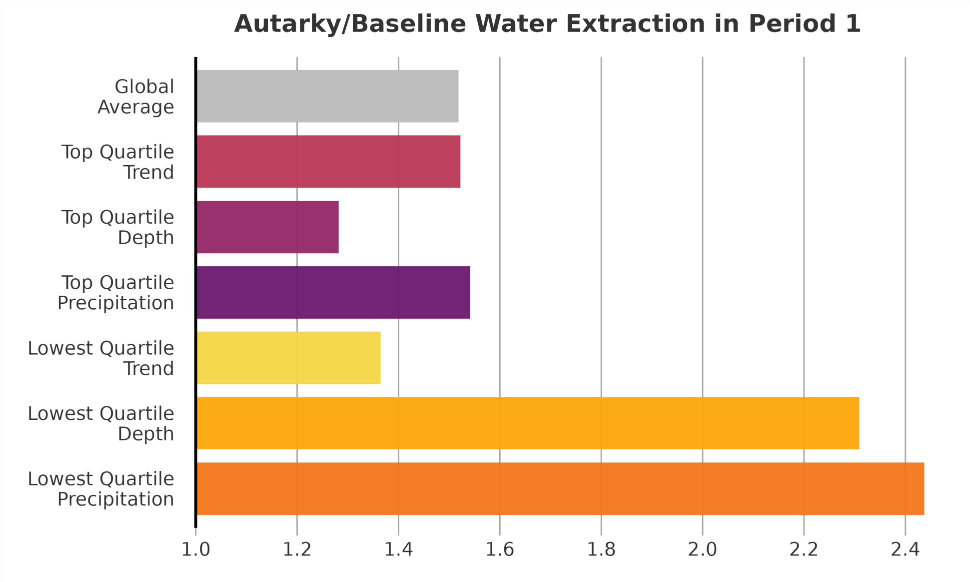
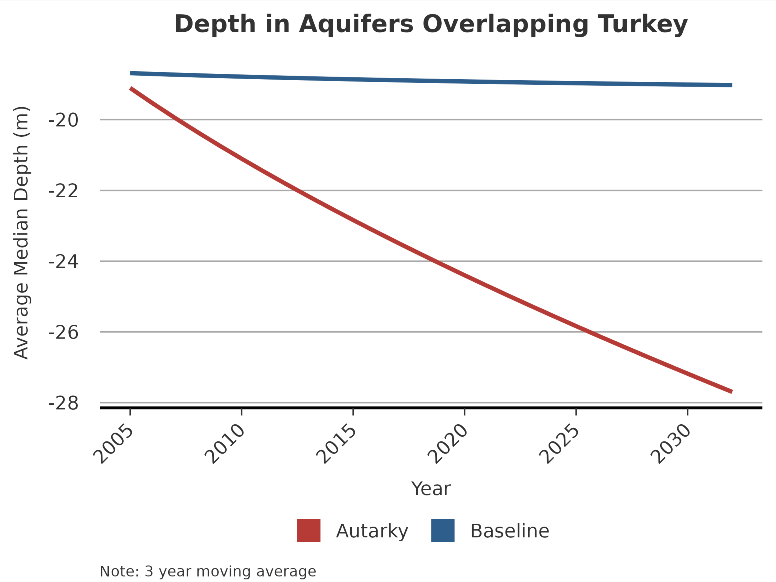


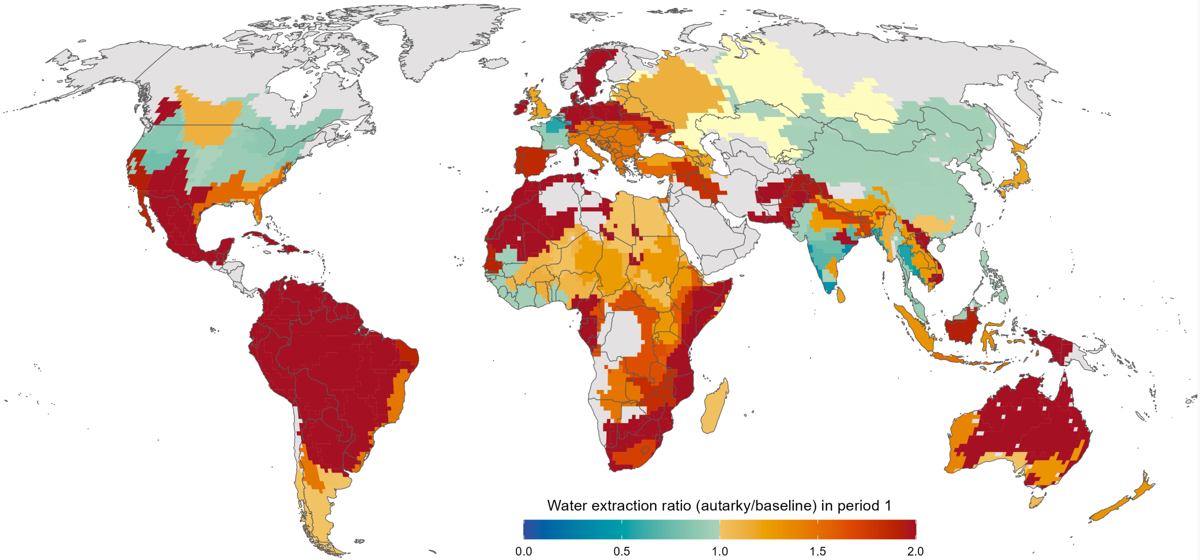
# . . . by lowering water use in water-stressed regions



# Autarky causes severe water depletion for some food importers...



# ... but prevents severe depletion for some food exporters



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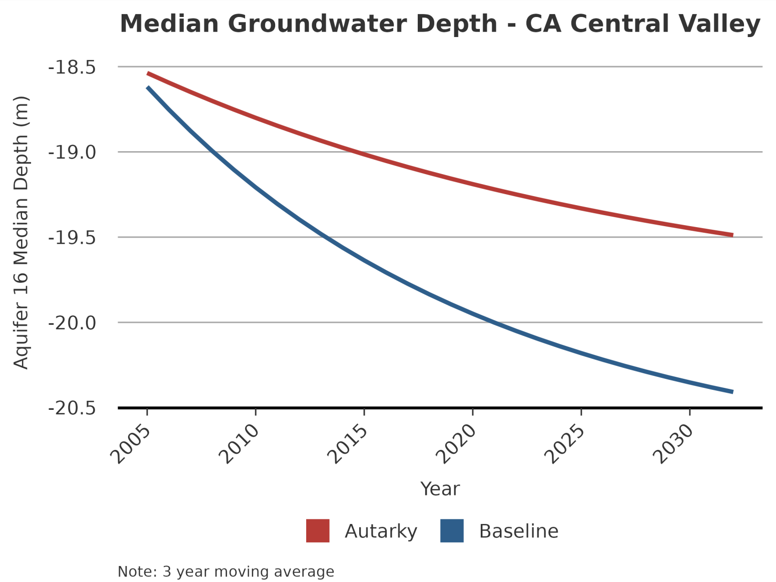

