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

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April 2025

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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- **∼12 liters of water used to grow one almond**

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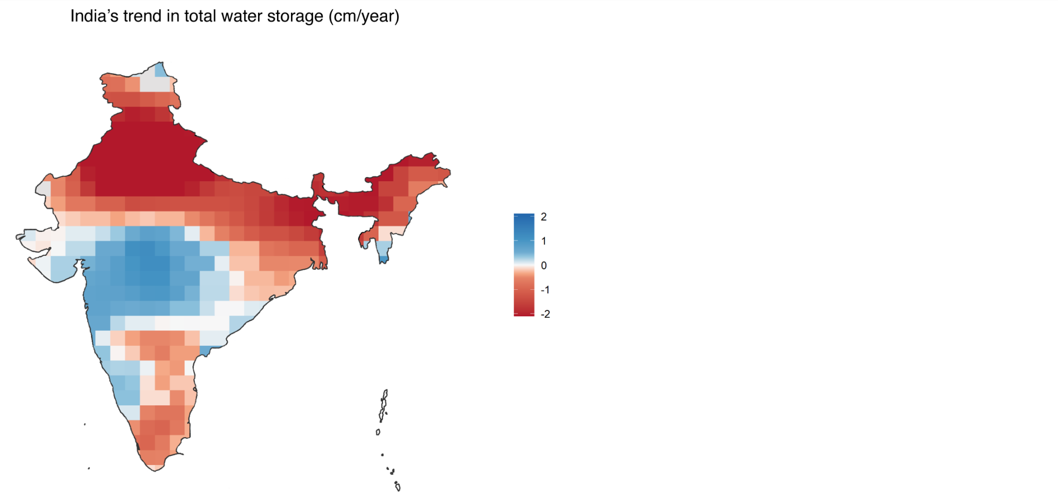

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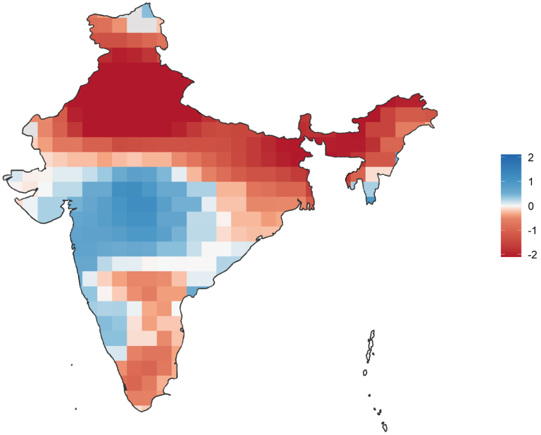
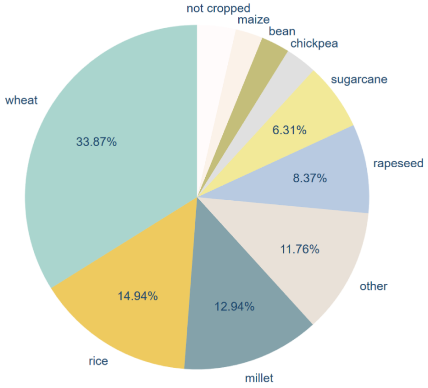
India's trend in total water storage (cm/year)



Land allocation in India's most water-stressed regions



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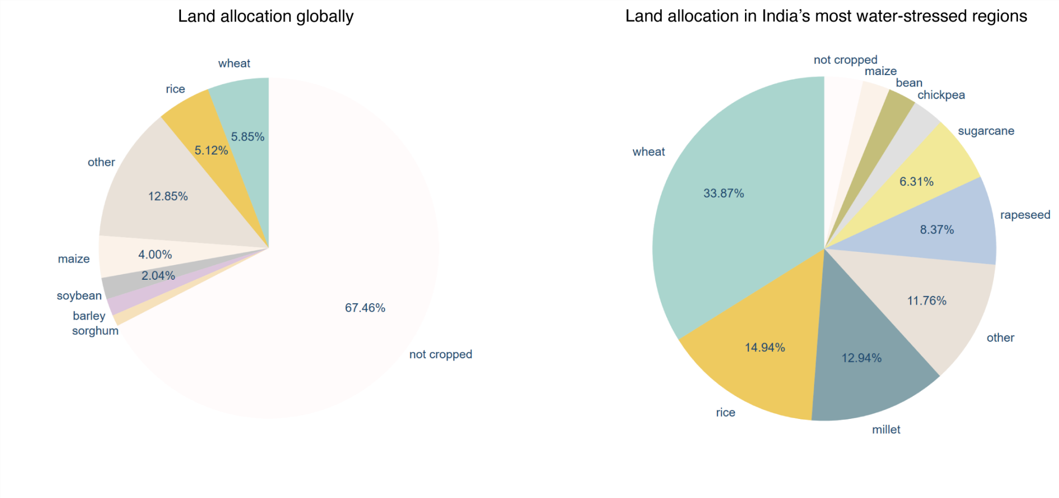

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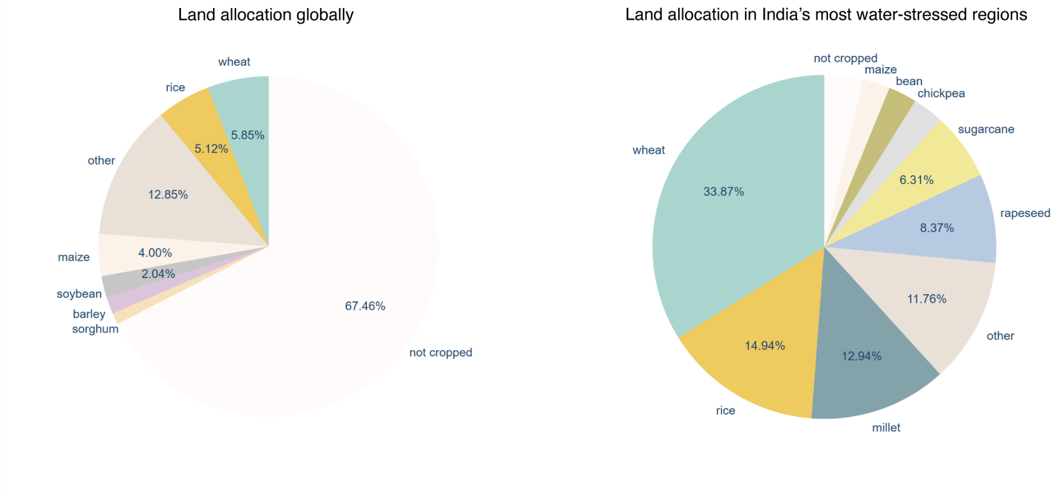

India is now the world's **leading exporter of rice**

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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  - **1–2.** Vast heterogeneity in water availability and use (ag. dominates) → **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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- Calibrate a **quantitative dynamic spatial equilibrium model** for world ag.
  - 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

1. **Global ag. trade dramatically reduces global land and water use**

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

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

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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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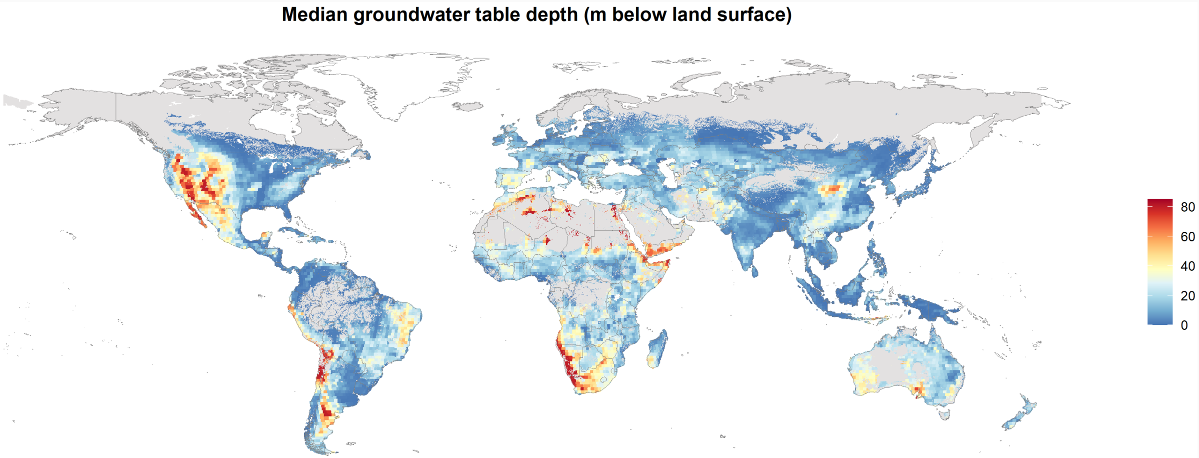

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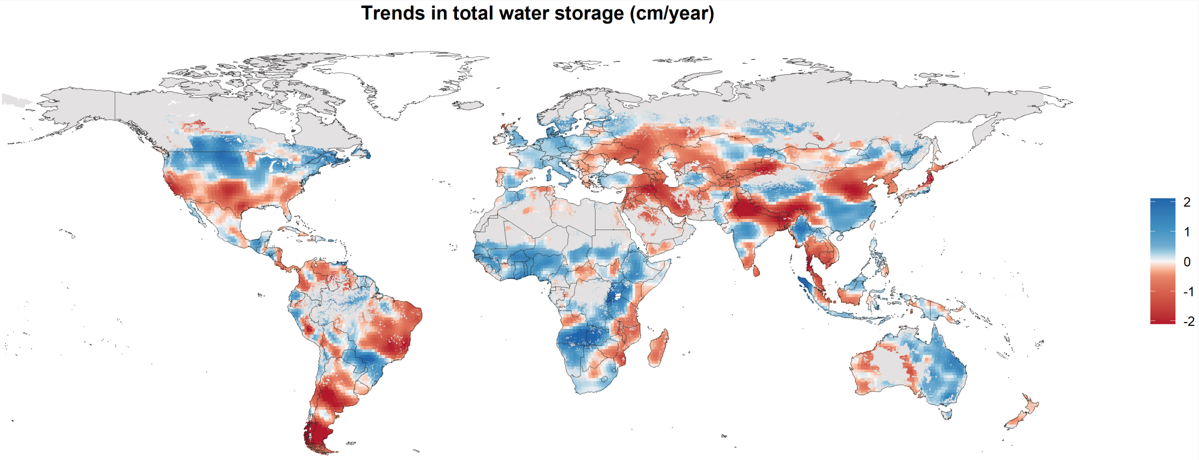

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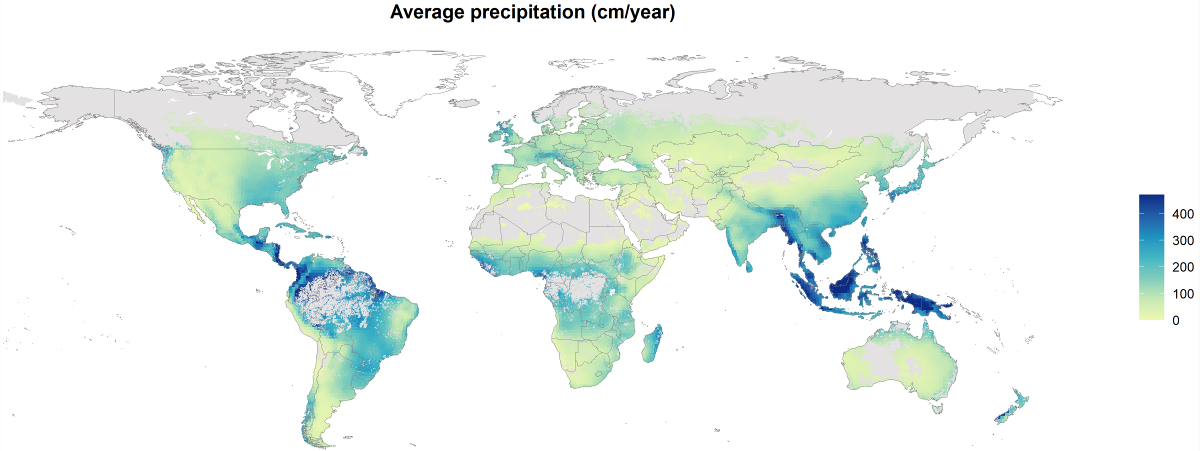

