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

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March 2024

Water-intensive production in water-scarce regions

SCIENCE

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I write about science and technology.

Sep 28, 2016, 05:20pm EDT

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- **∼12 liters of water used to grow <u>one</u> almond**

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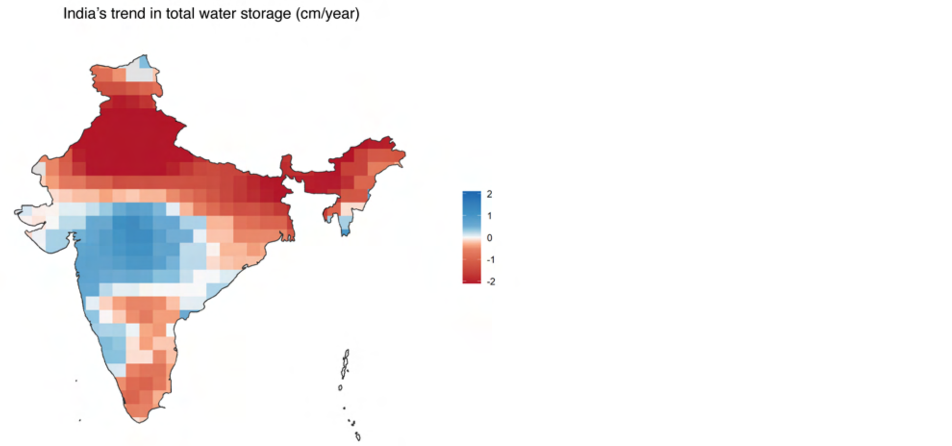

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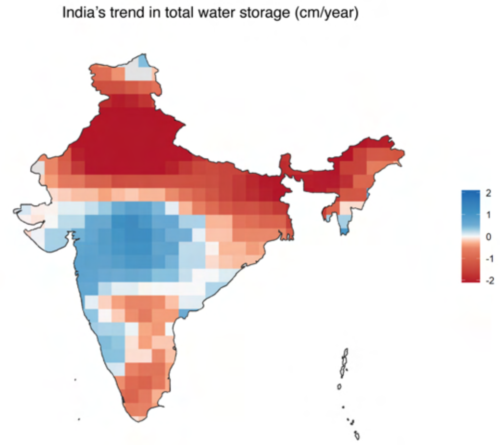

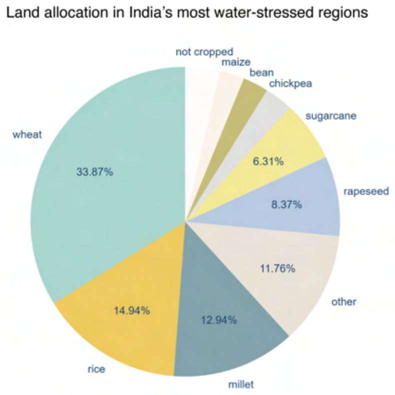

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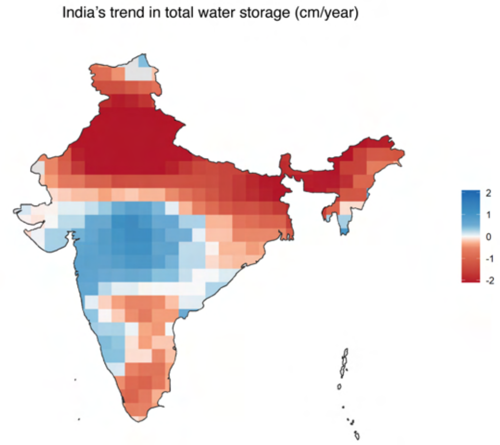

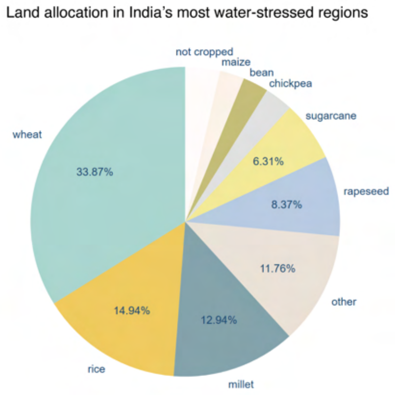

India is the world's **leading exporter** of rice

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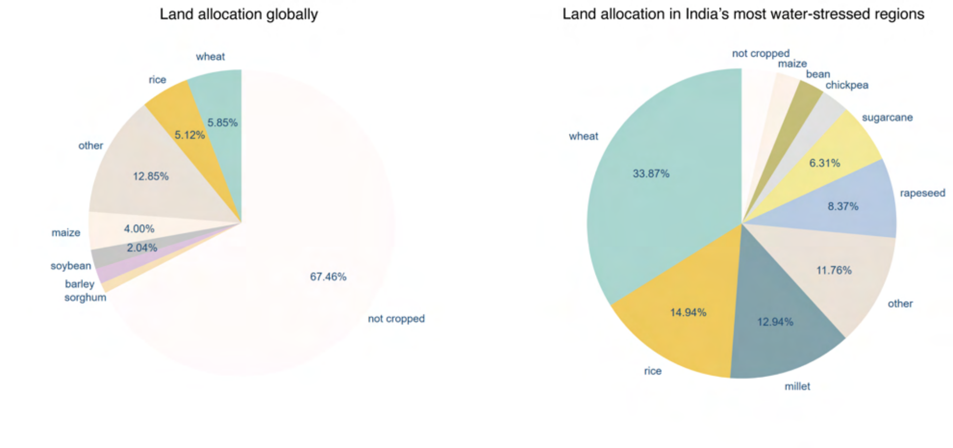

Crop trade depletes global groundwater

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 questions

Key Ideas:

1. Water is effectively non-tradable, but it is **embedded** in agricultural trade
2. Ag./trade policy $\rightarrow$ ag./trade spatial allocation $\leftrightarrow$ long-run water availability
3. Water as ag. input is **distorted** $\rightarrow$ trade can have **ambiguous** welfare effects

Research questions

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3. Water as ag. input is **distorted** $\rightarrow$ trade can have **ambiguous** welfare effects

With these in mind, we ask:

How do global ag. trade patterns & policies affect long-run water availability and welfare?

This paper

- 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:
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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**

   $\rightarrow$ prevents water depletion over time, raising welfare in the long run

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

Data

A global picture of water. . .

Water table depth: **Fan, Li, and Miguez-Macho (2013)**

- Global snapshot at 30 arc-second ($\sim$1km) resolution
- *How*: Hydrological model interpolates over measurements from $>$1.6 million well sites

Evolution of total water storage: **GRACE**

- Equal-area grid ($\approx 1^\circ \times 1^\circ$ at the equator) observed monthly over 2003–2016
- *How*: Variations in earth's gravity field—dominated by shifting water mass—change distance between two tandem satellites (Tapley et al., 2004)

Other global hydrological spatial data:

- Precipitation: **GMFD v.3**
- Aridity: **Trabucco and Zomer (2019)**
- Surface water occurrence: **Pekel et al. (2016)**
- Soil type: **Hengl et al. (2017)**
- Specific yield by soil type: **Loheide, Butler, and Gorelick (2005)**
- Water intensity by crop: **Mekonnen and Hoekstra (2011)**

. . . and agriculture

Potential agricultural yields: **GAEZ**

- Crop-specific **potential yields** at 5 arc-minute resolution ($\sim$2.2 million grid cells on land)
- *How*: Agronomic model combining detailed land & crop characteristics with different input mix and climate scenarios, taking time series average over 1961–90

Agricultural land use: **SAGE**

- **Cropped area fraction** for 175 crops (& pasture) at $\sim$10km$\times$10km resolution c. 2000
- *How*: Combine census data with remotely-sensed maps of land cover (Monfreda et al., 2008)