# Menu of counterfactuals

1. **Eliminate trade in agriculture**—set $\delta_{ji}^{k} = \infty$ for all $i, j, k$ with $i \neq j$
   **Existing trade alleviates water stress and improves welfare, but not everywhere**

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1. **Eliminate trade in agriculture**—set $\delta_{ji}^k = \infty$ for all $i, j, k$ with $i \neq j$
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2. **Evaluate historical changes in output market interventions**—compare allocation with $\tau_i^k$ from pre-Uruguay round of WTO negotiations ($\sim$1990) to $\tau_i^k$ from $\sim$2009
   **Spatial pattern of policy changes increased water extraction and lowered welfare**

3. **Eliminate all output market distortions**—set $\tau_i^k = 1$ for all $i, k$
   **Removing current distortions lowers water extraction and improves welfare**

# Conclusion

# Next steps

1. **Improve calibration**
   - ☑ Allow for double- and triple-cropping
   - ☐ Incorporate heterogeneous water intensities ($\phi^{fk}$)
   - ☐ Estimate $\theta$
   - ☐ Match ag. *share* of GDP + refine welfare calculations
2. **Additional counterfactuals**
   - ☐ India rice export ban
   - ☐ EU import restrictions from water-depleting regions
3. Solve **social planner's problem** and compare to optimal allocation (*next paper*)

# Conclusion

- Effects of ag. trade on water resources and long-run welfare **not ex ante obvious** with pervasive water property rights failures and ag. market distortions (**Facts 3–4**)
- Comprehensive global data show water-intensive production **highly concentrated** in water-abundant locations, but some **unsustainably** (**Fact 5**)
  - → Suggests a beneficial role for ag. trade in alleviating water stress
- **Model counterfactuals** show that eliminating ag. trade causes **global water depletion and welfare losses** over time, especially in drier food-importing regions
  - → But some historic agricultural trade/policy distortions were water-saving
  - → And some food exporters with poor property rights over water lose from trade

# Thank you!

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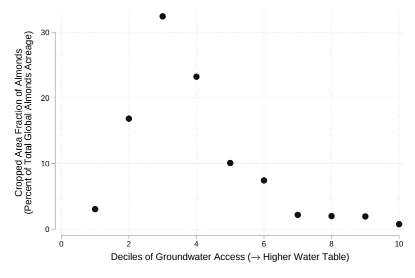
# Appendix

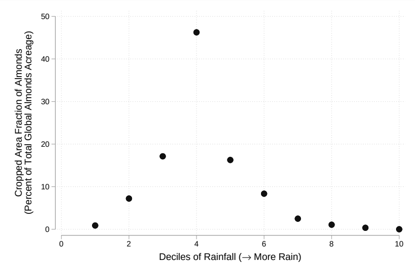
# Fact 5: Water-intensive crops locate primarily in water-abundant regions . . .

**Almonds**

# Fact 5: Water-intensive crops locate primarily in water-abundant regions . . .

## Almonds



# Fact 5: Water-intensive crops locate primarily in water-abundant regions . . .

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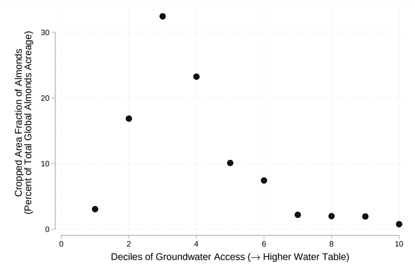
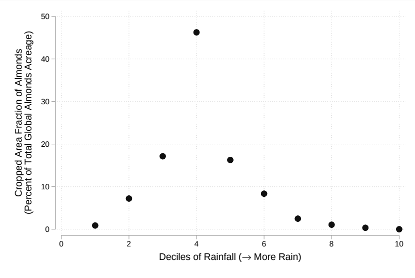
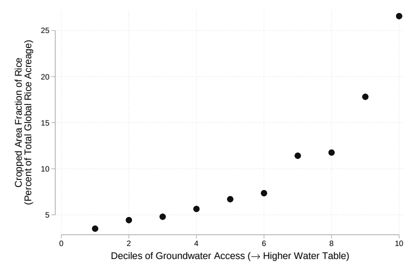
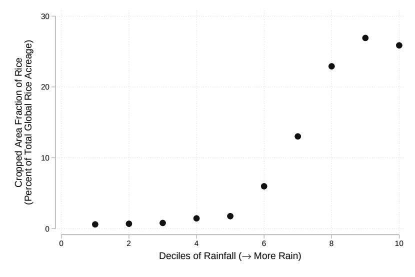


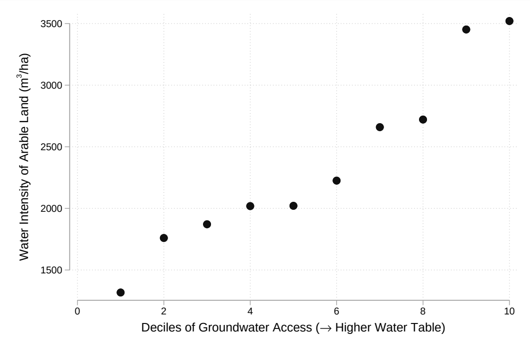



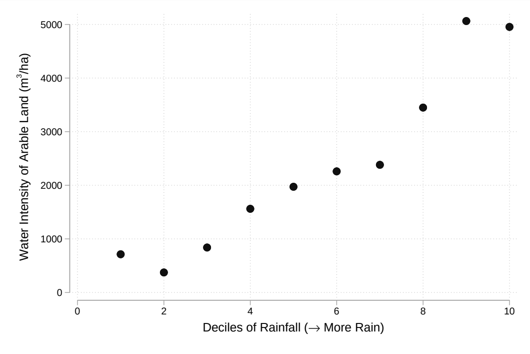

## Rice



# Fact 5: Water-intensive crops locate primarily in water-abundant regions . . .

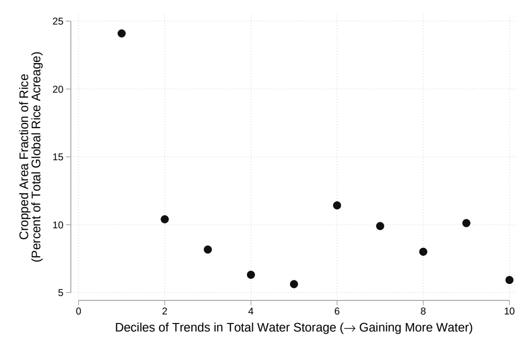


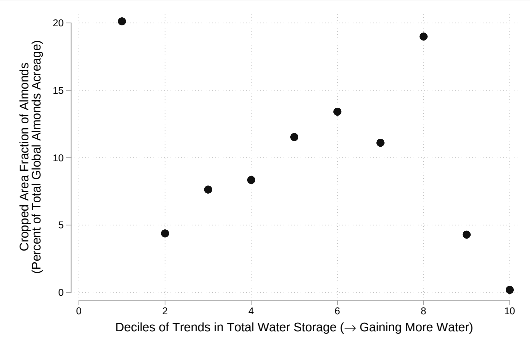

$$\text{Water Intensity of Arable Land } (\text{m}^3/\text{ha}) = \frac{\sum_{k\in\mathcal{K}} \text{hectares}^k \times \left(\frac{\text{water } (\text{m}^3)}{\text{hectare}}\right)^k}{\sum_{k\in\mathcal{K}} \text{hectares}^k + \text{pasture}}$$