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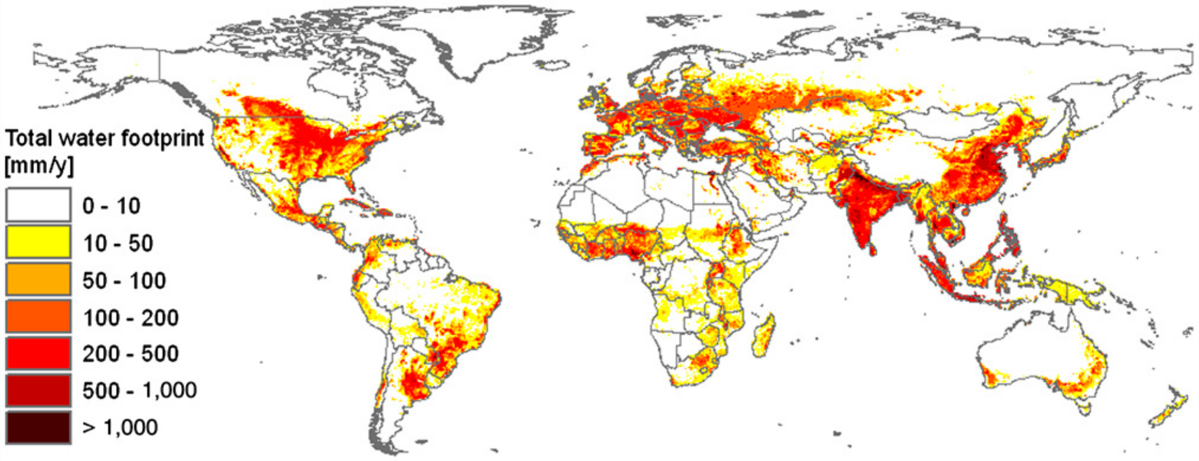

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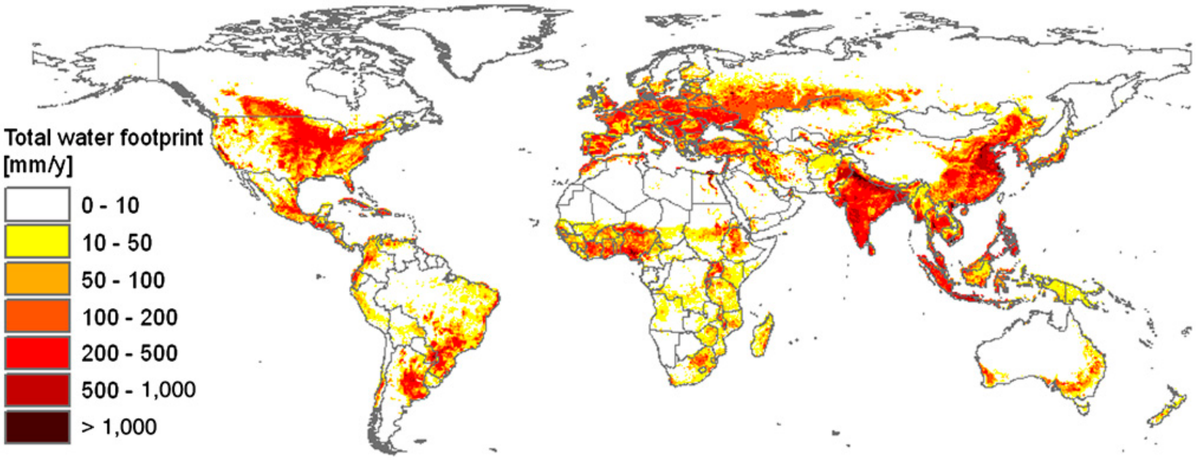

It's all about agriculture: $\sum_q$ **Consume$_{qt}$** $\approx$ **90% agricultural input use** (d'Odorico et al., 2019)

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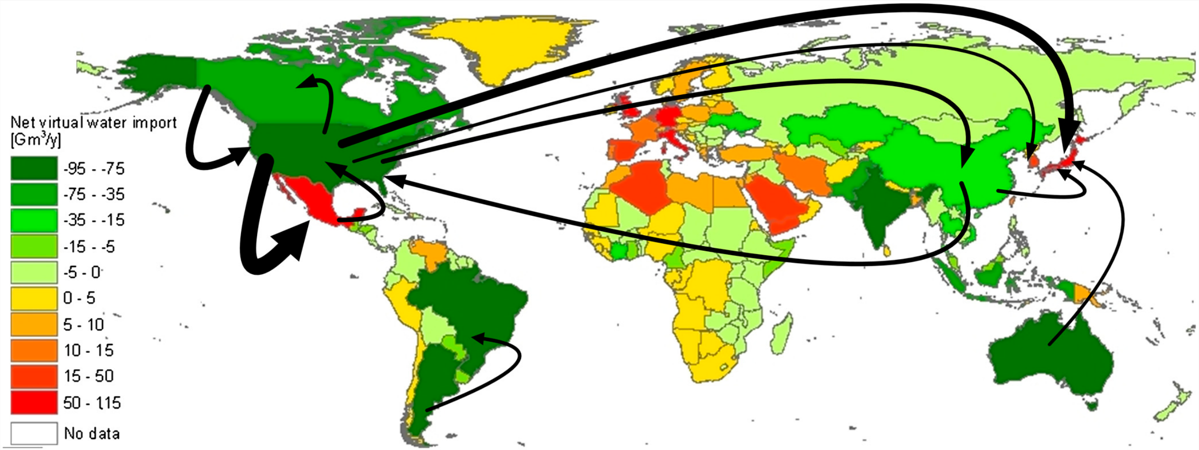
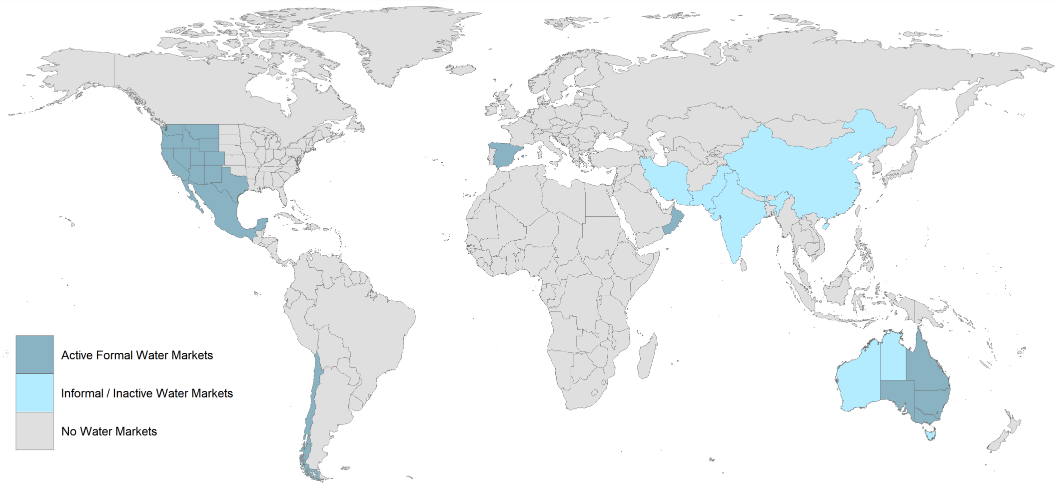


Ag. trade embeds **20–25%** of $\sum_q \textbf{Consume}_{\textbf{qt}}$ (Hoekstra and Mekonnen, 2012; Carr et al., 2013)

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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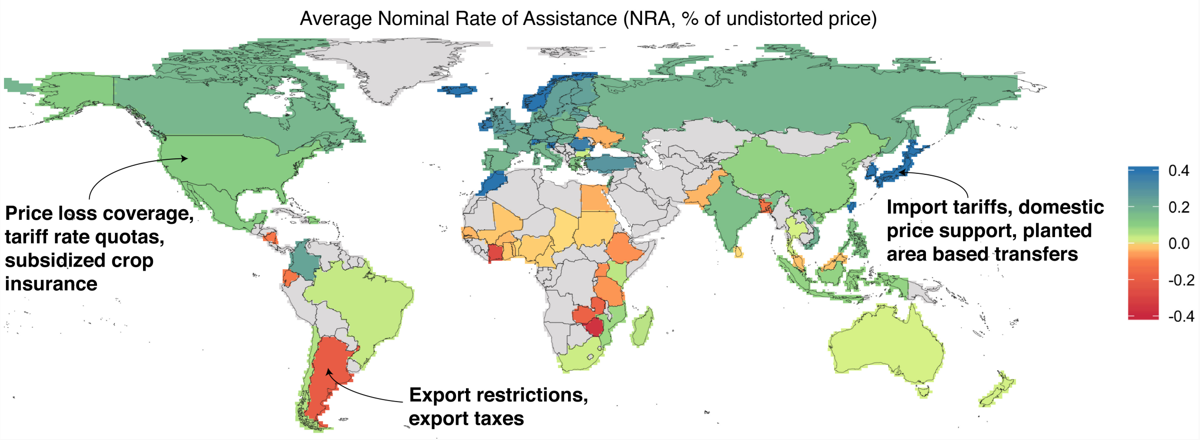

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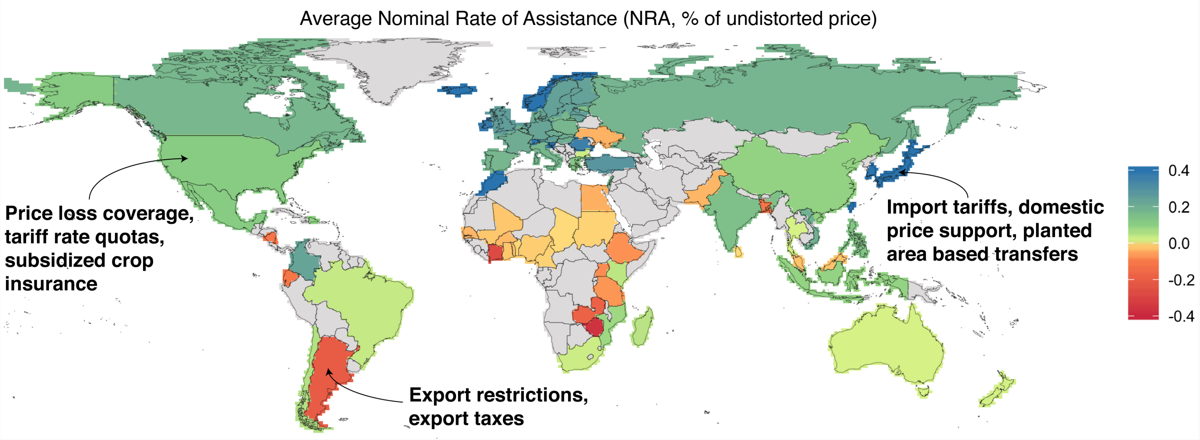

10pp inc. in net ag. subsidy → ΔDepth_{qt} from 50th to 75th pctl (Carleton, 2021)

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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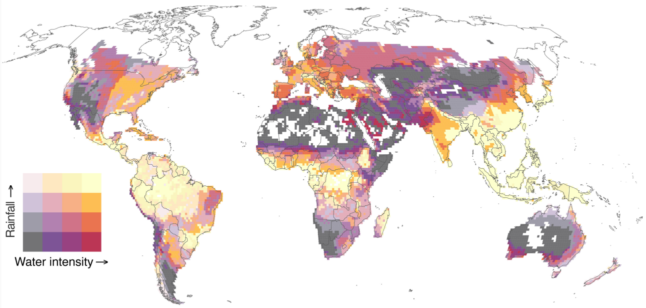