Agricultural production & trade: **FAOSTAT**

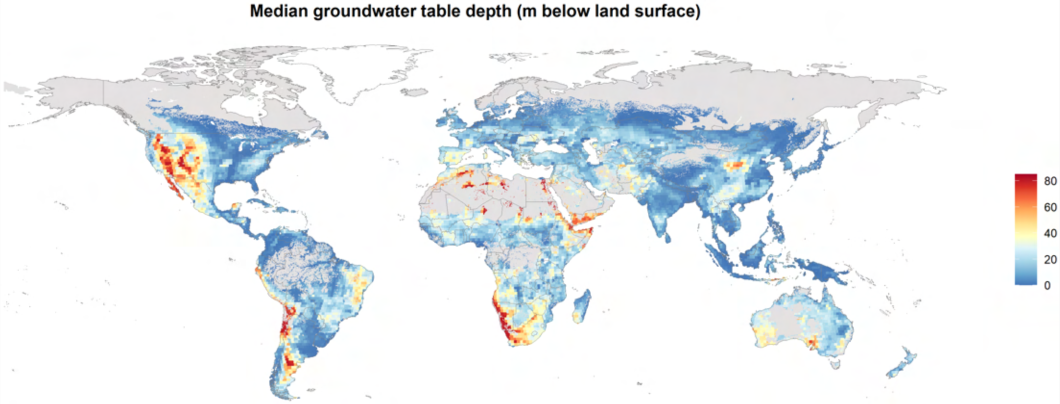
- Crop-specific quantities *and* farm-gate prices (USD/ton) for $>$200 countries back to 1961
- Bilateral trade flows in USD by crop, but we use **Comtrade** for better coverage

Distortions to agricultural incentives: **World Bank**

- Nominal Rates of Assistance (NRA) for $>$90% of world pop. & ag. GDP
- Includes: taxes and subsidies to producers, import tariffs, export subsidies, input subsidies/taxes, foreign exchange mkt. interventions (*but not water!*)

Facts

Fact 1: Vast spatial heterogeneity in water resources



- Source: **Fan, Li, and Miguez-Macho (2013)**
- Resolution: 30 arc-seconds (∼1km) observed as cross-section c. 2000
- *How:* Hydrological model interpolates over measurements from >1.6 million well sites

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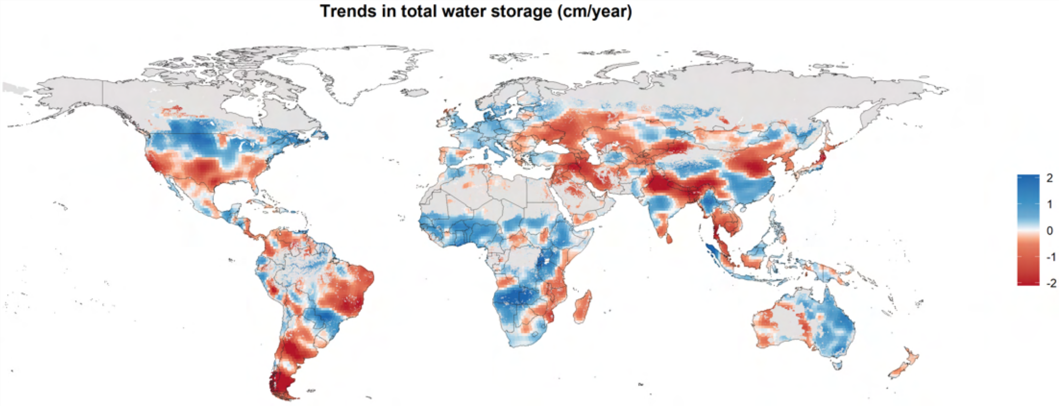

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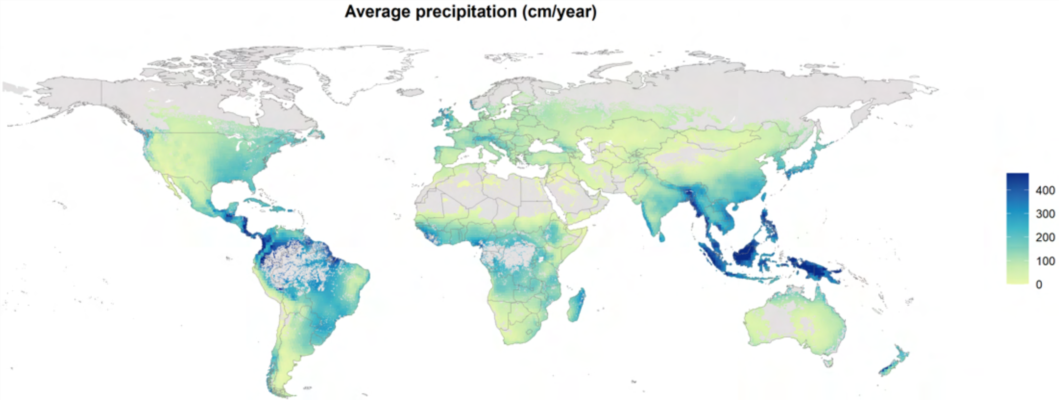
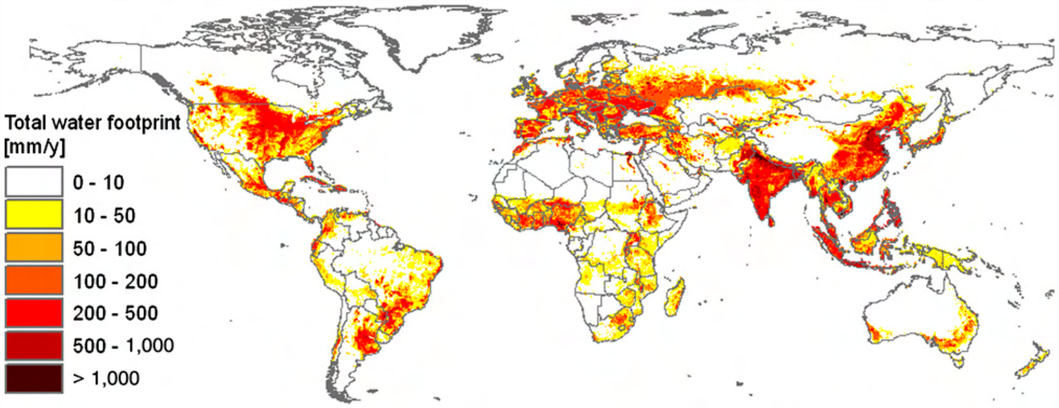


- Source: **Global Meteorological Forcing Dataset (GMFD) v.3**
- Resolution: 0.25° (∼28km) observed daily over 1948–2010
- *How*: Observational data → weather model → downscaled (Sheffield, Goteti, and Wood, 2006)

Fact 2: Agriculture dominates global water consumption



Agricultural *production* accounts for. . .

~**70%** of global water withdrawals (Dubois et al., 2011), but
~**90%** of global water *consumption* (Hoekstra and Mekonnen, 2012; d'Odorico et al., 2019)

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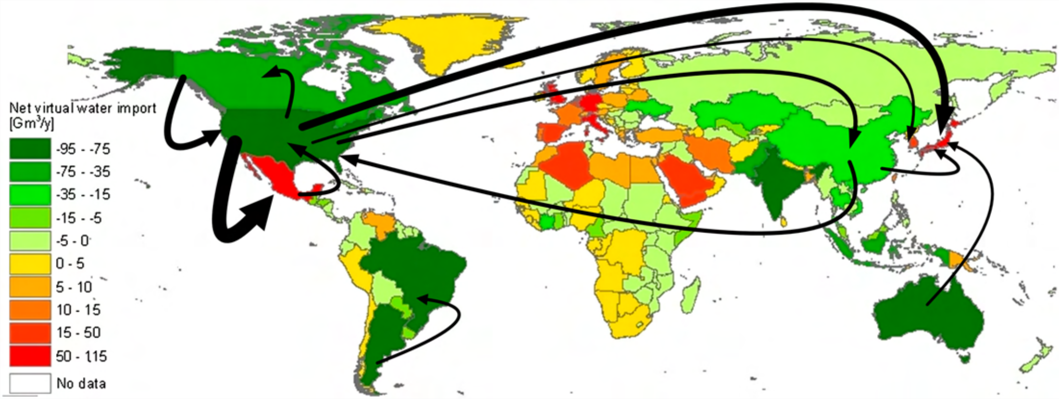
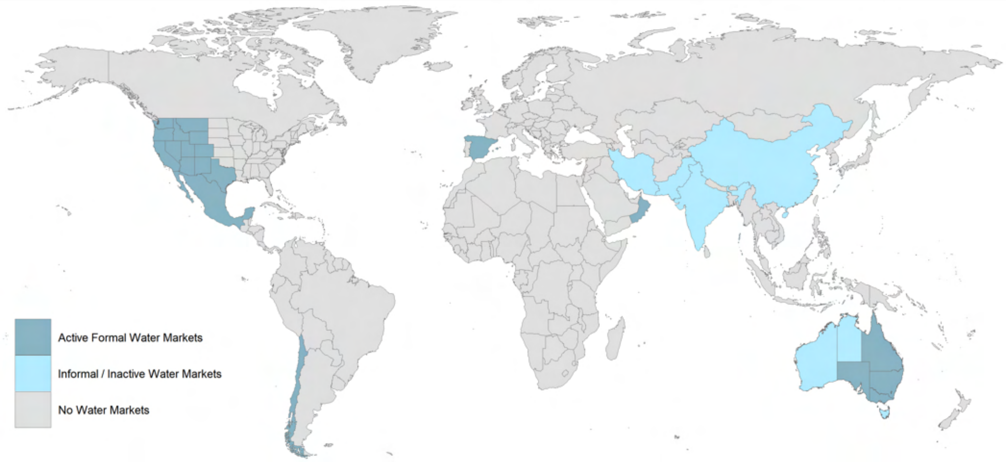


Agricultural *trade* embeds...