# Fact 5: ...but also in some regions losing water rapidly

## Rice Acreage by Water Trends




## Almond Acreage by Water Trends



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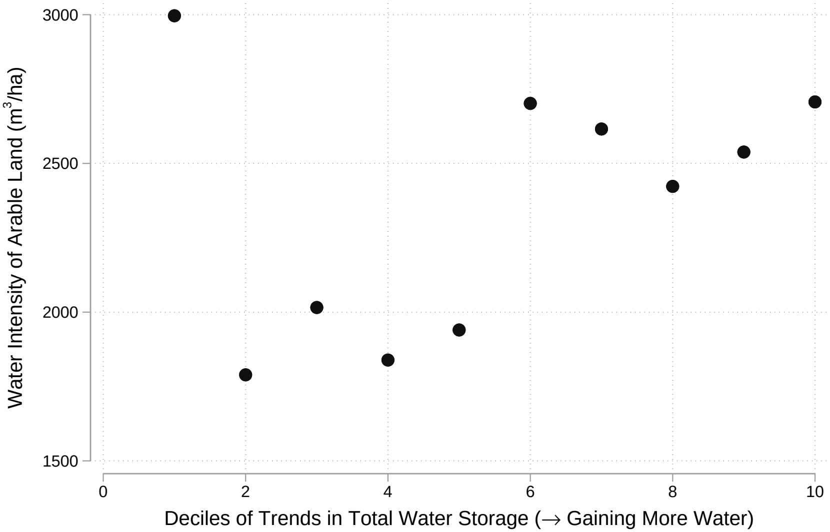

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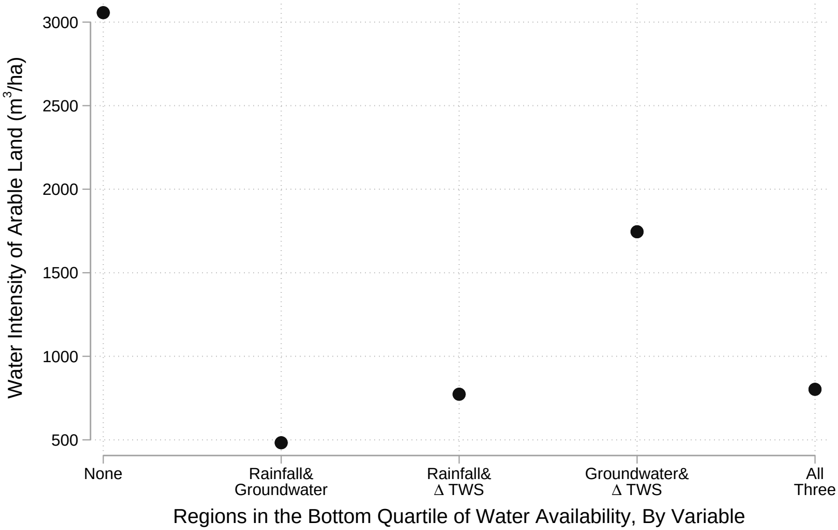
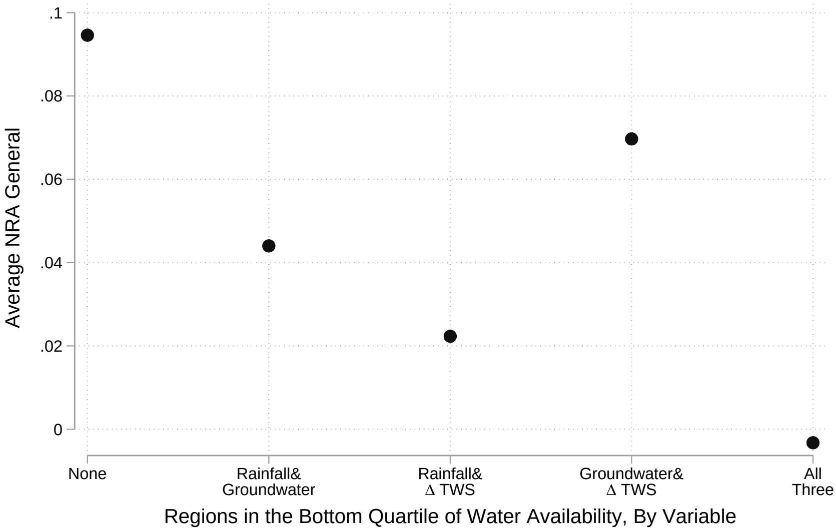
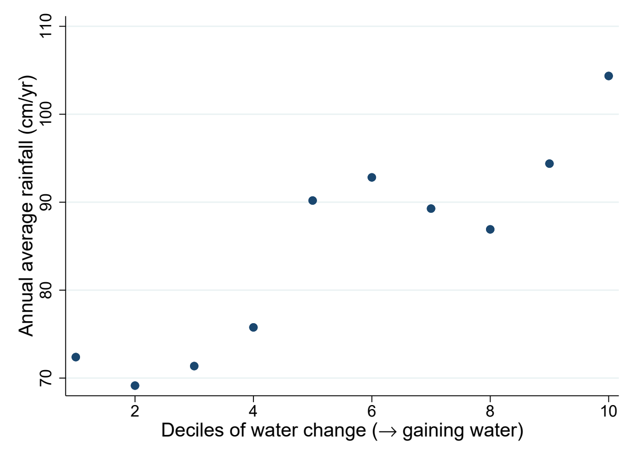


# Fact 5: Similar patterns in water intensity and agricultural policy



# Fact Aside: Characteristics of depleting regions (AEA P&P 2024)




Regions losing water rapidly are disproportionately **already water-scarce**

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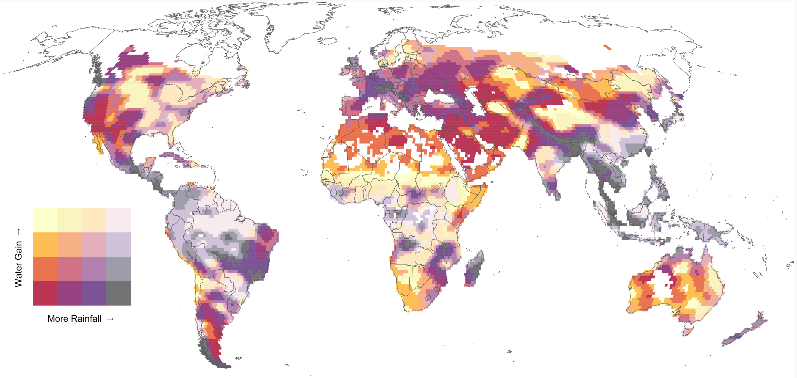