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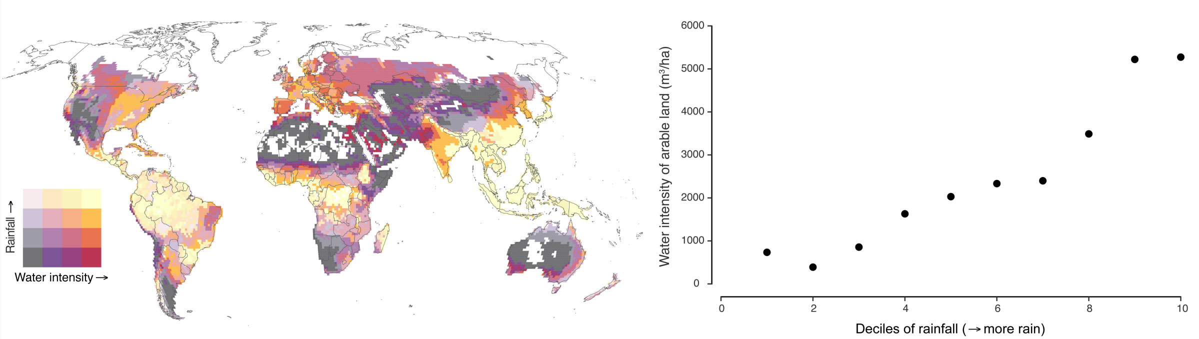

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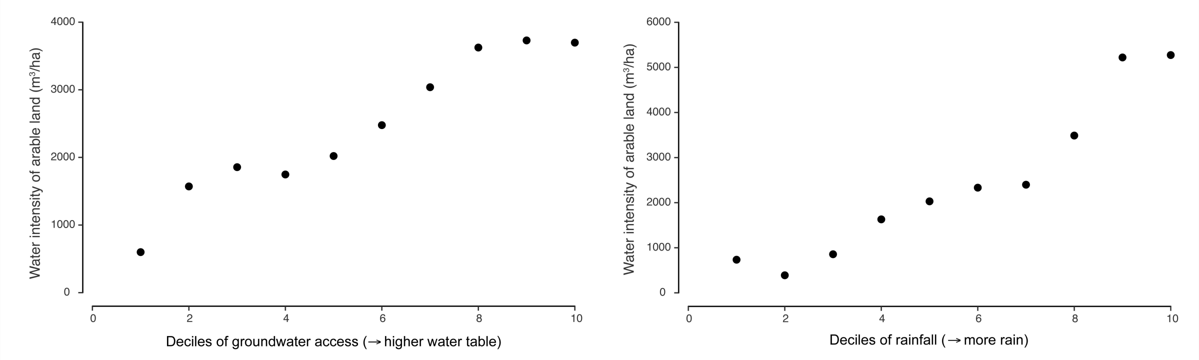

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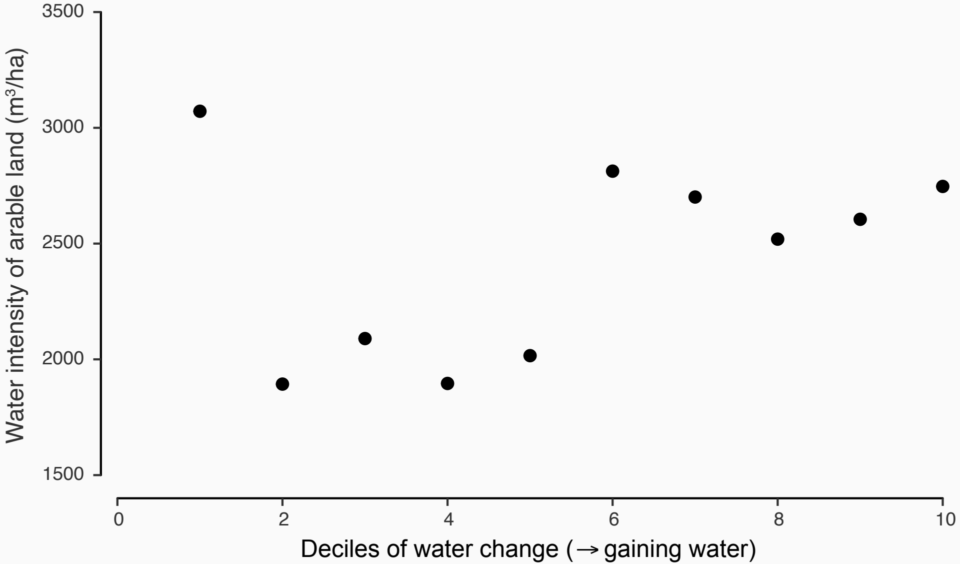

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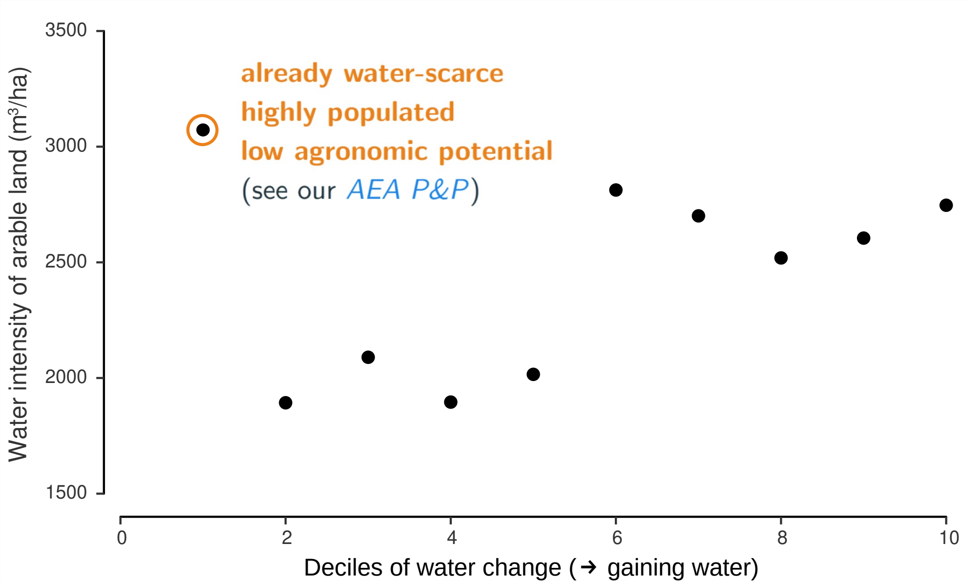

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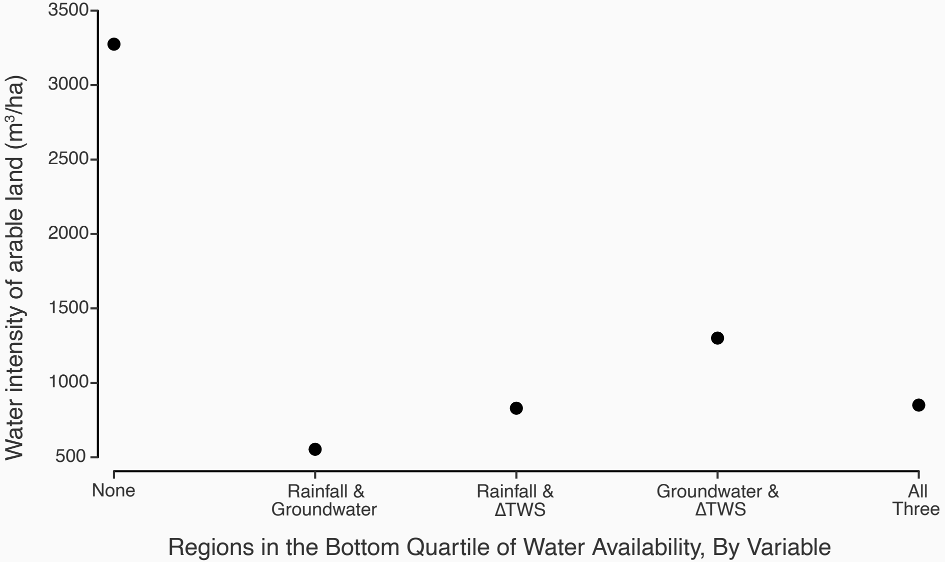
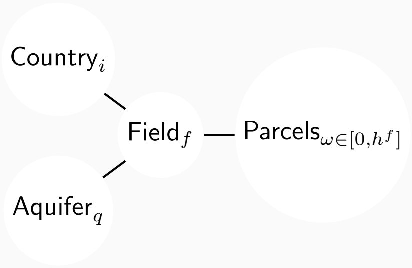


Model

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 ω
- **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:

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

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

Technology I: Agriculture

Consider the farmer of parcel ω 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

- ϕ^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 ϕ^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 ω is drawn i.i.d. from Fréchet with **same shape parameter** θ:

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

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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** τ^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
  - ρ_q is the **specific yield** of aquifer q (volume $\to$ depth)
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No dynamic choices, but the evolution of depths matters!

Equilibrium I: Utility maximization

Utility maximization by the representative household in each country requires that

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

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

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

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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 **EarthStat** at 5-arc minute level (~**1.9mil grid cells**)
  - crop-specific potential yields A^{fk}
  - crop-specific cropped area fractions π^{fk}
  - area h^f
- Country-level (i): from **FAOSTAT** and **World Bank**
  - crop-specific output Q_{it}^k
  - crop-specific NRA τ_{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 $D_{q,0}$ ($\rightarrow$ starting **out-of-S.S.**)
  - change in total water storage $\propto \Delta D_{q,t}$

Parameters to be calibrated/estimated

☐	σ, κ	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
☐	θ	technological heterogeneity
☐	$\{A_i^o\}$	mean labor prod. in outside sector
☐	ψ	return flow rate
☐	$\{\rho_q\}$	specific yield
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☑ calibrated: lit. & data

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☑ (estimated)	σ, κ	demand elasticities
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☑ (grey) calibrated: lit. & data