20–25% of global water consumption (Hoekstra and Mekonnen, 2012; Carr et al., 2013)

11% of global *ground*water depletion (Dalin et al., 2017)

Fact 3: Local markets for water rarely exist



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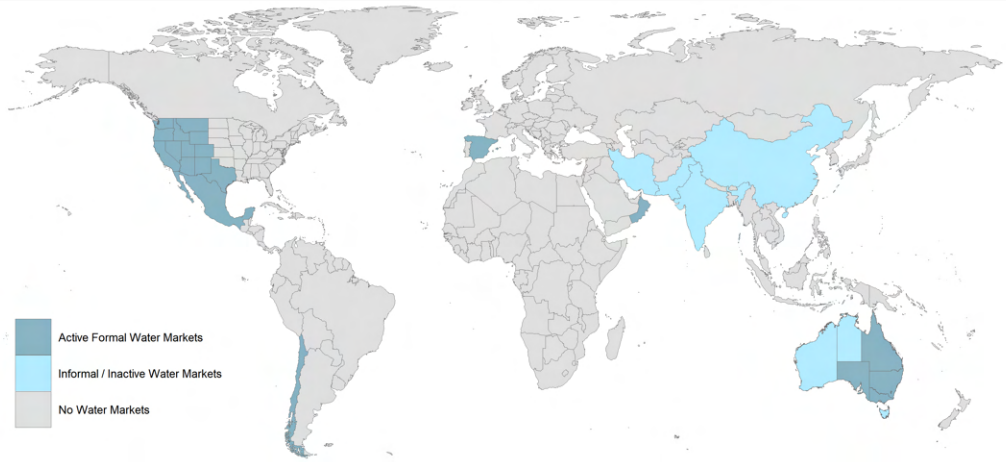
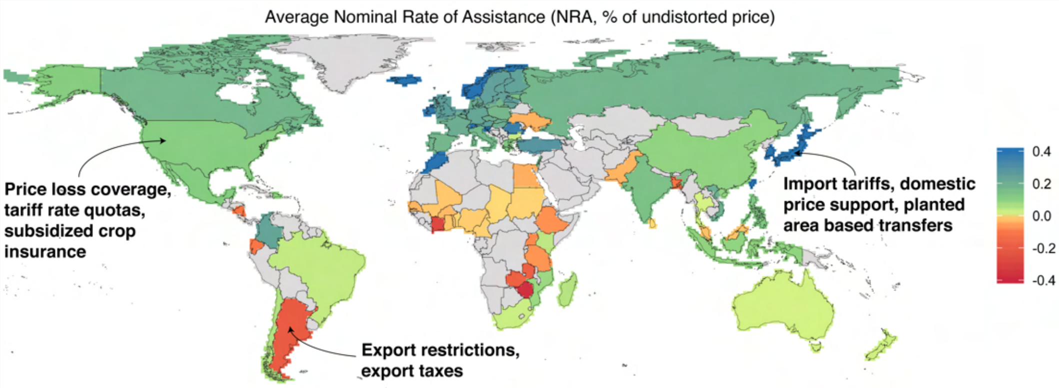


- >**93%** of global agricultural production occurs in regions with no formal water markets
- >**50%** of countries with "water-scarce" basins lack any regulatory control (Richter, 2016)

Fact 4: Agricultural policy plays a critical role in driving water use



- **Nominal Rate of Assistance (NRA)** = pct. wedge of domestic over international price
- NRAs for 80 farm products in 82 countries (>90% of world pop. & ag. GDP)
- distortions: direct taxes and subsidies to producers, import tariffs, export subsidies, input subsidies or taxes, foreign exchange market interventions (*don't include water!*)

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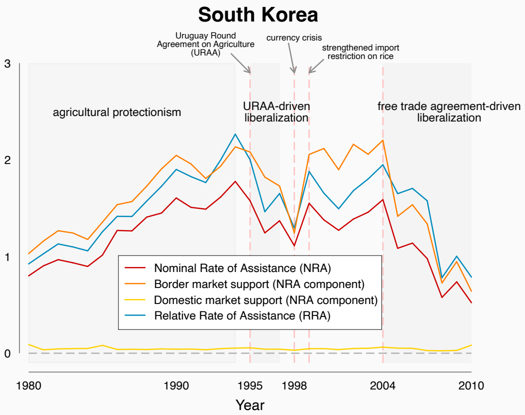
Direct evidence from Carleton (2021): increasing net agricultural subsidies **causes extremely large declines** in total water volumes



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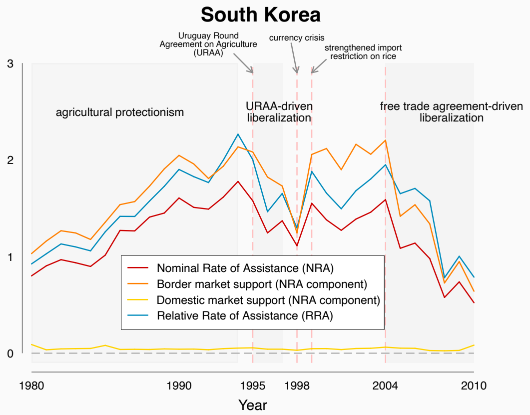
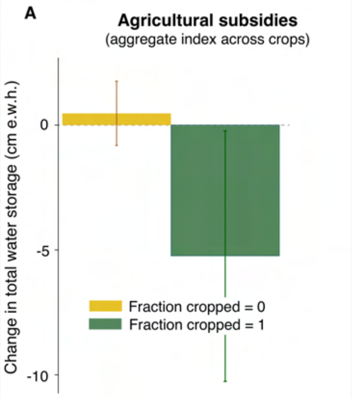
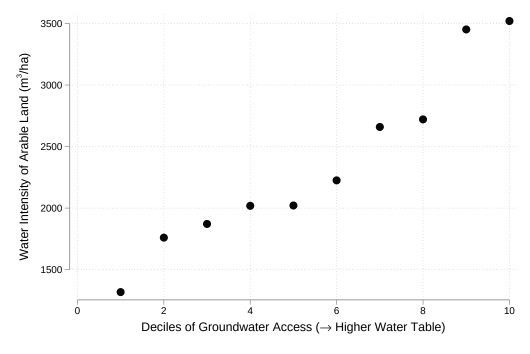
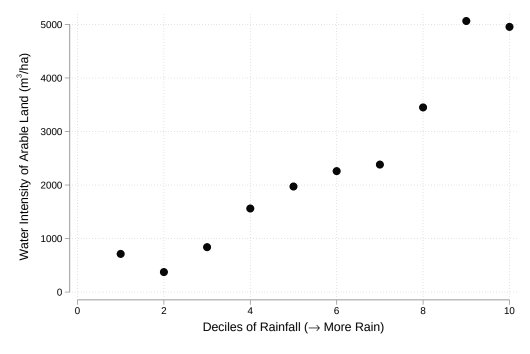




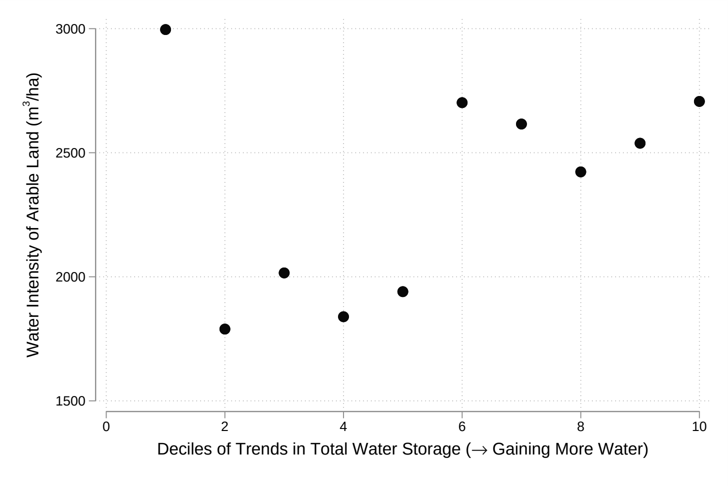
Fact 5: Water-intensive crops locate primarily in water-abundant regions...