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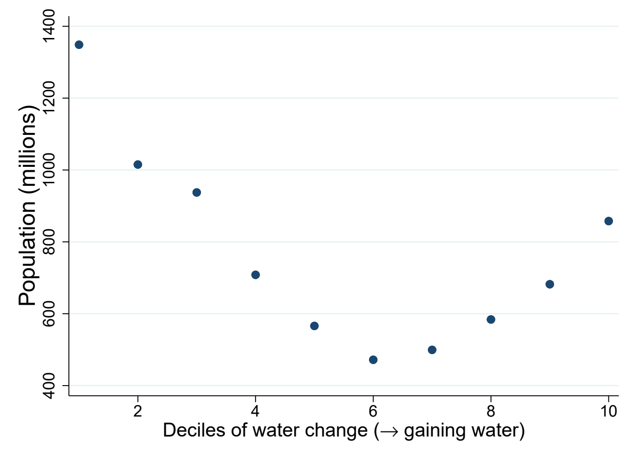


Regions losing water rapidly are very **highly populated**

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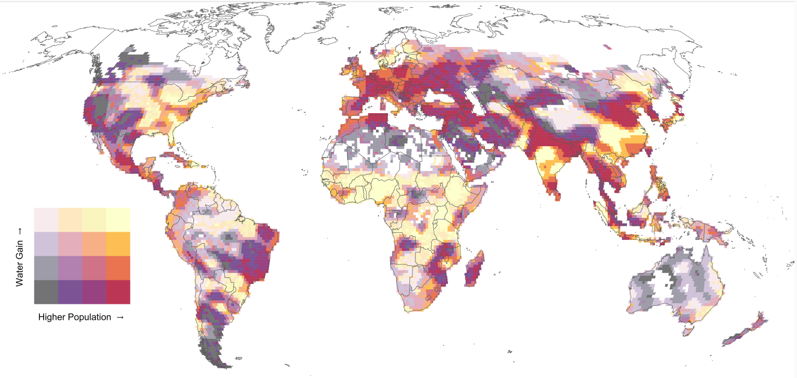


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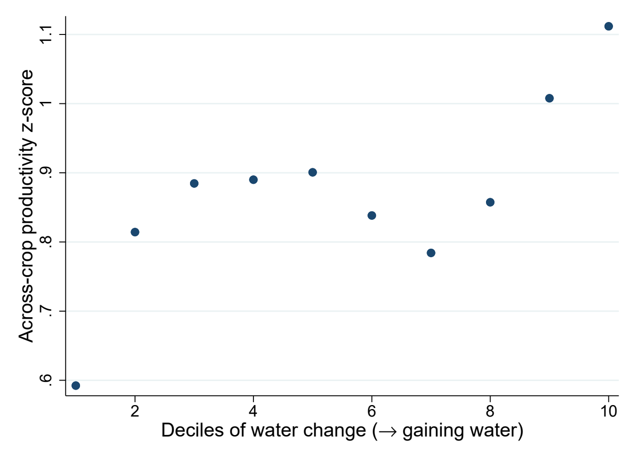
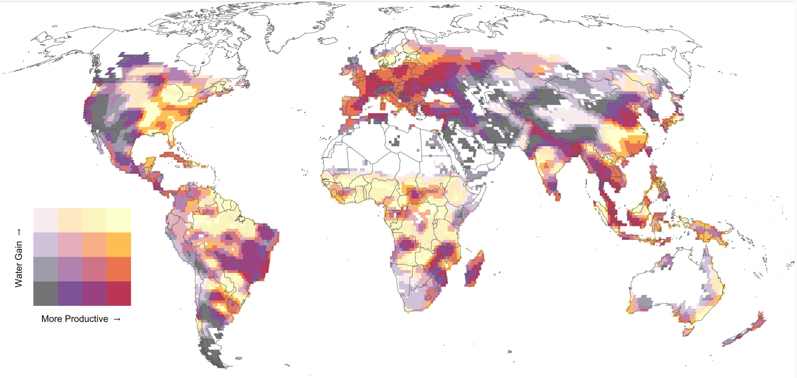



Regions losing water rapidly have **low suitability for crops**

# Fact Aside: Characteristics of depleting regions (AEA P&P 2024)




Regions losing water rapidly have **low suitability for crops**

# Equilibrium I: Utility maximization

Utility maximization by the representative household in each country requires that

$$C_{jit}^{k} = \zeta_i \frac{\zeta_i^k \left(P_{it}^k\right)^{1-\kappa}}{\sum_{\ell \in \mathcal{K}} \zeta_i^\ell \left(P_{it}^\ell\right)^{1-\kappa}} \frac{\zeta_{ji}^k \left(\delta_{ji}^k p_{jt}^k\right)^{-\sigma}}{\sum_{n \in \mathcal{I}} \zeta_{ni}^k \left(\delta_{ni}^k p_{nt}^k\right)^{1-\sigma}} \quad \text{for all } i, j \in \mathcal{I}, \;\; k \in \mathcal{K},$$

where

$$P_{it}^k = \left[\sum_{n \in \mathcal{I}} \zeta_{ni}^k \left(\delta_{ni}^k p_{nt}^k\right)^{1-\sigma}\right]^{\frac{1}{1-\sigma}}$$

denotes the CES price index associated with crop $k$ in country $i$ at time $t$.

# Equilibrium II: Profit maximization and labor choice

- Each laborer $\omega$ selects the activity (outside good or crop $k$) that achieves

$$\max\{A_i^o(\omega), r_t^{f1}(\omega), \ldots, r_t^{fK}(\omega)\}$$

where $r_t^{fk}(\omega) = \tau_{i(f)t}^k p_{i(f)t}^k A^{fk}(\omega) M(\phi^k, D_{q(f)t})$ is his **revenue** from producing crop $k$

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- By i.i.d. Fréchet with common shape parameter,

$$\pi_t^{fk} \equiv \mathbb{P}\left\{r_t^{fk}(\omega) = \max\{A_i^o(\omega), r_t^{f1}(\omega), \ldots, r_t^{fK}(\omega)\}\right\}$$
$$= \frac{\left(\tau_{i(f)t}^k p_{i(f)t}^k A^{fk} M(\phi^k, D_{q(f)t})\right)^\theta}{\left(A_{i(f)}^o\right)^\theta + \sum_{\ell \in \mathcal{K}} \left(\tau_{i(f)t}^\ell p_{i(f)t}^\ell A^{f\ell} M(\phi^\ell, D_{q(f)t})\right)^\theta}$$

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- **Total production**: adding across fields & incorporating selection

$$Q_{it}^k = \sum_{f \in \mathcal{F}_i} h^f A^{fk} M(\phi^k, D_{qt}) \left(\pi_t^{fk}\right)^{\frac{\theta-1}{\theta}}$$