☑ (blue) estimated: follow **CDS (2016)**

Parameters to be calibrated/estimated

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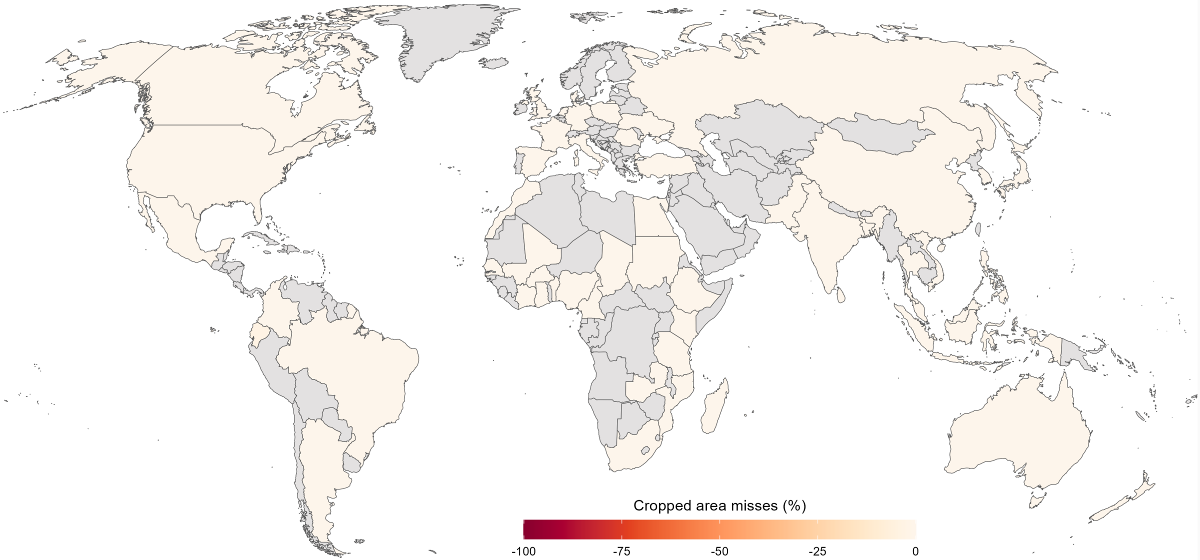
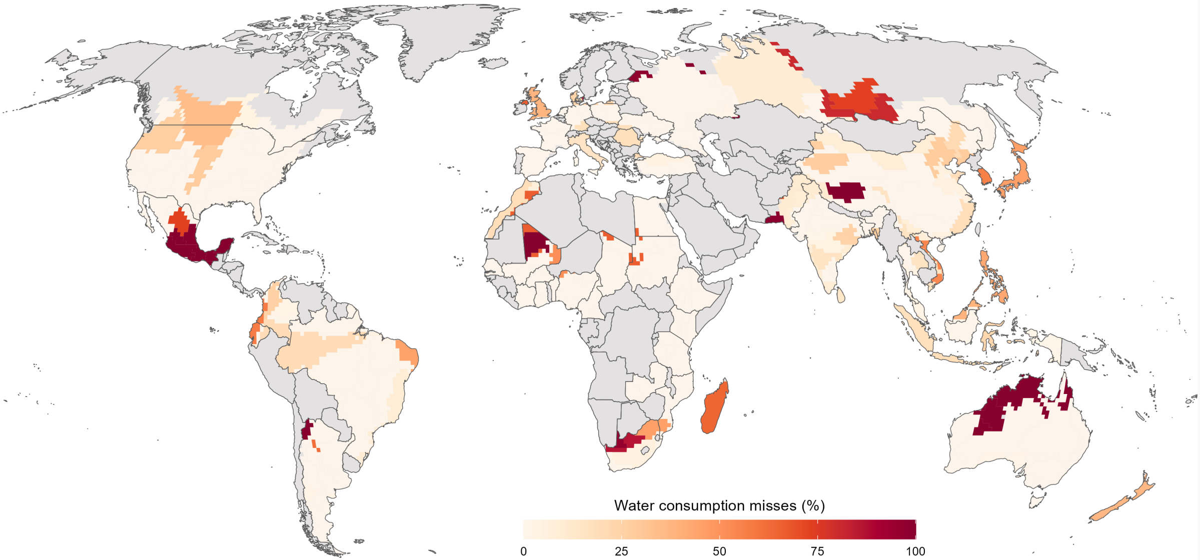
- ☑ calibrated: lit. & data
- ☑ estimated: follow **CDS (2016)**
- ☑ estimated: **NLS** (land & water use)

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?

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   What are the impacts of a major historic global ag. market liberalization?

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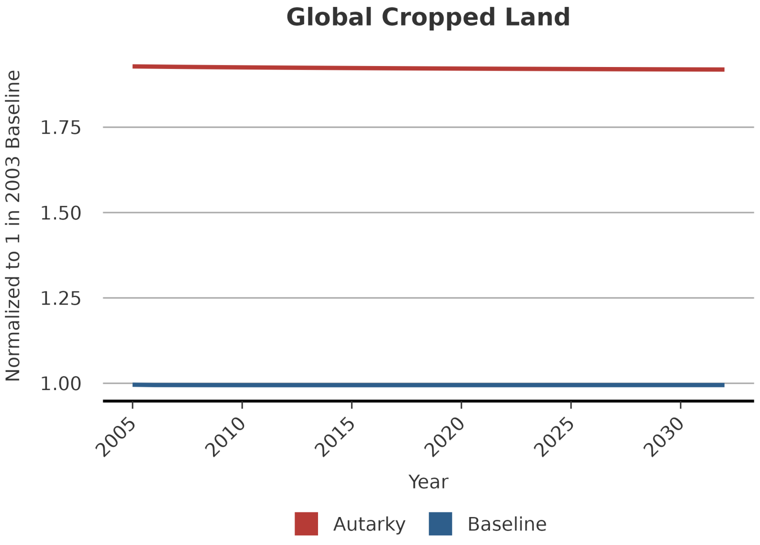
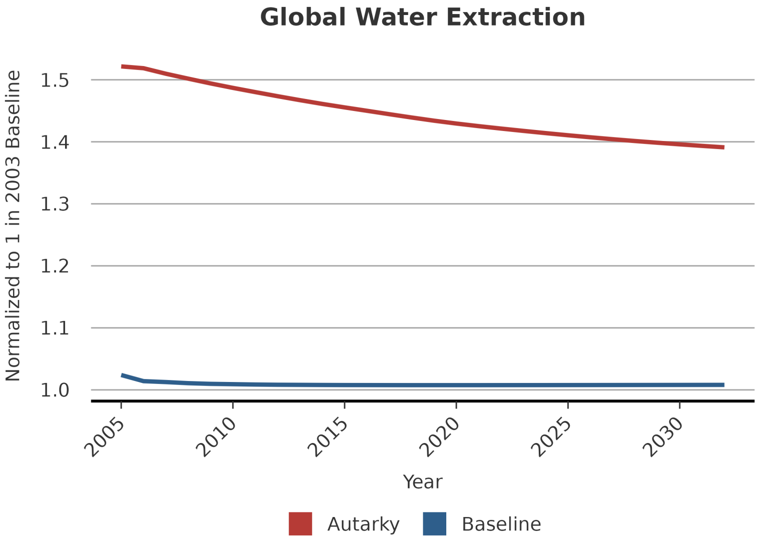
3. **Eliminate all output market distortions**—set $\tau_i^k = 1$ for all i, k
   Do all observed agricultural market interventions exacerbate input market failures?

Total global cropped area nearly doubles in autarky



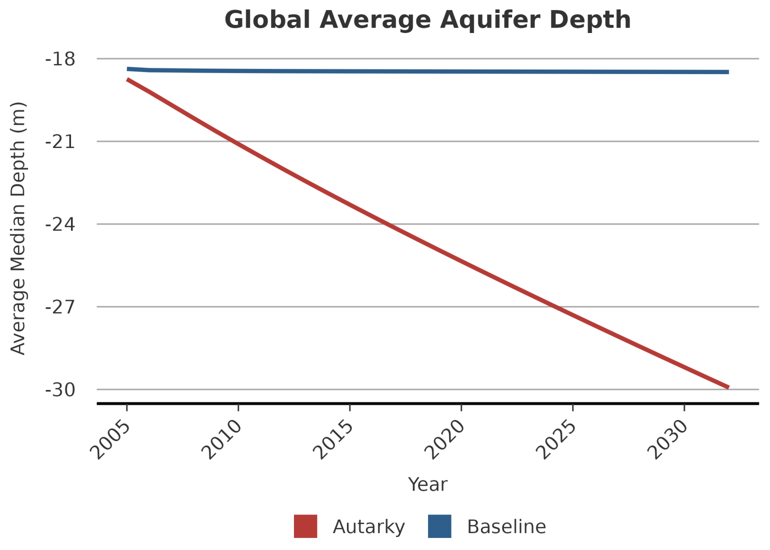
Note: 3 year moving average

Total global water use also much higher in autarky



Note: 3 year moving average

Allowing trade prevents global aquifer depletion



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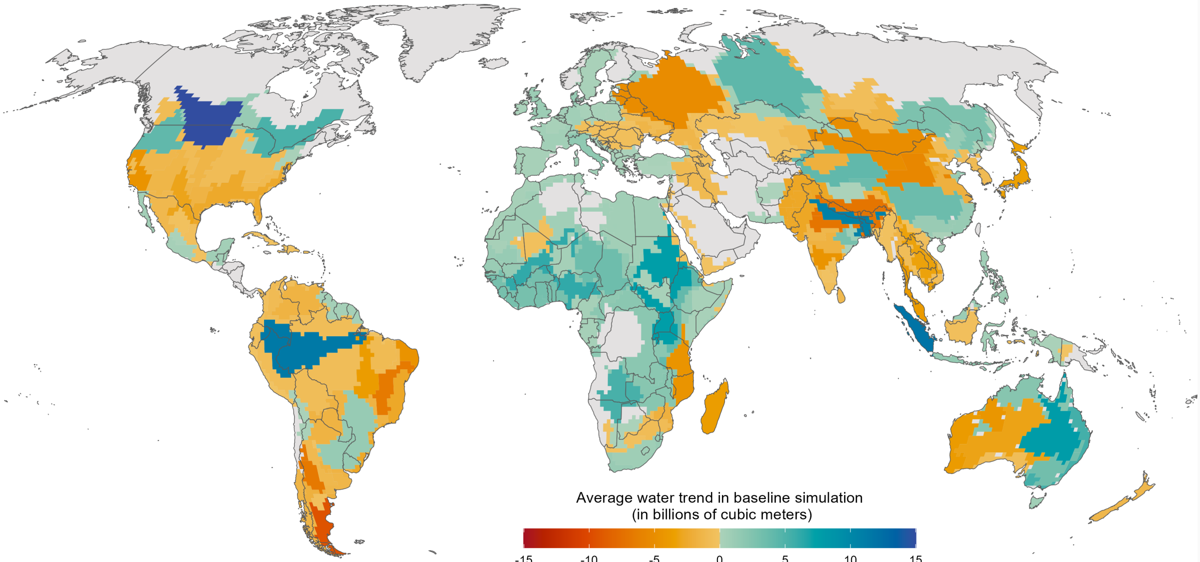
Allowing trade prevents extreme regional depletion. . .