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

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



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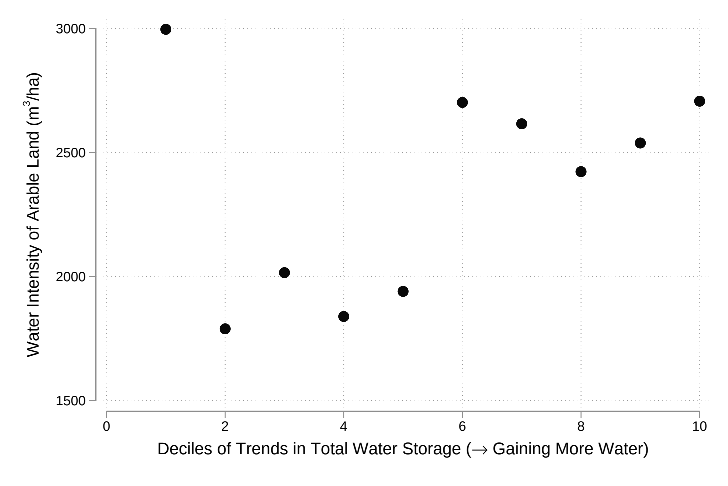

Aside: Regions losing water fastest are **already water-scarce**, are **highly populated**, and have **low agronomic potential** (see our *AEA P&P*)

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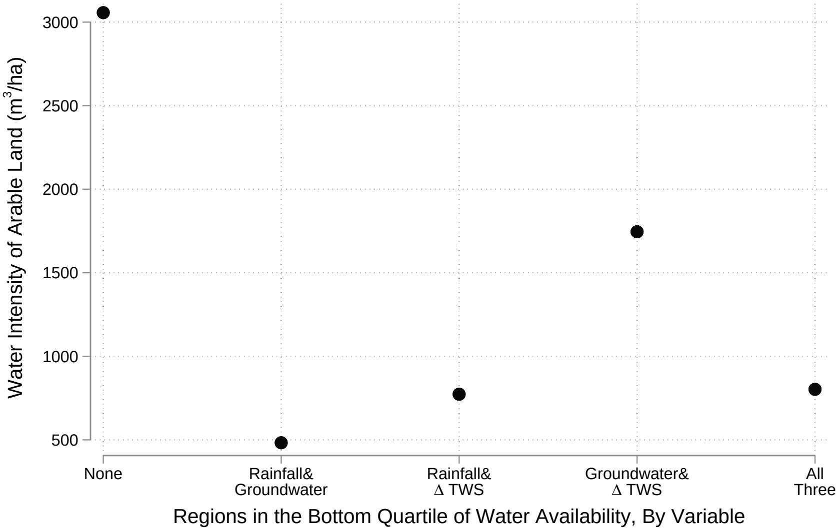

Fact summary

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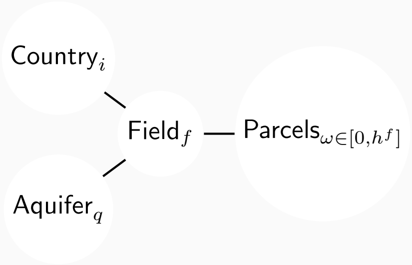
1. Vast spatial heterogeneity in water resources $\rightarrow$ **comparative advantage + dynamics**
2. Agriculture dominates global water consumption $\rightarrow$ **focus on agriculture & trade**
3. Local markets for water rarely exist $\rightarrow$ **spatial & temporal externalities**
4. Agricultural policy greatly affects water use $\rightarrow$ **maybe it hurts, but maybe it can help**
5. Water-intensive crops primarily locate in water-abundant regions, but also in some water-losing regions $\rightarrow$ **gains from trade, but possible exceptions in some regions**

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:

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

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

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:

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

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

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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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  - 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/...
- **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 $\rightarrow$ depth)
- ψ is the rate of **return flow** per unit extracted

Tying components together: Market structure and groundwater evolution

- All markets are **perfectly competitive**
- **Trade**:
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  - trade in crops is subject to **iceberg costs**: $p^k_{jit} = \delta^k_{ji} p^k_{jt}$
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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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- 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

Overview

- Want to match **global** trends in water resources **out-of-steady state**
- Proceed in **four steps**:
  1. select broad sample of countries and crops
  2. calibrate some technological and hydrological parameters
  3. estimate demand side following Costinot, Donaldson, and Smith (2016)
  4. estimate (remaining) supply side via nonlinear least squares

Sample selection: Countries

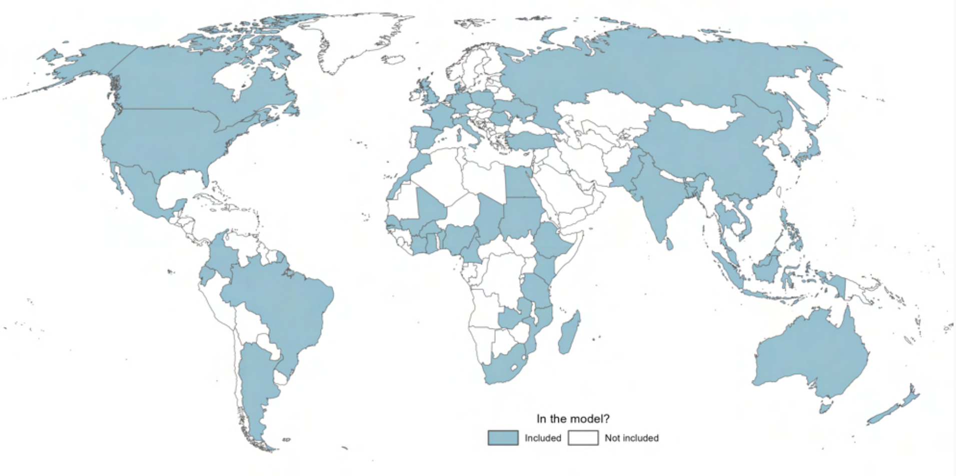
Include countries in the **top 40** globally in any of. . .

(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

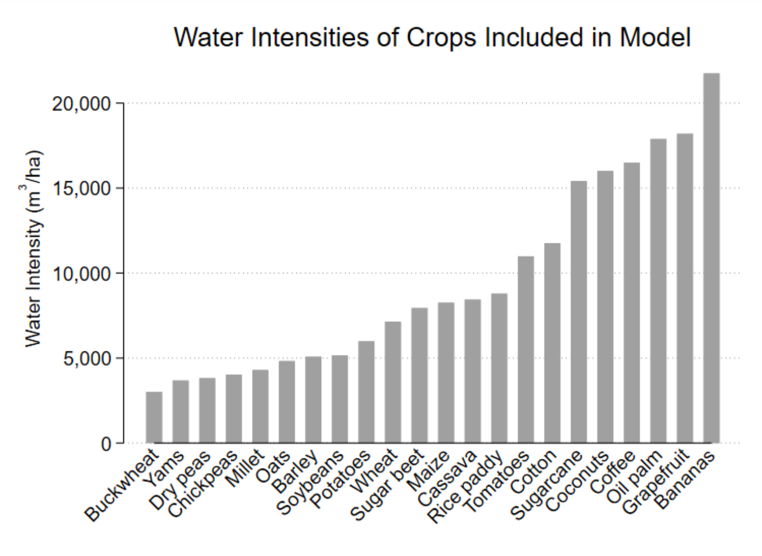
Include **high-value** and **staples** (global *and* regional) + **span** water intensities | in GAEZ (38)