## Sample selection: Countries

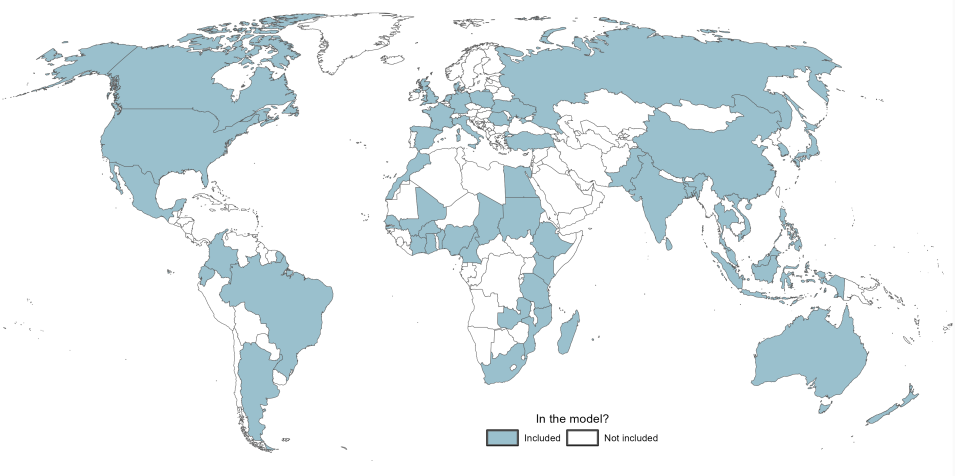
Include countries in the **top 40** globally in any of. . .

(1) number of agricultural workers, (2) agricultural production, or (3) total population

# Sample selection: Countries

Resulting sample has **52 countries** that cover. . .

**99%** of ag. workers, **97%** of ag. production value, **97%** of population, and **94%** of GDP



# Sample selection: Crops

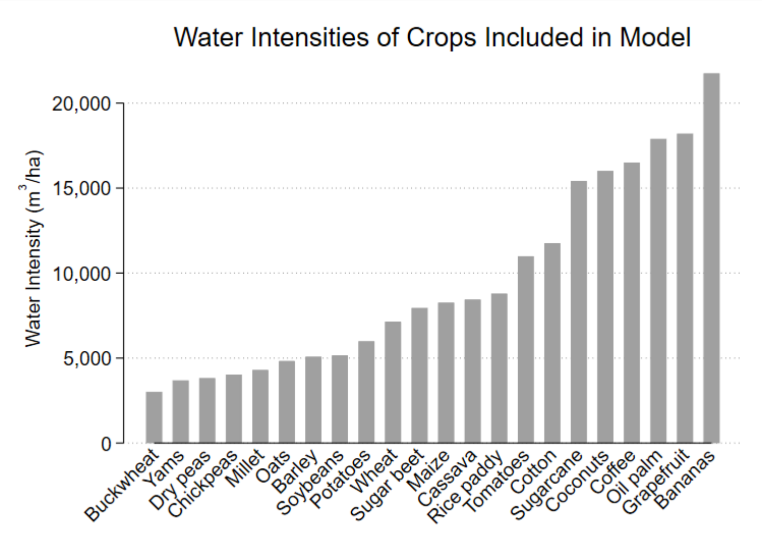
Include **high-value** and **staples** (global *and* regional) + **span** water intensities | in GAEZ (38)

# Sample selection: Crops

Resulting sample has **22 crops** covering **56%** of global value and **59%** of global water use

- **high-value + global staples**: wheat, rice, maize, soybeans, sugarcane, cotton, potatoes, tomatoes, oil palm, bananas (Costinot, Donaldson, and Smith, 2016)
- **regional staples**: cassava, sorghum, millet, barley, sugar beets
- **high water-intensity crops**: coffee, grapefruit, coconuts
- **low water-intensity crops**: yams, buckwheat, chickpeas, dry peas

# Sample selection: Crops

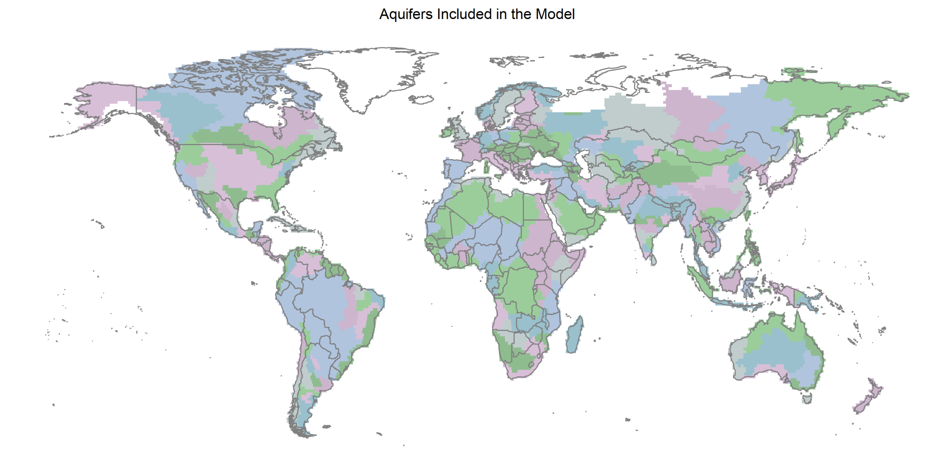


# Sample selection: Aquifers

Include **37 aquifers** (WHYMAP), then cluster GRACE grid cells s.t. **180 water basins** (NASA)

# Sample selection: Aquifers

Partition land area into 278 “aquifers,” of which **205** intersect chosen countries



# Parameters to be calibrated/estimated

| | | |
|---|---|---|
| ☐ | $\sigma$, $\kappa$ | demand elasticities |
| ☐ | $\{\zeta_j, \zeta_j^k, \zeta_{ij}^k\}$ | demand shifters |
| ☐ | $\{\delta_{ij}^k\}$ | bilateral crop-specific trade costs |
| ☐ | $1-\alpha$ | land share in crop production |
| ☐ | $\{\phi^k\}$ | crop-specific water intensity |
| ☐ | $\theta$ | technological heterogeneity |
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| ☐ | $\psi$ | return flow rate |
| ☐ | $\{\rho_q\}$ | specific yield |
| ☐ | $\{R_q\}$ | natural recharge |
| ☐ | $\{\Upsilon_q\}$ | scale of extraction productivity |
| ☐ | $\upsilon$ | elasticity of extraction productivity |

# Calibrating technological and hydrological parameters

| Parameter | | Value | Source |
|---|---|---|---|
| land share | $1-\alpha$ | 0.25 | Boppart et al. (2019) |
| return flow rate | $\psi$ | 0.25 | Dewandel et al. (2008) |
| extraction elasticity | $\upsilon$ | 1.0 | Burlig, Preonas, and Woerman (2021) |
| water intensity | $\{\phi^k\}$ | | convert from Mekonnen and Hoekstra (2011) |
| specific yield | $\{\rho_q\}$ | | s.y. by soil type (Loheide, Butler, and Gorelick, 2005) |
| | | | soil type (Hengl et al., 2017) |
| natural recharge | $\{R_q\}$ | | residual of avg. $\Delta$TWS from NASA's GRACE data |
| | | | & implied water use based on $\{\phi^k\}$ and obs. $\{\pi^{fk}\}$ |
| | | | from SAGE (Monfreda, Ramankutty, and Foley, 2008) |