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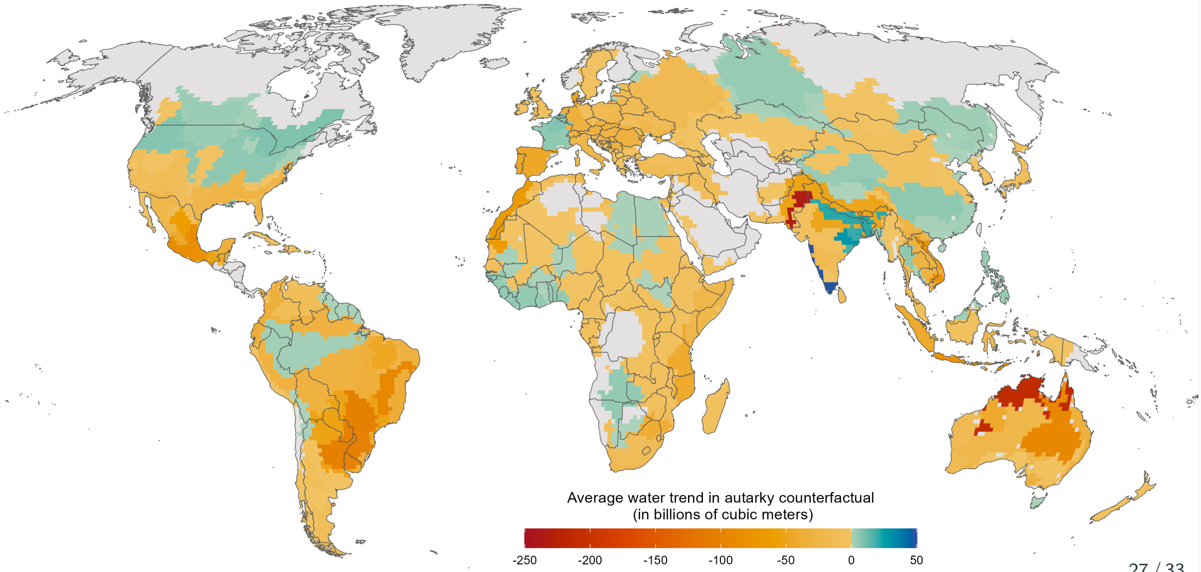
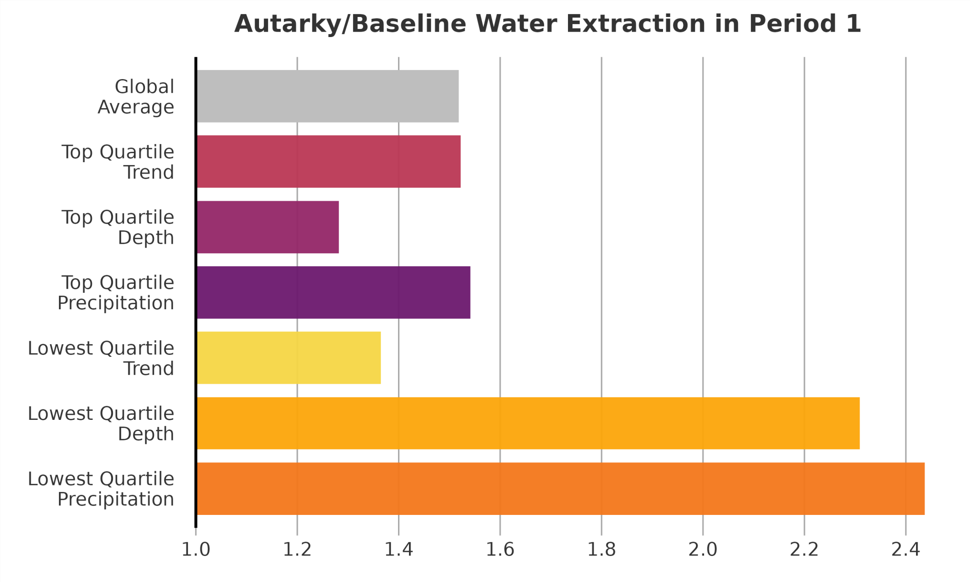
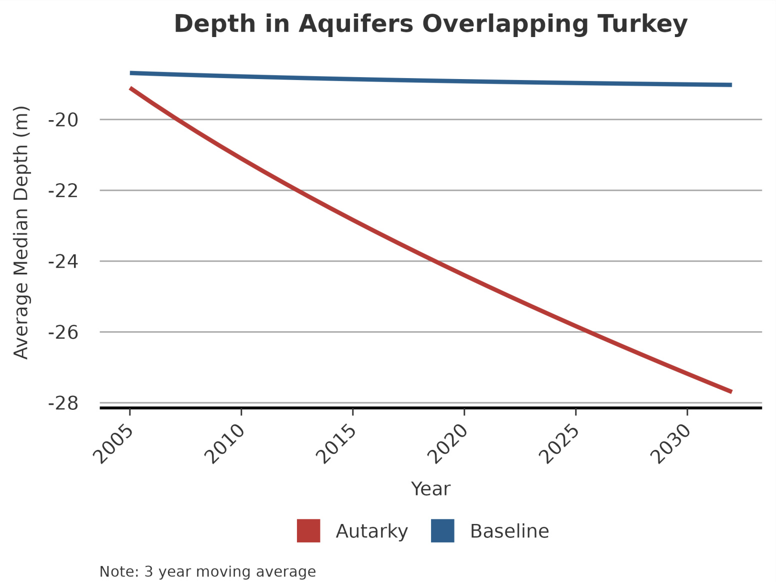


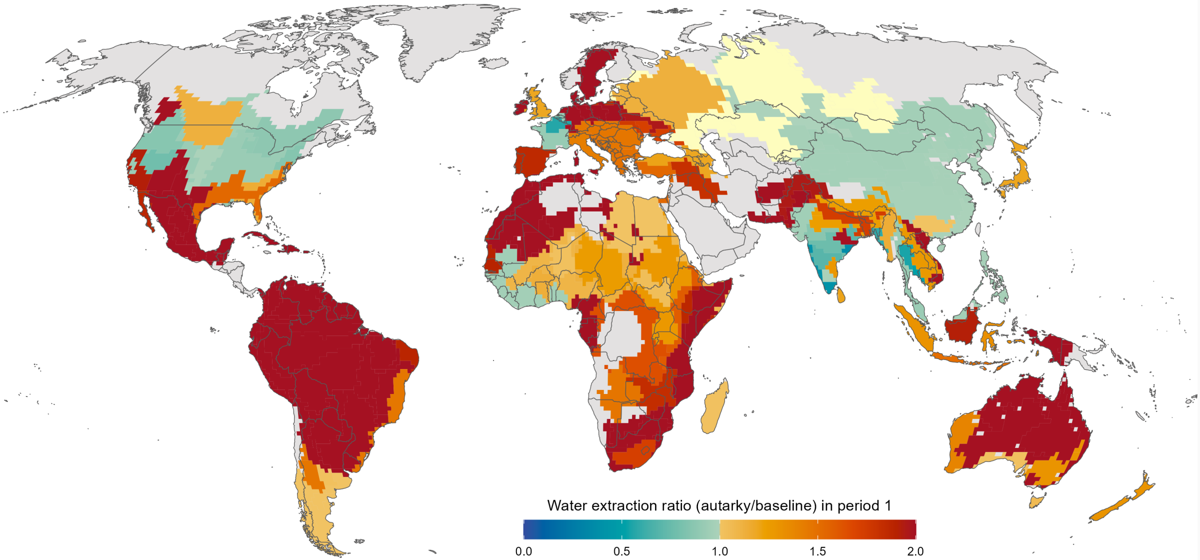
... by lowering water use in water-stressed regions



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



. . . but prevents severe depletion for some food exporters



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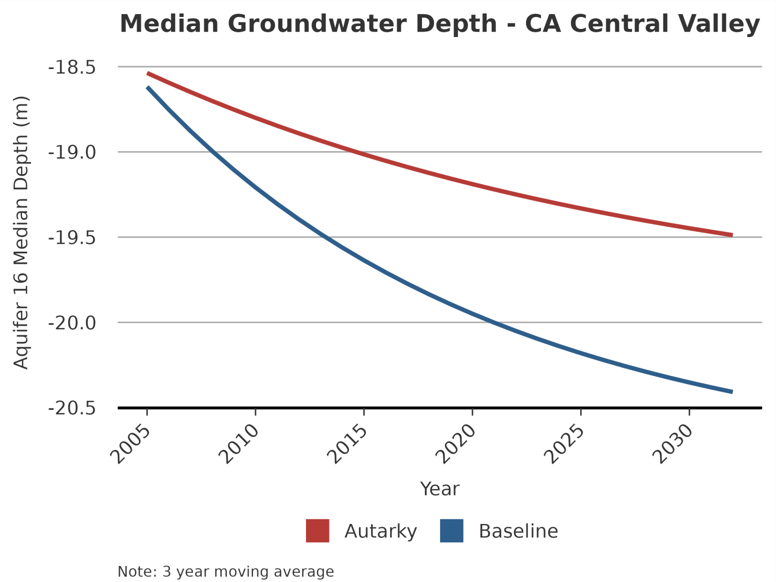

Menu of counterfactuals

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

Menu of counterfactuals

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   Existing trade alleviates water stress and improves welfare, but not everywhere

2. **Evaluate historical changes in output market interventions**—compare allocation with τ_i^k from pre-Uruguay round of WTO negotiations (∼1990) to τ_i^k from ∼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

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!

lgcrews@econ.ucla.edu

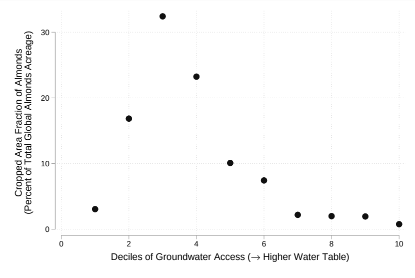
Appendix

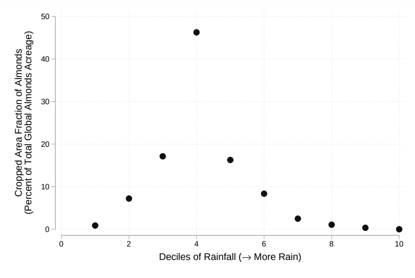
Fact 5: Water-intensive crops locate primarily in water-abundant regions . . .

Almonds

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

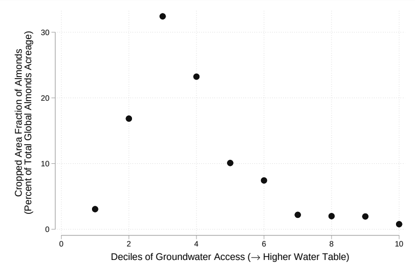
Almonds

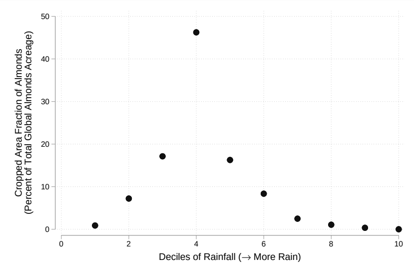




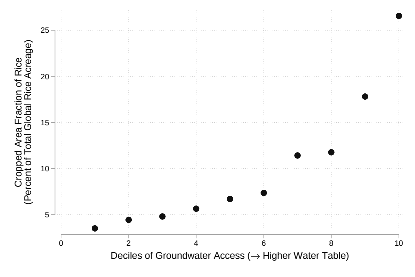
Fact 5: Water-intensive crops locate primarily in water-abundant regions . . .

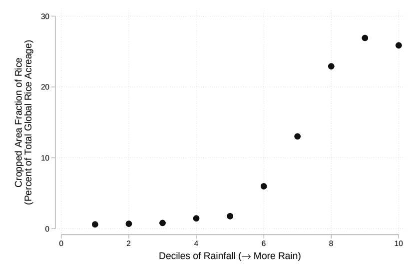
Almonds





Rice





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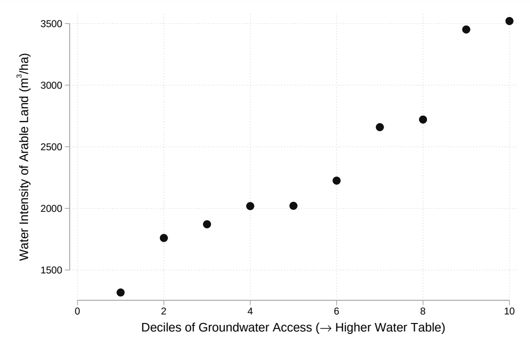
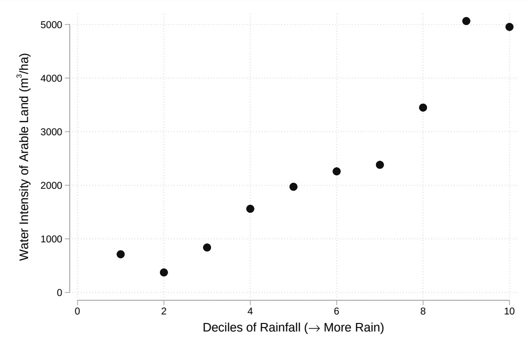
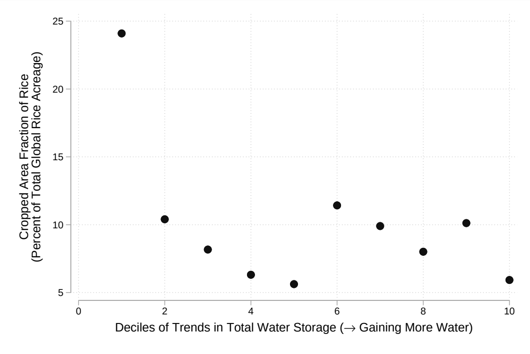