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

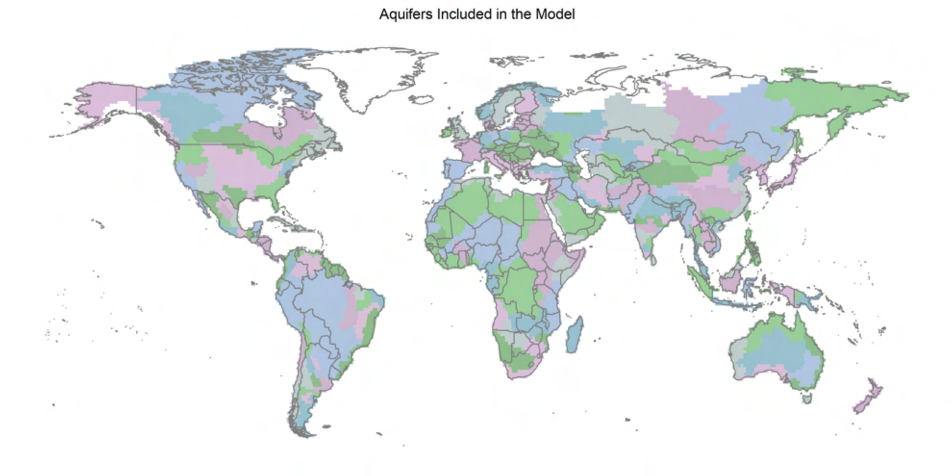


Sample selection: Aquifers

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



Data

- 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 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 $D_{q,0}$
  - 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
☐	α	labor share in crop production
☐	$\{\phi^k\}$	crop-specific water intensity
☐	θ	technological heterogeneity (Fréchet shape parameter)
☐	$\{A_i^o\}$	mean labor productivity in outside sector
☐	ψ	return flow rate
☐	$\{\rho_q\}$	specific yield
☐	$\{R_q\}$	natural recharge
☐	$\{\Upsilon_q\}$	scale of extraction productivity $A_q^w(D) = \Upsilon_q D^{-\upsilon}$
☐	υ	elasticity of extraction productivity

Calibrating technological and hydrological parameters

Parameter		Value	Source
labor share	α	0.75	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)

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

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

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

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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

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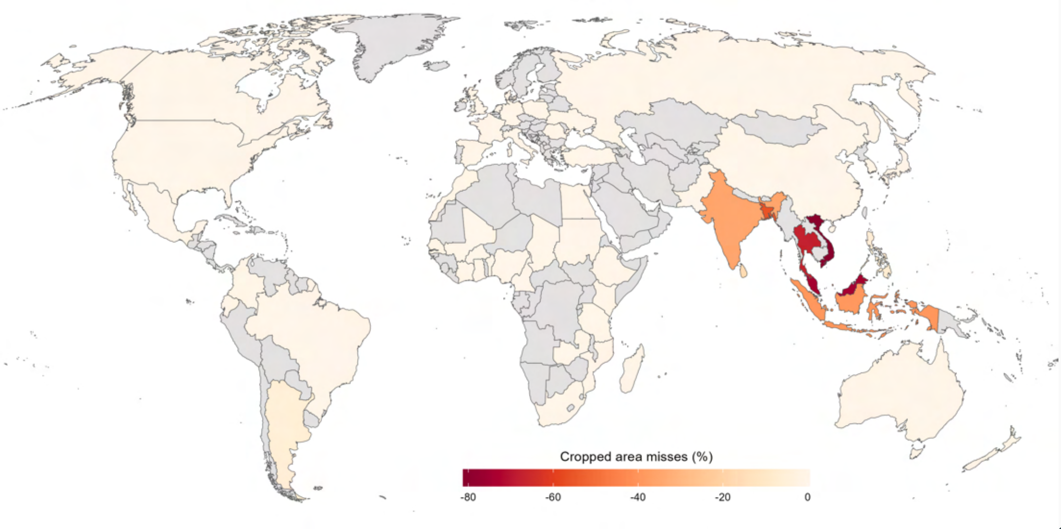
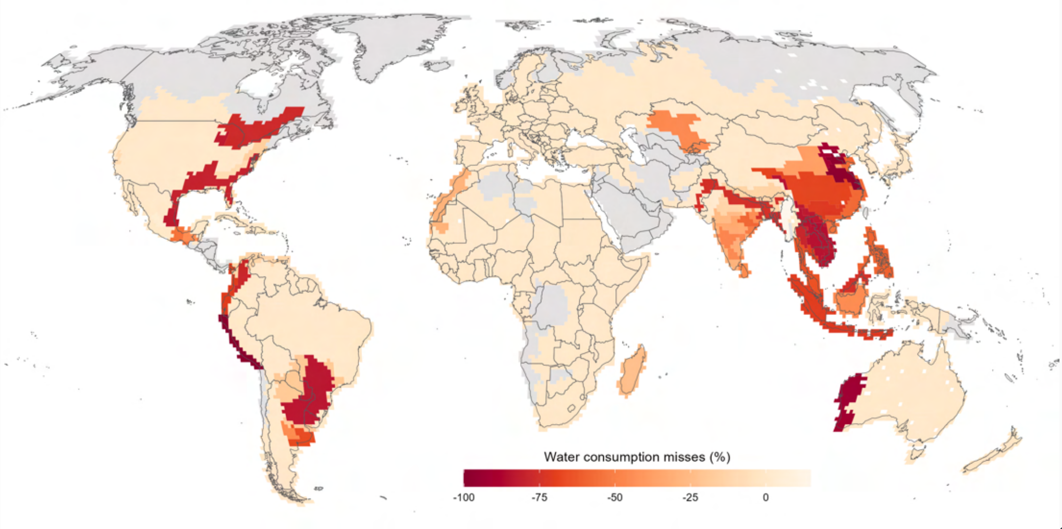
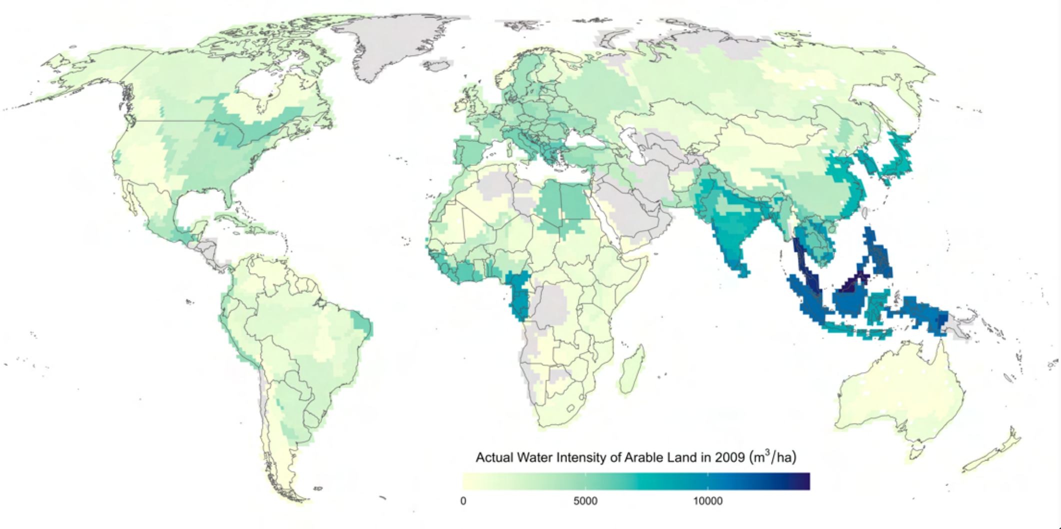
Model fit: Cropped area



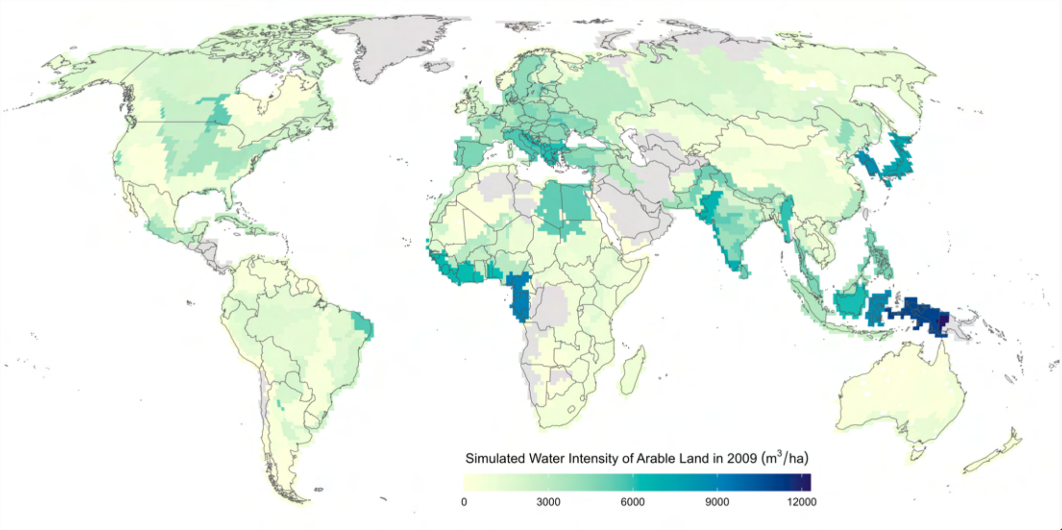
Model fit: Agricultural water extraction