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☑ calibrated: lit. & data

# Estimating the demand side: Go inside out, nest by nest

1. If zero trade flow, set $\zeta_{ij}^k (\delta_{ij}^k)^{1-\sigma} = 0$
2. If positive, run IV on

$$\ln(E_{ij}^k / E_j^k) = \mathsf{FE}_j^k + (1-\sigma)\ln\left(p_i^k\right) + \epsilon_{ij}^k$$

   under the normalization that the shocks sum to zero, with instrument

$$Z_i^k \equiv \ln\left(\frac{1}{F_i}\sum_{f\in\mathcal{F}_i} A_i^{fk}\right)$$

   $\implies$ variation in $p_i^k$ independent of preferences and trade costs
3. That regression identifies $\sigma$, and we set $\ln[\zeta_{ij}^k (\delta_{ij}^k)^{1-\sigma}] \equiv \epsilon_{ij}^k$

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4. Construct $P_j^k$ from the price data and previous estimate. Repeat 1–3 at the mid-tier (across crops) to identify $\kappa$ and construct $\zeta_j^k$, using $Z_j^k$ to instrument for $P_j^k$

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5. $\zeta_j$ is just the value of expenditure on agricultural goods by $j$

Absorb all extra variation in taste $\times$ trade cost parameters $\implies$ **exactly** match demand side

# Parameters to be calibrated/estimated

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|---|---|---|
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☑ calibrated: lit. & data

☑ estimated: follow **CDS (2016)**

# Estimating the supply side

Estimate $\theta$, $\{A_i^o\}$, and $\{\Upsilon_q\}$ jointly via **nonlinear least squares** (NLS):

$$\min_{\theta,\{A_i^o\},\{\Upsilon_q\}} \sum_i \sum_k \left[\ln Q_i^k(\theta,\{A_i^o\},\{\Upsilon_q\}) - \ln Q_i^k\right]^2 \ \text{ s.t. } \ X_q = X_q(\theta,\{A_i^o\},\{\Upsilon_q\}), \quad \forall q$$

$$L_i = L_i(\theta,\{A_i^o\},\{\Upsilon_q\}), \quad \forall i$$

where *observed* extraction is

$$X_q := \sum_{f\in\mathcal{F}_q} \sum_{k\in\mathcal{K}} h^f \pi^{fk} \phi^k$$

## Intuition for identification

- Share of non-cultivated land $\leftrightarrow$ non-agricultural labor productivity
- Water extracted $\leftrightarrow$ labor productivity of extraction
- Cross-parcel dispersion in productivity $\leftrightarrow$ cross-crop dispersion in output

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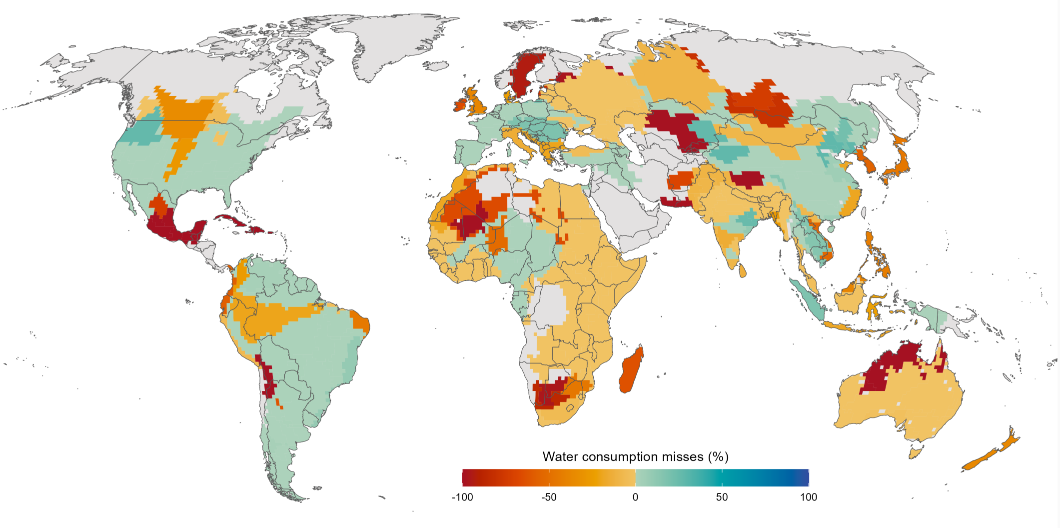
☑ calibrated: lit. & data

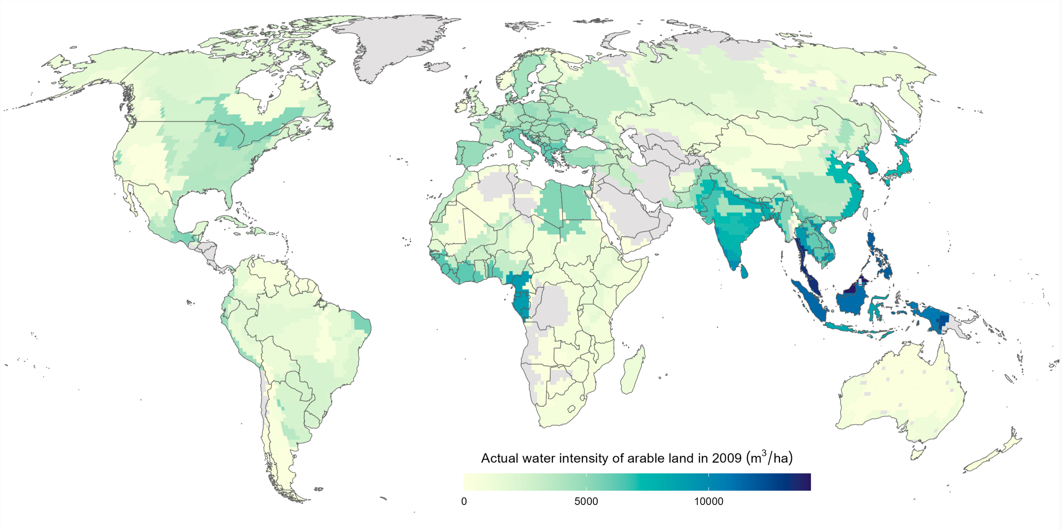
☑ estimated: follow **CDS (2016)**

☑ estimated: **NLS** (land & water use)