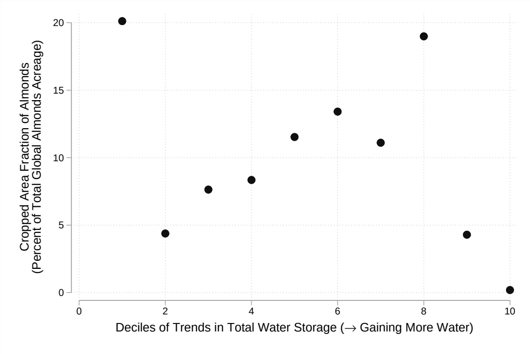
$$\text{Water Intensity of Arable Land } (\text{m}^3/\text{ha}) = \frac{\sum_{k\in\mathcal{K}} \text{hectares}^k \times \left(\frac{\text{water } (\text{m}^3)}{\text{hectare}}\right)^k}{\sum_{k\in\mathcal{K}} \text{hectares}^k + \text{pasture}}$$

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

Rice Acreage by Water Trends



Almond Acreage by Water Trends



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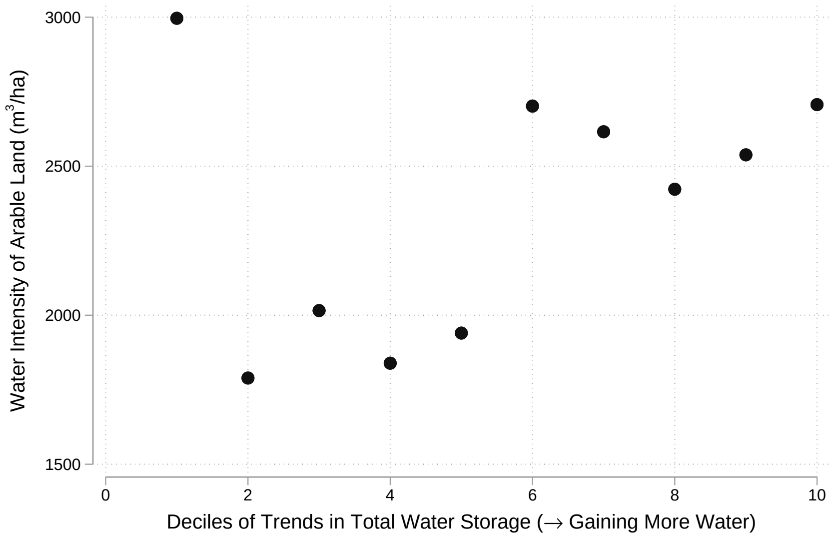

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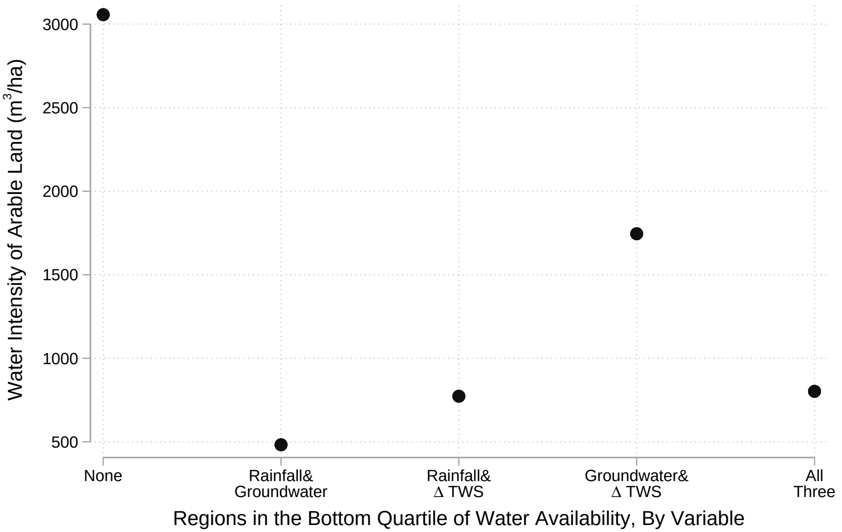
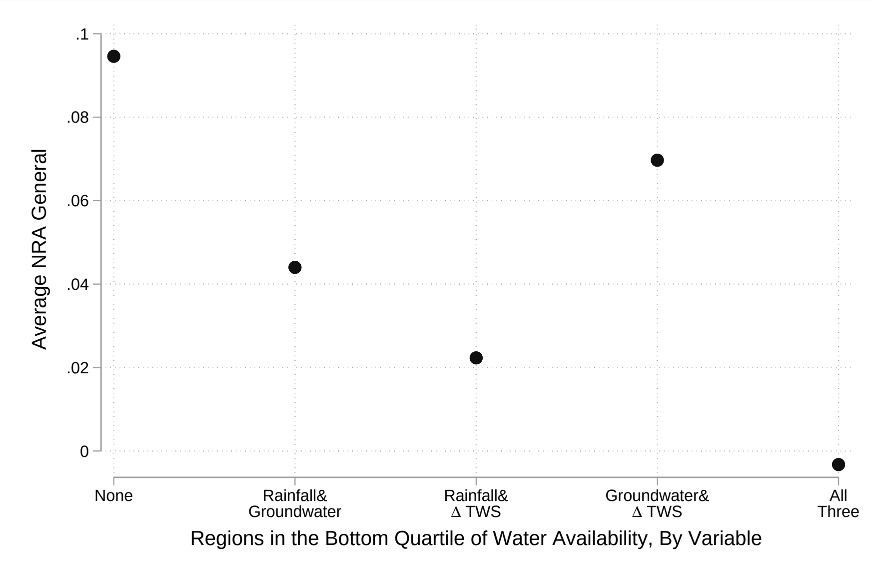
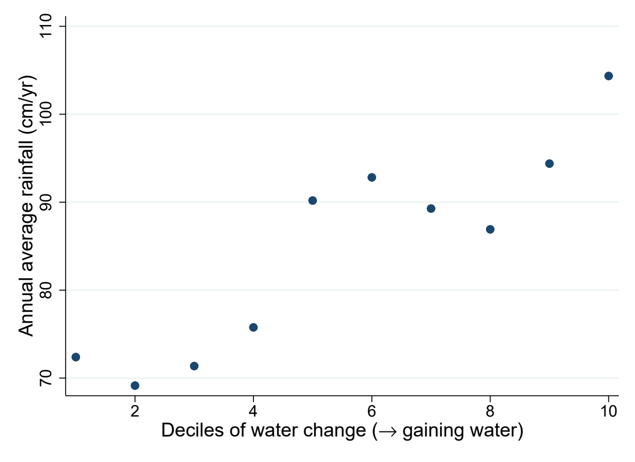


Fact 5: Similar patterns in water intensity and agricultural policy



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



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

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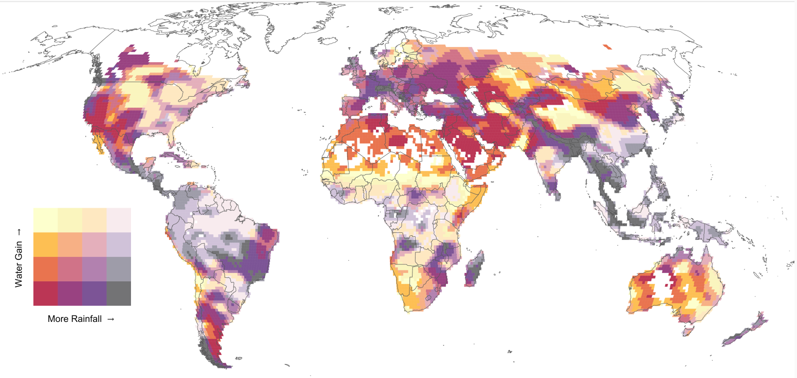

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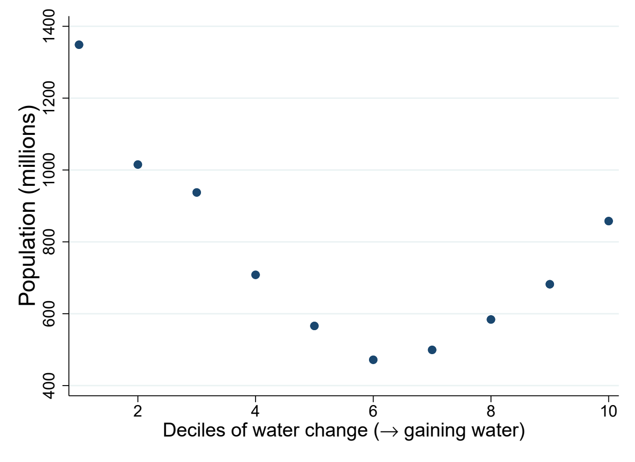

Regions losing water rapidly are very **highly populated**

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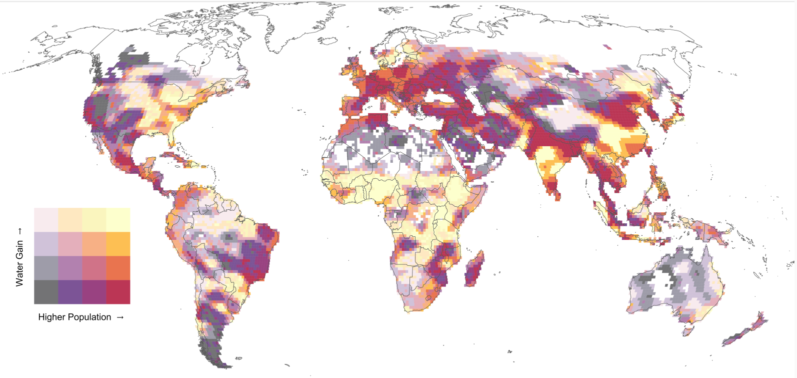

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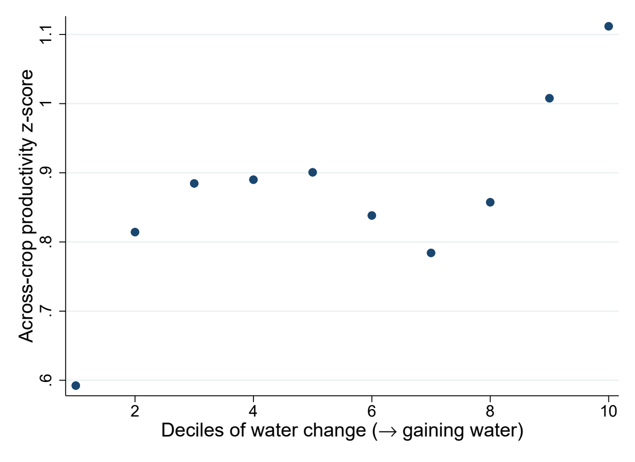

Regions losing water rapidly have **low suitability for crops**

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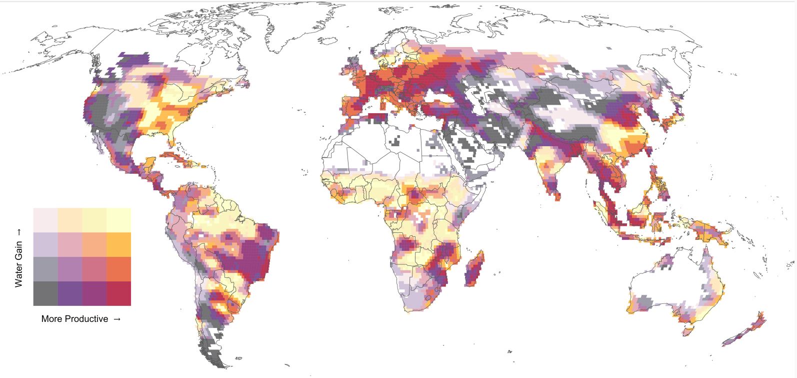

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where

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

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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

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

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

- **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

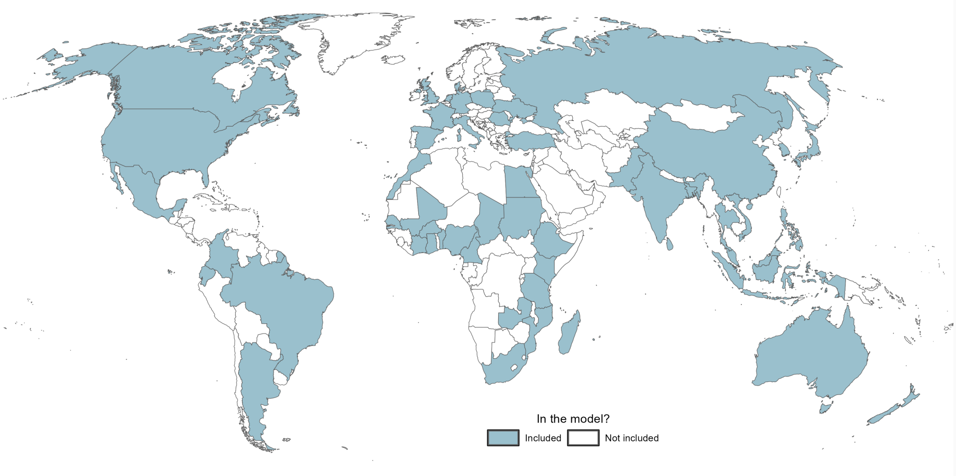
Include countries in the **top 40** globally in any of...