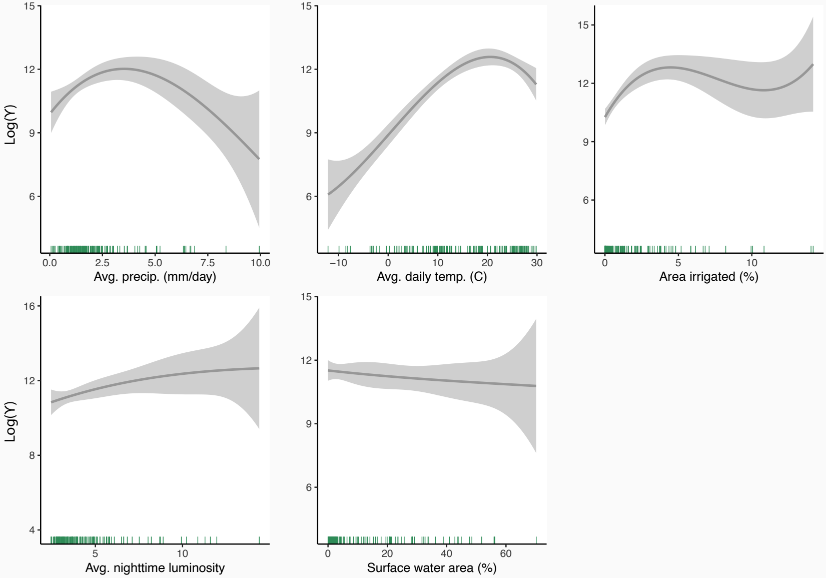
Model fit: Agricultural water extraction (target)



Model fit: Agricultural water extraction (simulated)



Model validation: Water extraction productivity



These factors explain **56%** of the variation in Υ across aquifers

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

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

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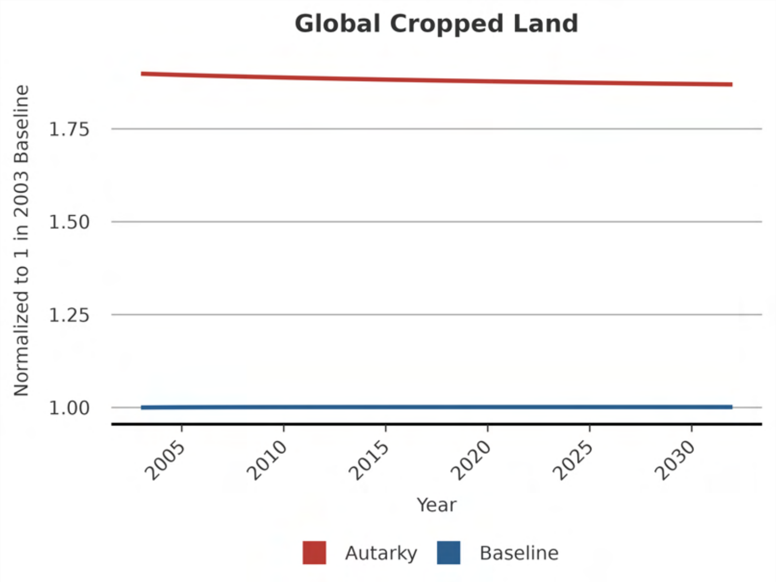
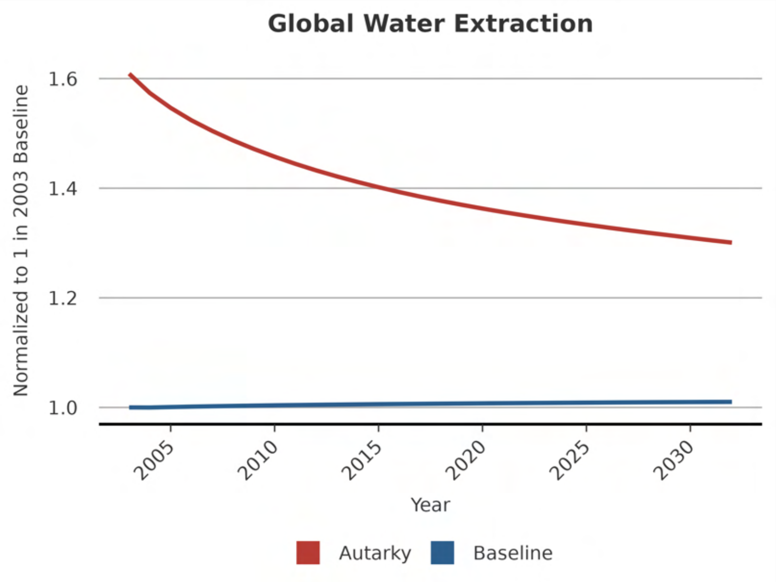
4. **Unilateral country policy changes**—e.g. rice export ban in India, EU import restrictions from certain countries, etc.

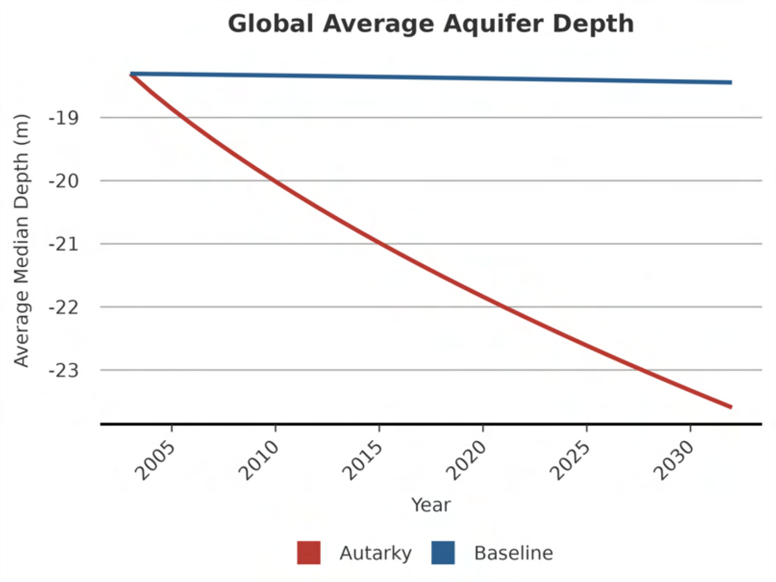
Global cropped area more than doubles in autarky



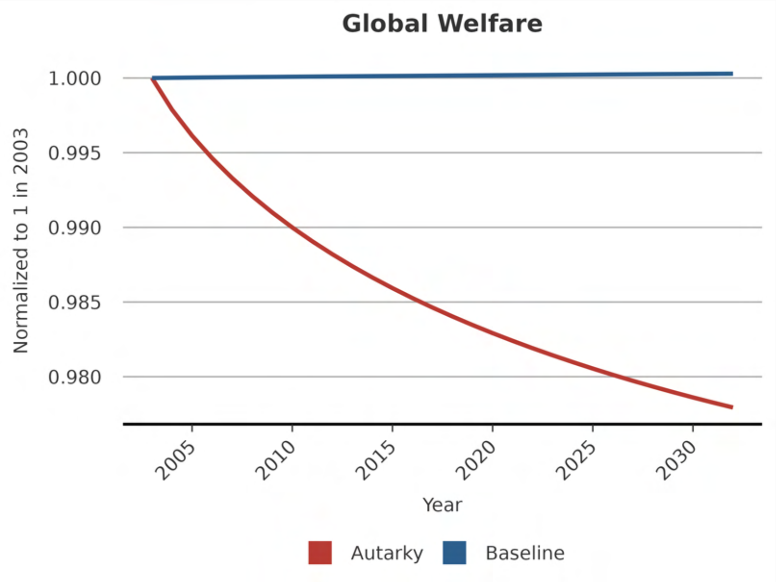
Total global water use much higher in autarky