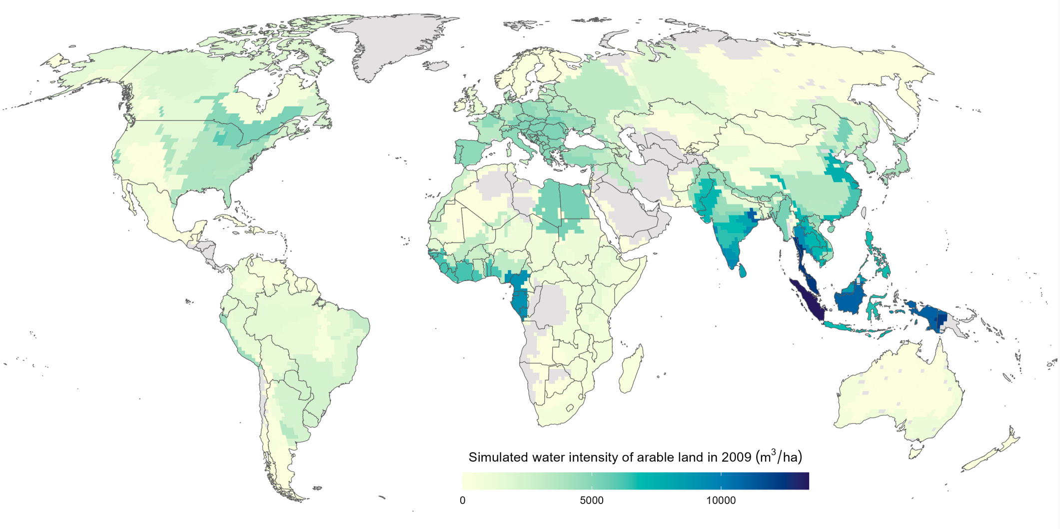
# Model fit: Agricultural water extraction



# Model fit: Agricultural water extraction (target)



# Model fit: Agricultural water extraction (simulated)



# Model validation: Water extraction productivity

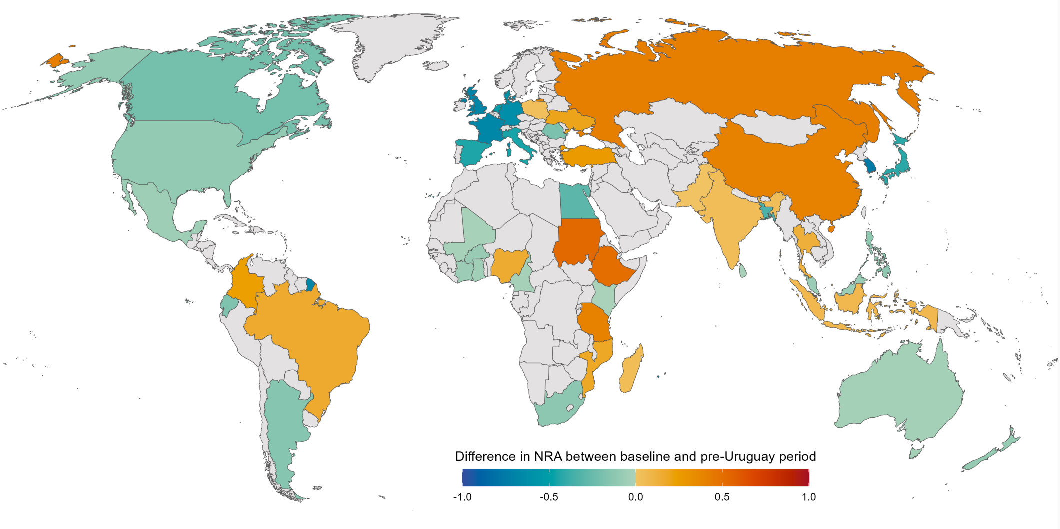
**Table 1:** Partial Correlations of Aquifer-Level Covariates, Impact of Depth on Extraction Productivity ($\Upsilon_q$), and Extraction Productivity ($A_q^w(D_{qt})$)

| | Dependent Variable | |
|---|---|---|
| | log($\Upsilon$) | log($A_q^w(D_{qt})$) |
| Precipitation | 0.64$^{**}$ | 0.54$^{*}$ |
| | (0.25) | (0.28) |
| Precipitation$^2$ | -0.11$^{**}$ | -0.08$^{**}$ |
| | (0.03) | (0.03) |
| Temperature | 0.26$^{***}$ | 0.17$^{***}$ |
| | (0.04) | (0.05) |
| Temperature$^2$ | -0.004$^{***}$ | -0.003$^{*}$ |
| | (0.001) | (0.002) |
| Area irrigated (%) | 0.10$^{*}$ | 0.10$^{*}$ |
| | (0.05) | (0.05) |
| Nighttime luminosity | 0.20$^{***}$ | 0.18$^{**}$ |
| | (0.07) | (0.01) |
| Surface water area (%) | -0.02$^{**}$ | -0.02$^{*}$ |
| | (0.01) | (0.01) |
| Groundwater depth (m) | | 0.04$^{***}$ |
| | | (0.01) |
| $R^2$ | 0.56 | 0.40 |

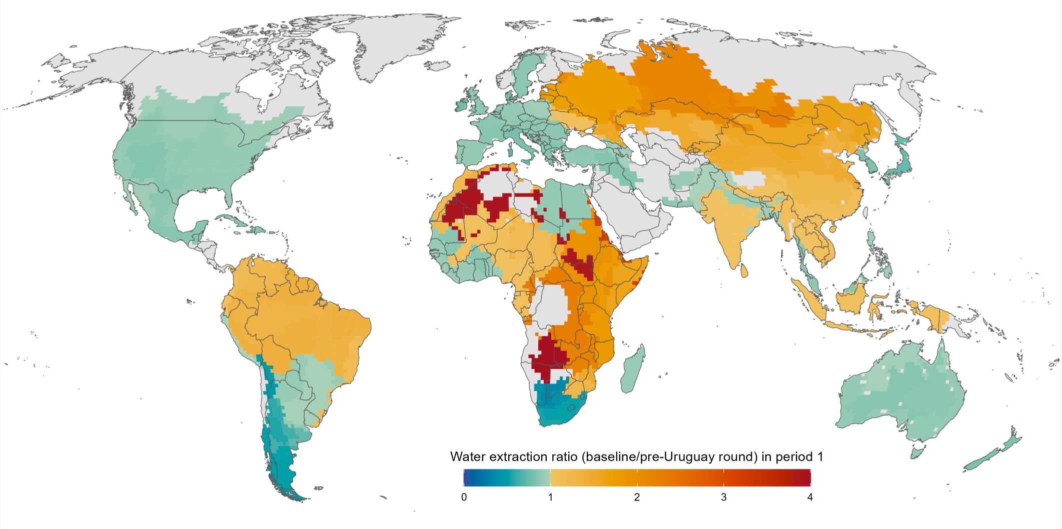
# Alternative policy counterfactuals

2. **1994 Uruguay Round of WTO Negotiations:** Largest global ag. liberalization
    - Prior trade agreements (GATT) largely excluded agriculture
    - "Tariffication" of non-tariff barriers to agricultural trade with maximum tariff rates imposed
    - *Implementation:* set $\tau_i^k = 1+$ avg. from Uruguay Round (1986-1994)
3. **Removal of current output market distortions:** Smaller but significant distortions remain despite multi- and bi-lateral trade agreements
    - *Implementation:* set $\tau_i^k = 1$ for all $i$, $k$