(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

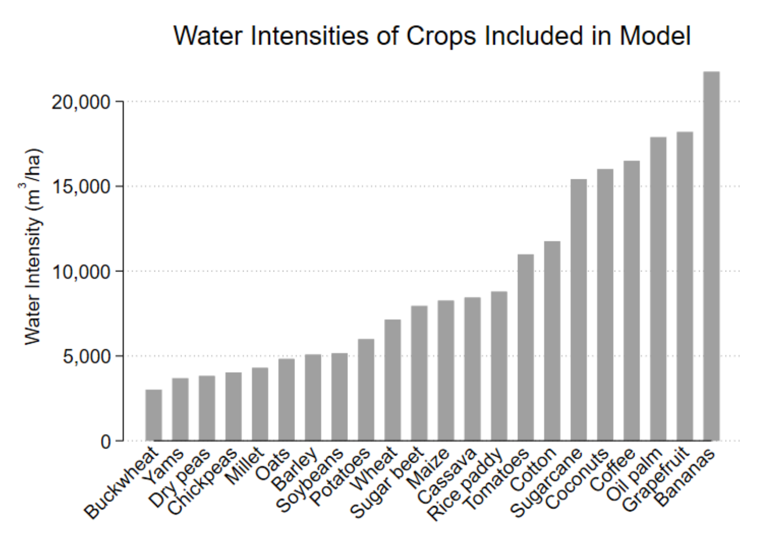
Include **high-value** and **staples** (global *and* regional) + **span** water intensities | in GAEZ (38)

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

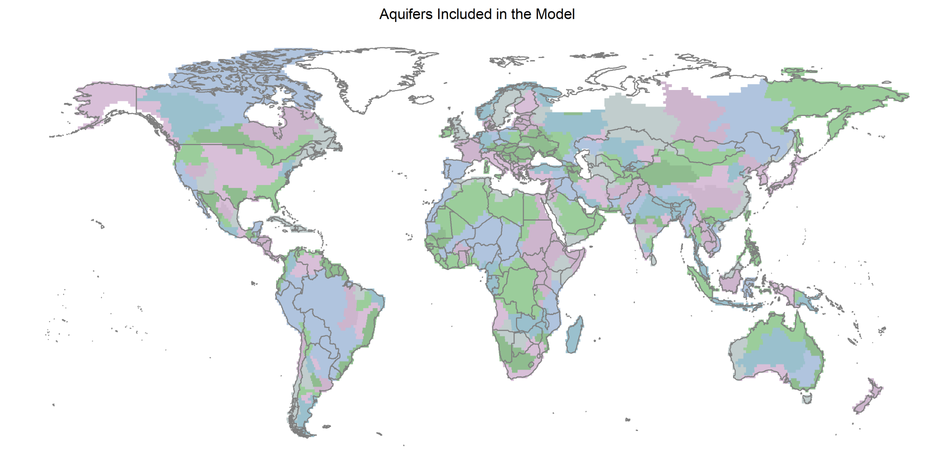


Sample selection: Aquifers

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
☐	θ	technological heterogeneity
☐	$\{A_i^o\}$	mean labor prod. in outside sector
☐	ψ	return flow rate
☐	$\{\rho_q\}$	specific yield
☐	$\{R_q\}$	natural recharge
☐	$\{\Upsilon_q\}$	scale of extraction productivity
☐	υ	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	ψ	0.25	Dewandel et al. (2008)
extraction elasticity	υ	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. ΔTWS from NASA's GRACE data
			& implied water use based on $\{\phi^k\}$ and obs. $\{\pi^{fk}\}$
			from SAGE (Monfreda, Ramankutty, and Foley, 2008)

Parameters to be calibrated/estimated

☐	$\sigma,\ \kappa$	demand elasticities
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☑	υ	elasticity of extraction productivity

☑ 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 σ, and we set $\ln[\zeta_{ij}^k(\delta_{ij}^k)^{1-\sigma}] \equiv \epsilon_{ij}^k$

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

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3. That regression identifies σ, and we set $\ln[\zeta_{ij}^{k}(\delta_{ij}^{k})^{1-\sigma}] \equiv \epsilon_{ij}^{k}$
4. Construct P_{j}^{k} from the price data and previous estimate. Repeat 1–3 at the mid-tier (across crops) to identify κ and construct ζ_{j}^{k}, using Z_{j}^{k} to instrument for P_{j}^{k}

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5. ζ_j is just the value of expenditure on agricultural goods by j

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

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

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5. ζ_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

☑ (estimated)	$\sigma,\ \kappa$	demand elasticities
☑ (estimated)	$\{\zeta_j, \zeta_j^k, \zeta_{ij}^k\}$	demand shifters
☑ (estimated)	$\{\delta_{ij}^k\}$	bilateral crop-specific trade costs
☑ (calibrated)	$1-\alpha$	land share in crop production
☑ (calibrated)	$\{\phi^k\}$	crop-specific water intensity
☐	θ	technological heterogeneity
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☐	$\{\Upsilon_q\}$	scale of extraction productivity
☑ (calibrated)	υ	elasticity of extraction productivity

☑ (grey) calibrated: lit. & data

☑ (blue) estimated: follow **CDS (2016)**

Estimating the supply side

Estimate θ, $\{A_i^o\}$, 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

☑ (estimated: follow CDS)	$\sigma,\ \kappa$	demand elasticities
☑ (estimated: follow CDS)	$\{\zeta_j, \zeta_j^k, \zeta_{ij}^k\}$	demand shifters
☑ (estimated: follow CDS)	$\{\delta_{ij}^k\}$	bilateral crop-specific trade costs
☑ (calibrated)	$1-\alpha$	land share in crop production
☑ (calibrated)	$\{\phi^k\}$	crop-specific water intensity
☑ (estimated: NLS)	θ	technological heterogeneity
☑ (estimated: NLS)	$\{A_i^o\}$	mean labor prod. in outside sector
☑ (calibrated)	ψ	return flow rate
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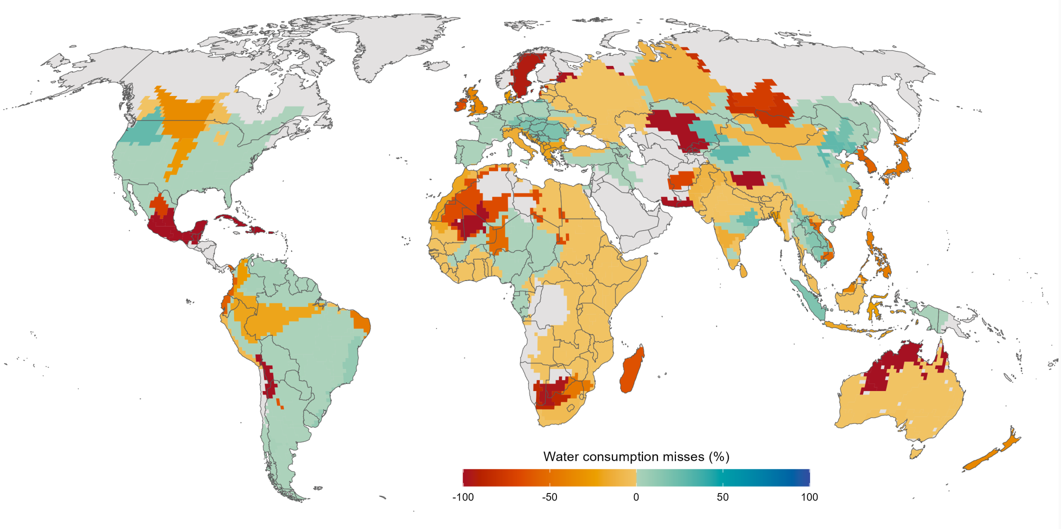
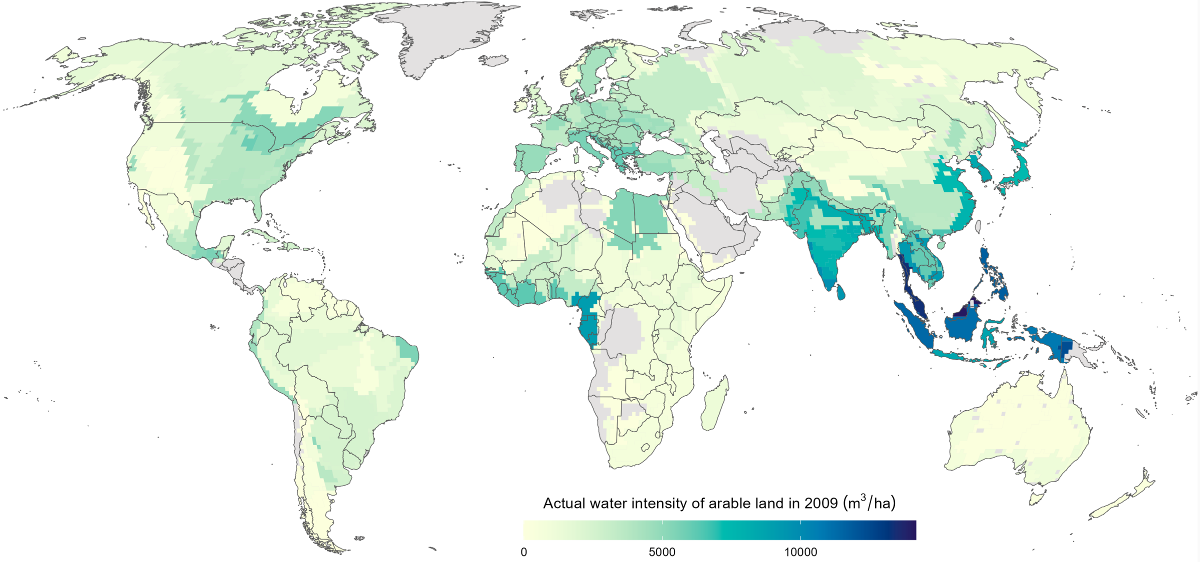
☑ (calibrated)	$\{R_q\}$	natural recharge
☑ (estimated: NLS)	$\{\Upsilon_q\}$	scale of extraction productivity
☑ (calibrated)	υ	elasticity of extraction productivity

- ☑ calibrated: lit. & data
- ☑ estimated: follow **CDS (2016)**
- ☑ estimated: **NLS** (land & water use)