Allowing trade prevents global aquifer depletion

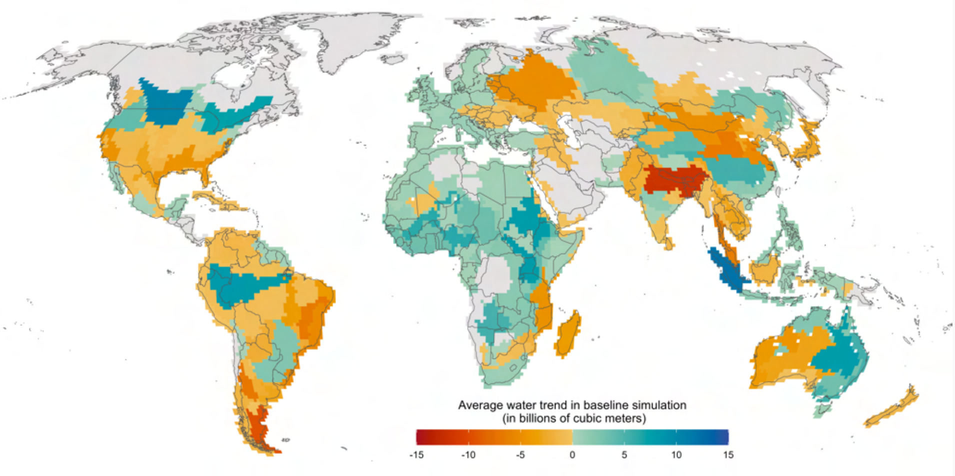


Welfare declines over time in autarky as aquifers deplete



Allowing trade prevents extreme regional depletion . . .

Trends in local water resources - baseline



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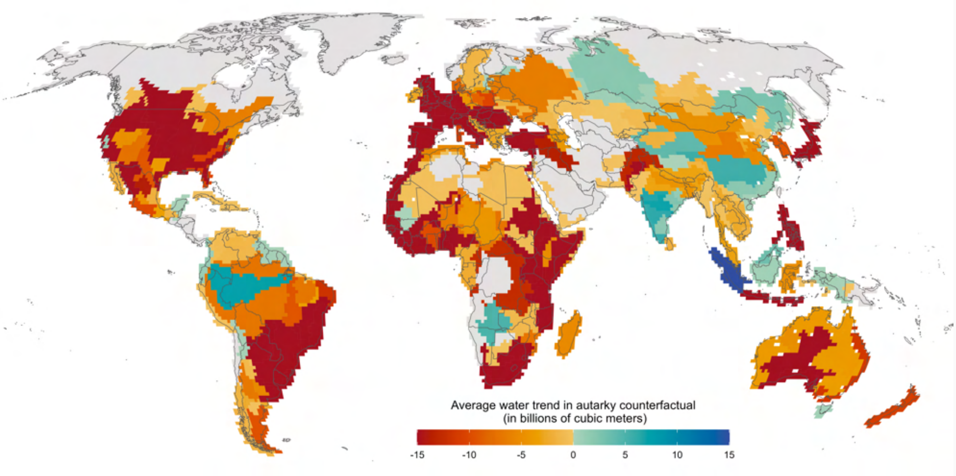
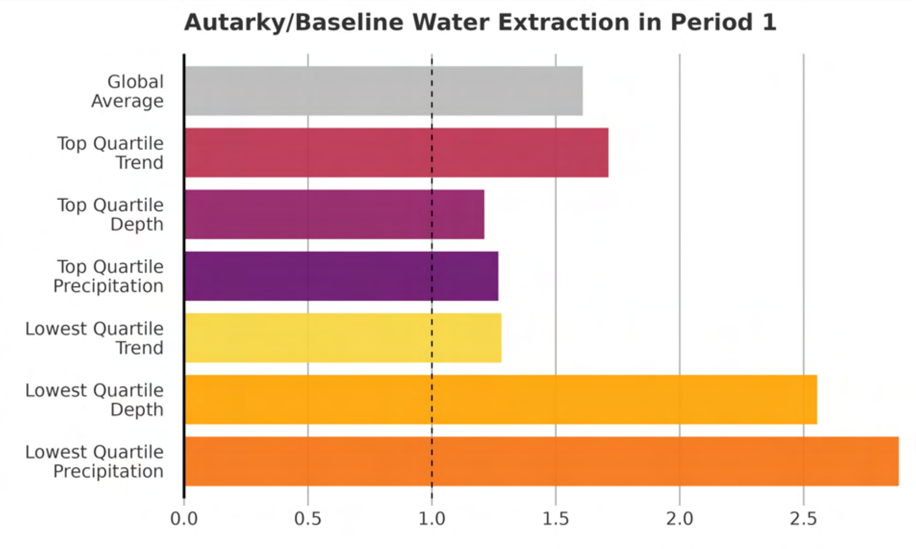
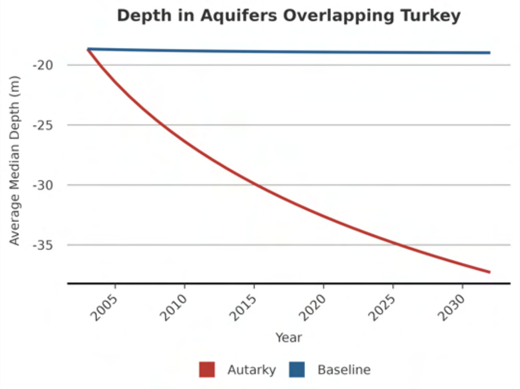
Trends in local water resources - autarky

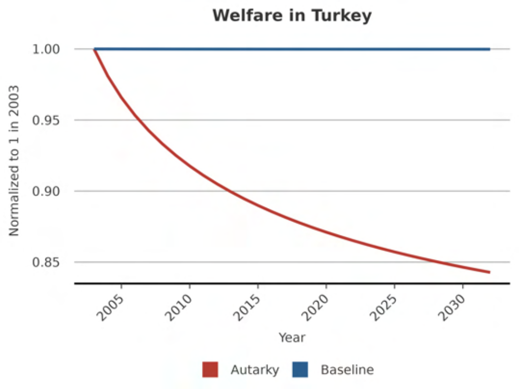


. . . by lowering water use in water-stressed regions



Autarky causes severe water depletion for some food importers

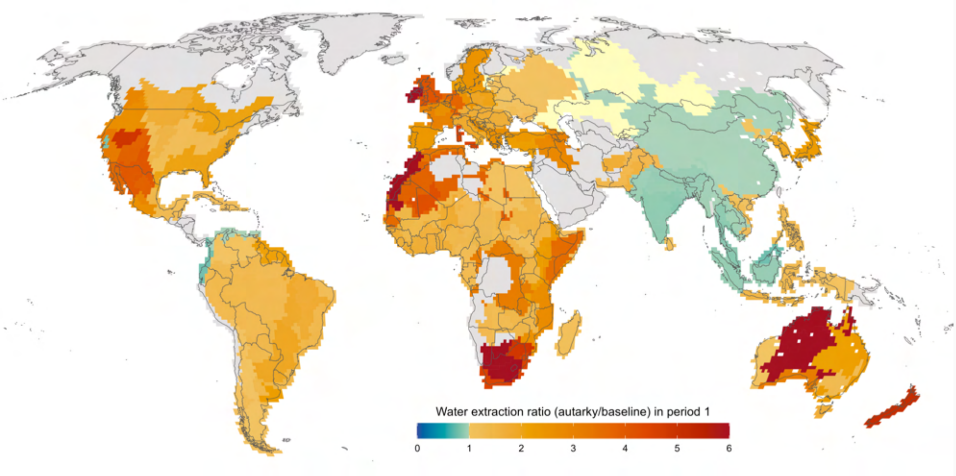




$\longrightarrow$ Cropped area increases >250% in autarky in Turkey

But, autarky prevents severe depletion for some food exporters

Water extraction *ratio* between autarky and baseline



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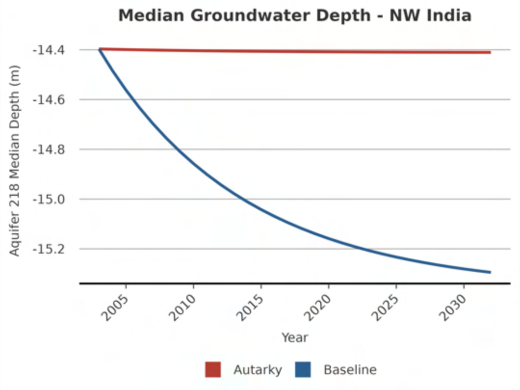
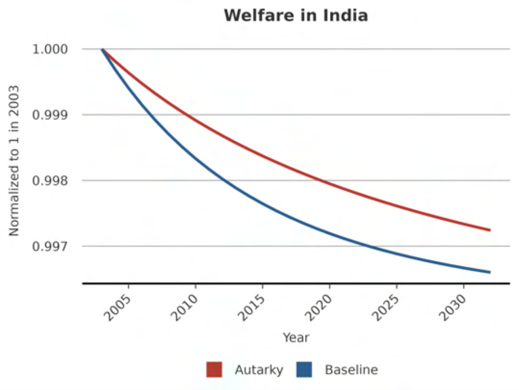