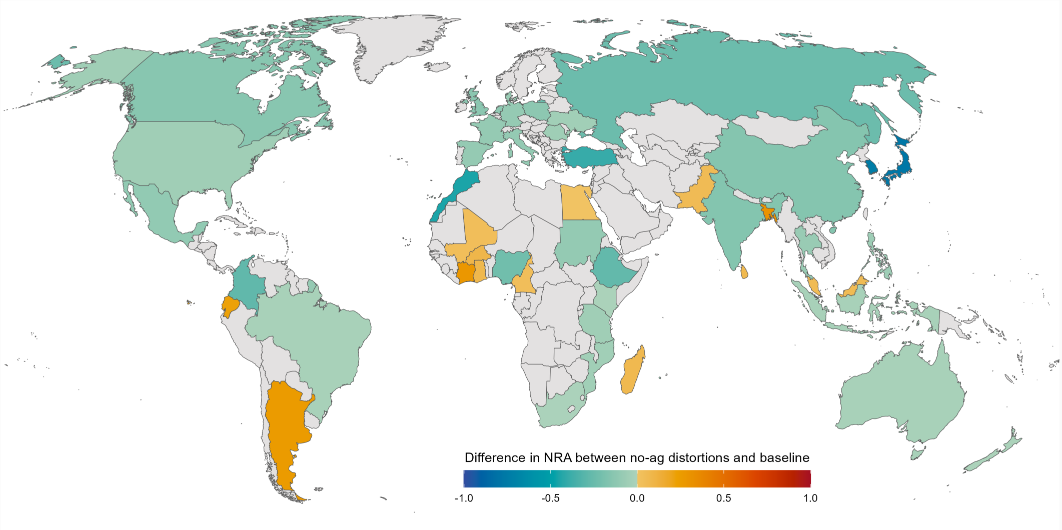
# Uruguay Round lowered subsidies in the north, raised them in the south



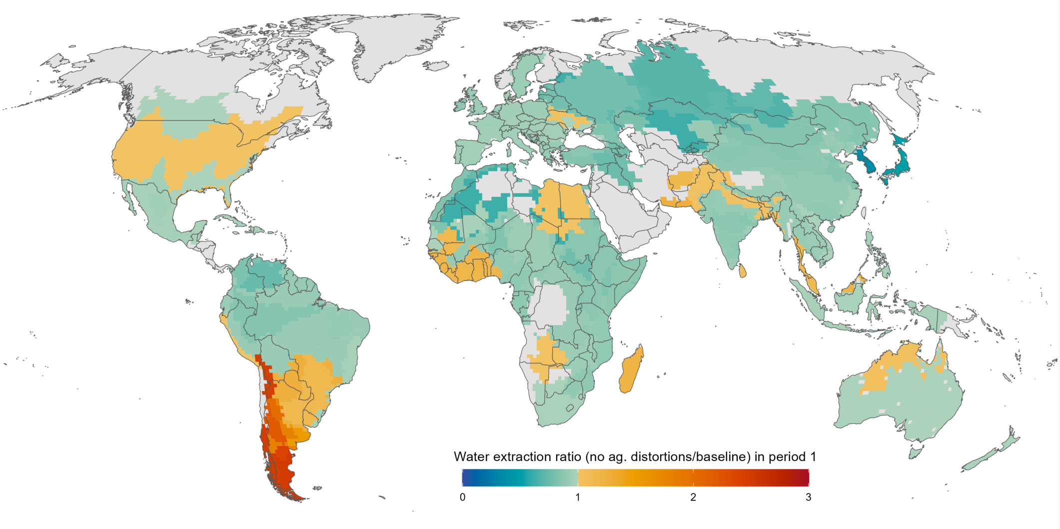
# Uruguay Round increased water extraction in the south



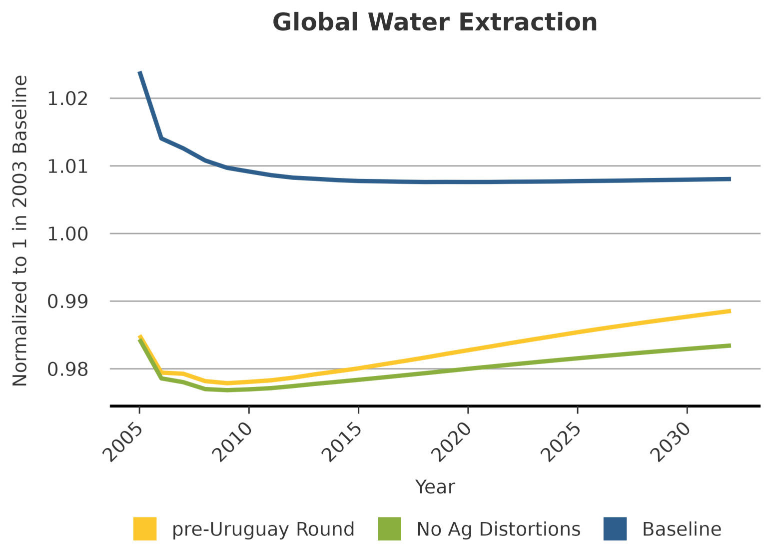
# Removing current distortions lowers subsidies to ag. nearly everywhere



# Removing current distortions lowers water extraction nearly everywhere

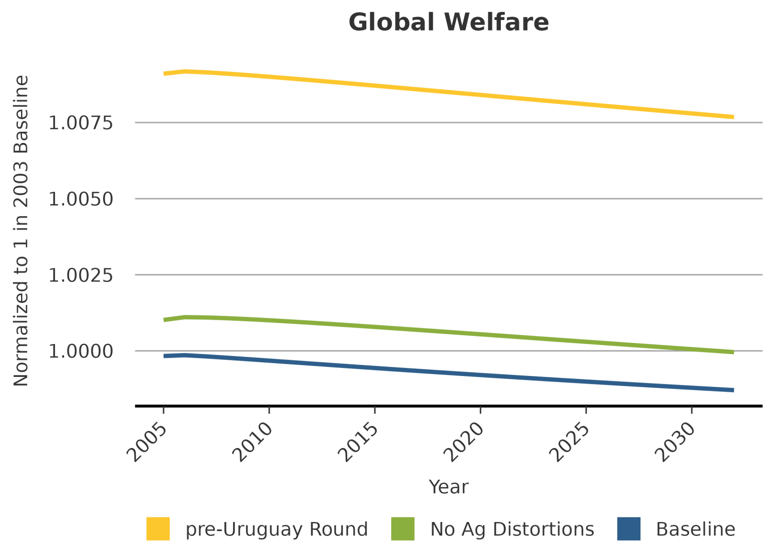


# Global water extraction falls under both counterfactual policies




Note: 3 year moving average

# Global welfare rises under both counterfactual policies




Note: 3 year moving average

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