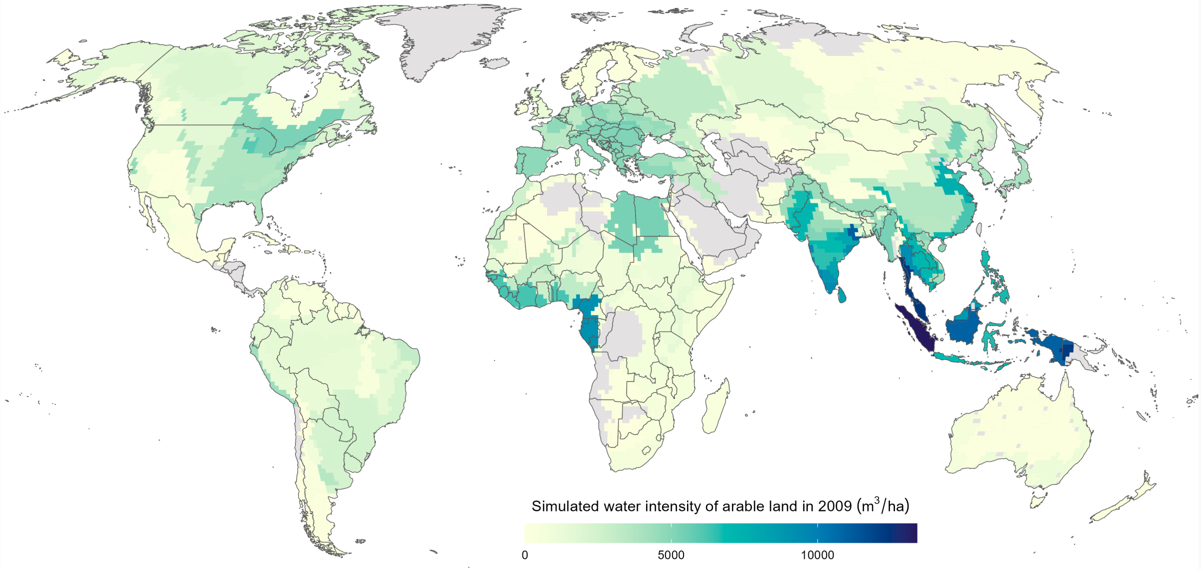
Model fit: Agricultural water extraction



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 (Υ_q), and Extraction Productivity ($A_q^w(D_{qt})$)

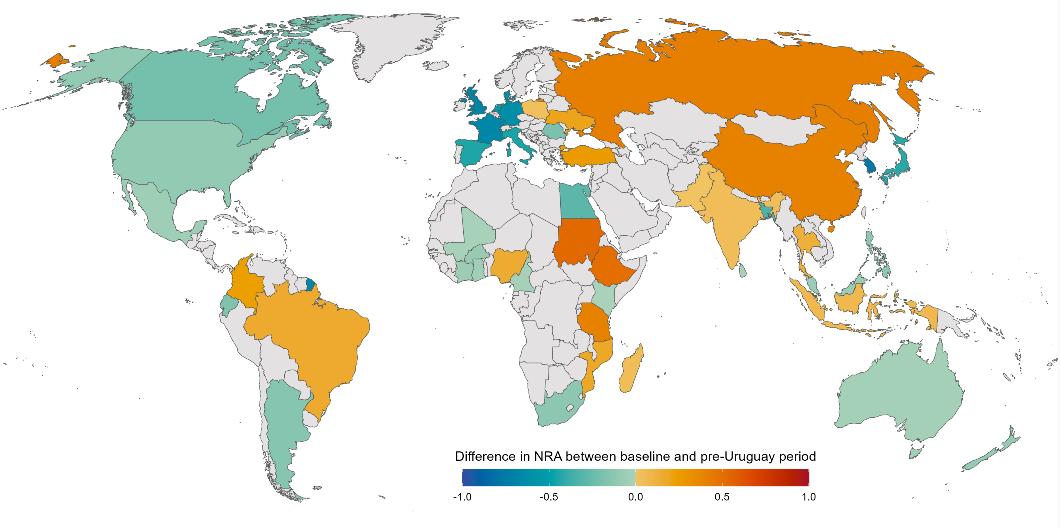
	Dependent Variable	
	log(Υ)	log($A_q^w(D_{qt})$)
Precipitation	0.64**	0.54*
	(0.25)	(0.28)
Precipitation^2	-0.11**	-0.08**
	(0.03)	(0.03)
Temperature	0.26***	0.17***
	(0.04)	(0.05)
Temperature^2	-0.004***	-0.003*
	(0.001)	(0.002)
Area irrigated (%)	0.10*	0.10*
	(0.05)	(0.05)
Nighttime luminosity	0.20***	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

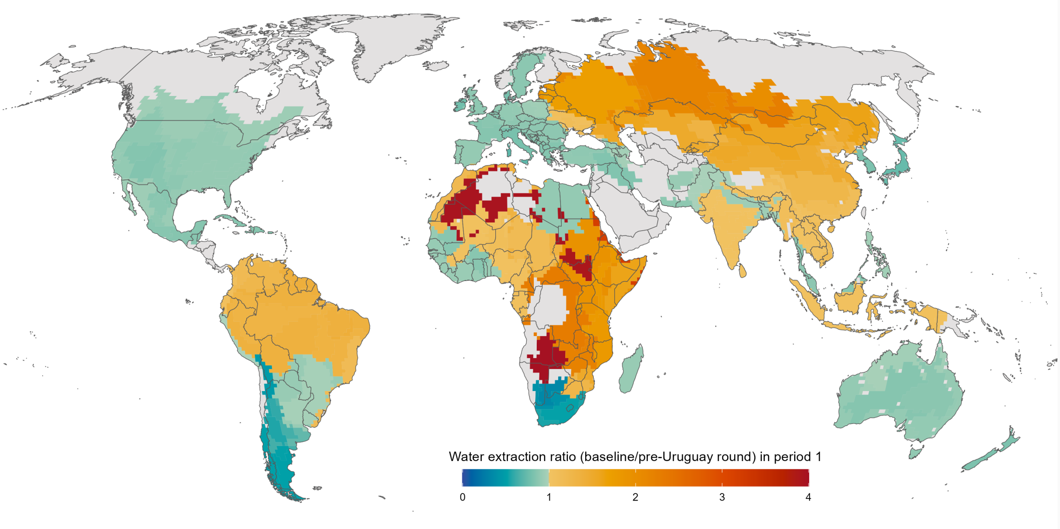
2. **1994 Uruguay Round of WTO Negotiations:** Largest global ag. liberalization
    - Prior trade agreements (GATT) largely excluded agriculture
    - "Tariffication" of non-tariff barriers to agricultural trade with maximum tariff rates imposed
    - *Implementation:* set $\tau_i^k = 1+$ avg. from 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

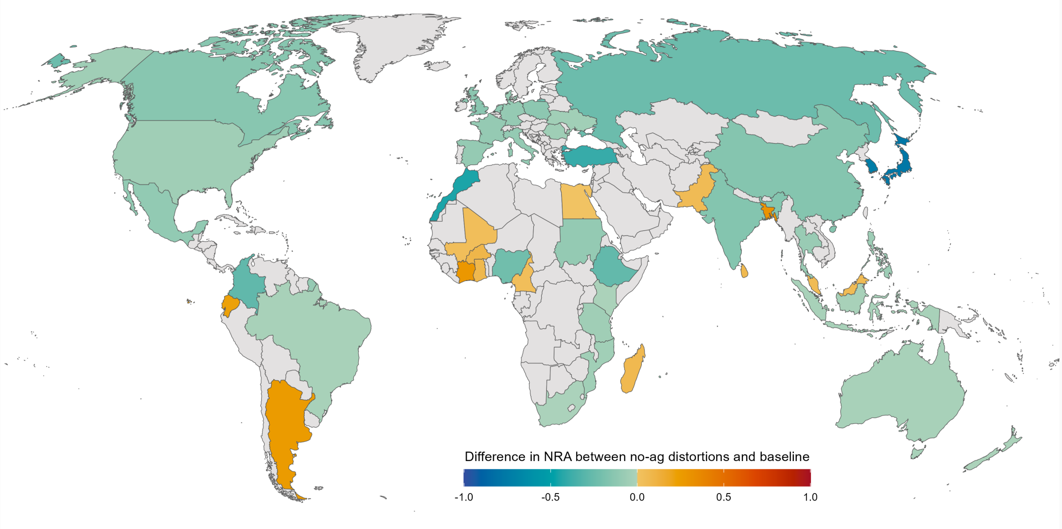
Uruguay Round lowered subsidies in the north, raised them in the south



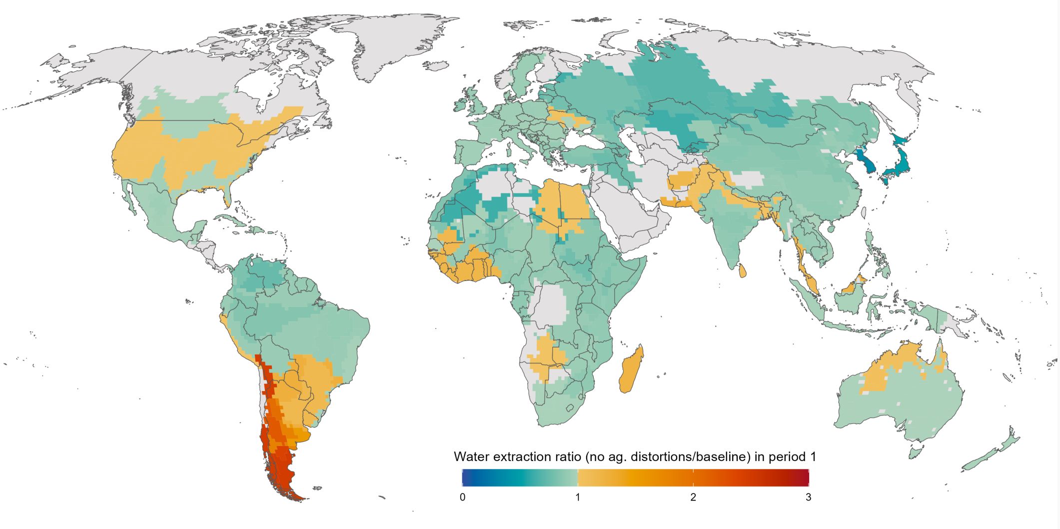
Uruguay Round increased water extraction in the south



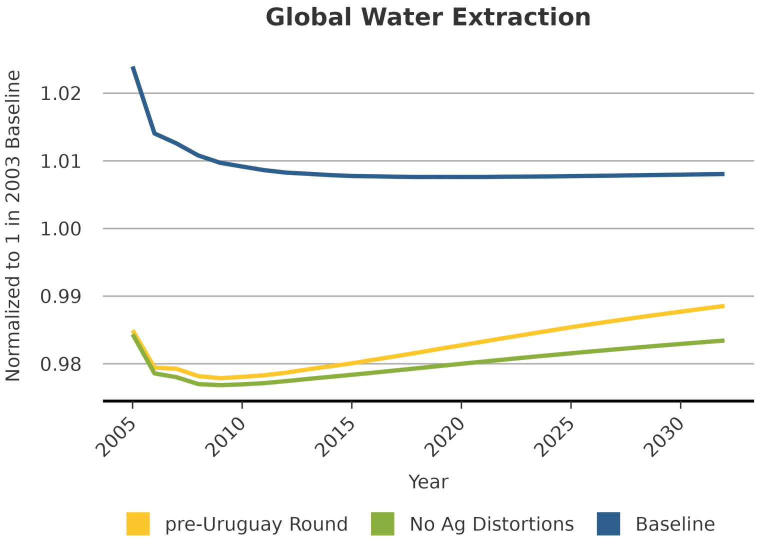
Removing current distortions lowers subsidies to ag. nearly everywhere



Removing current distortions lowers water extraction nearly everywhere



Global water extraction falls under both counterfactual policies



Note: 3 year moving average

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