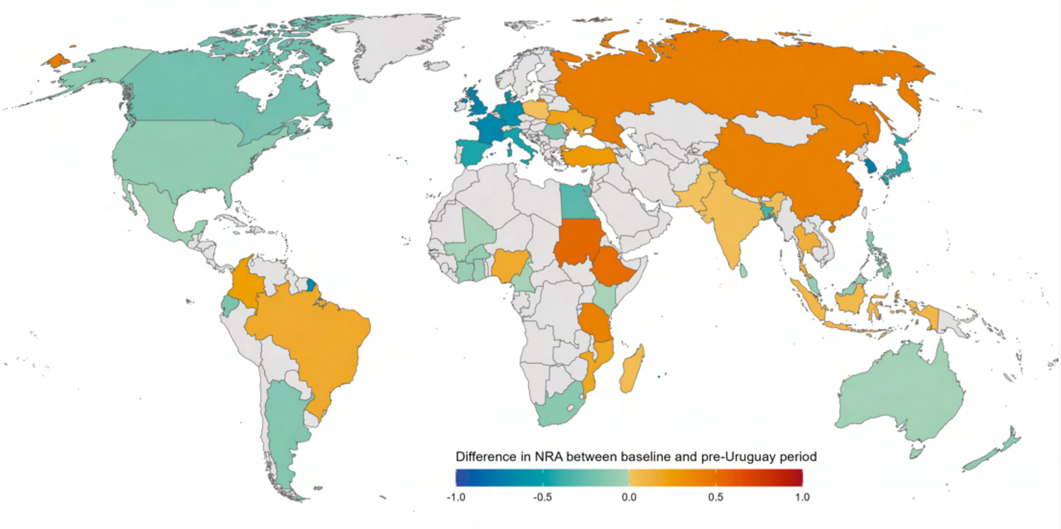
$\longrightarrow$ Autarky prevents continued water depletion in the region currently losing water fastest

Alternative policy counterfactuals

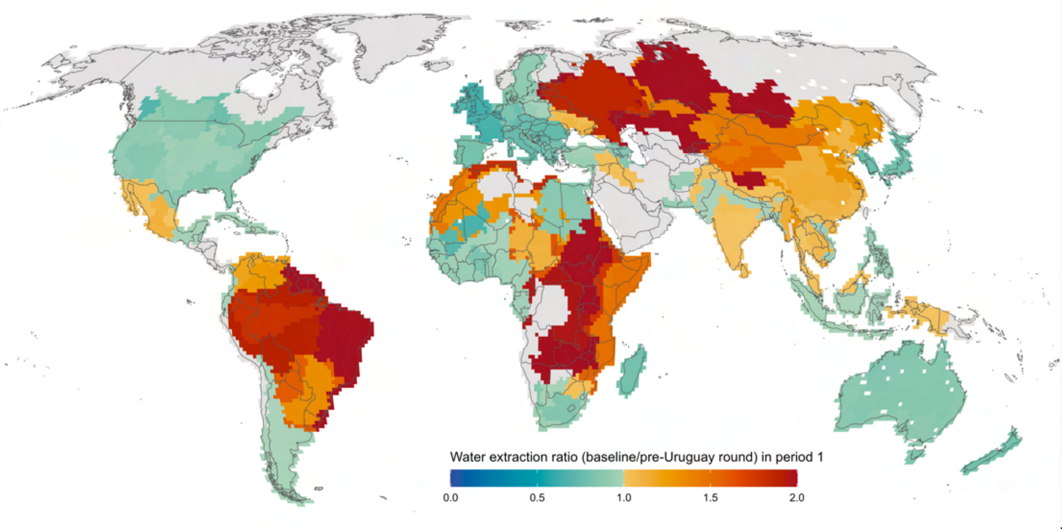
2. **1994 Uruguay Round of WTO Negotiations:** Largest global ag. liberalization
    - Prior trade agreements (GATT) largely excluded agriculture
    - "Tariffication" of non-tariff barriers to agricultural trade with maximum tariff rates imposed
    - *Implementation:* set $\tau_i^k = 1+$ avg. from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

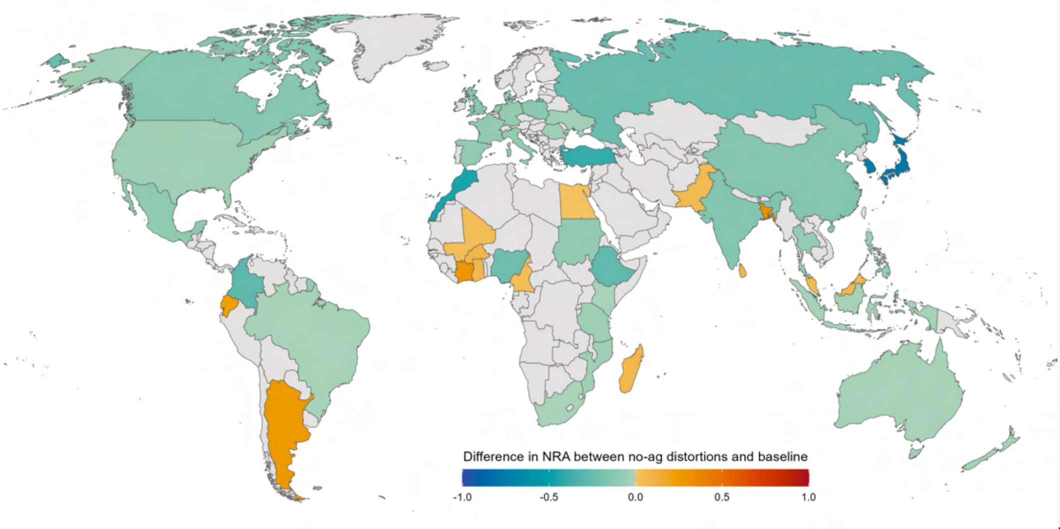
Uruguay Round lowered subsidies in the north, raised them in the south



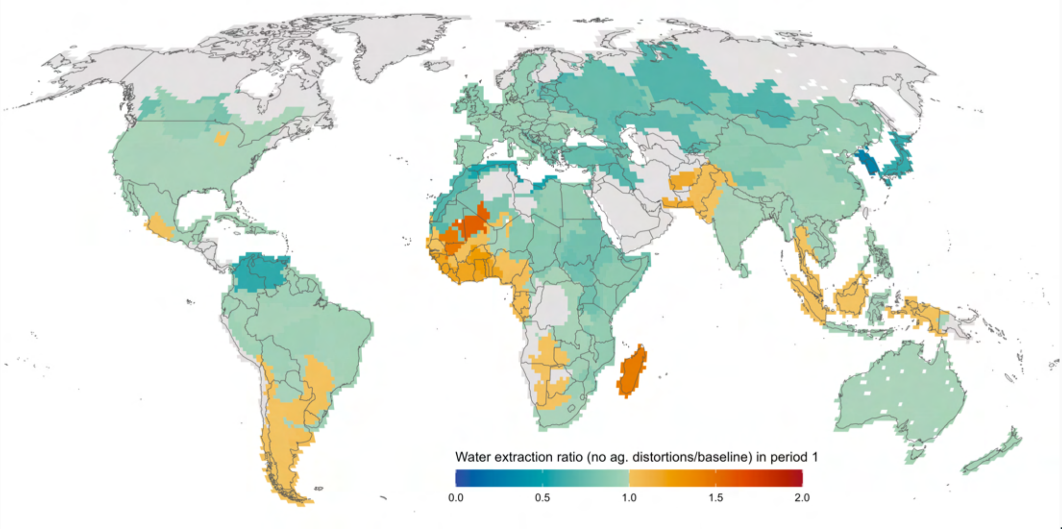
Uruguay Round increased water extraction in the south



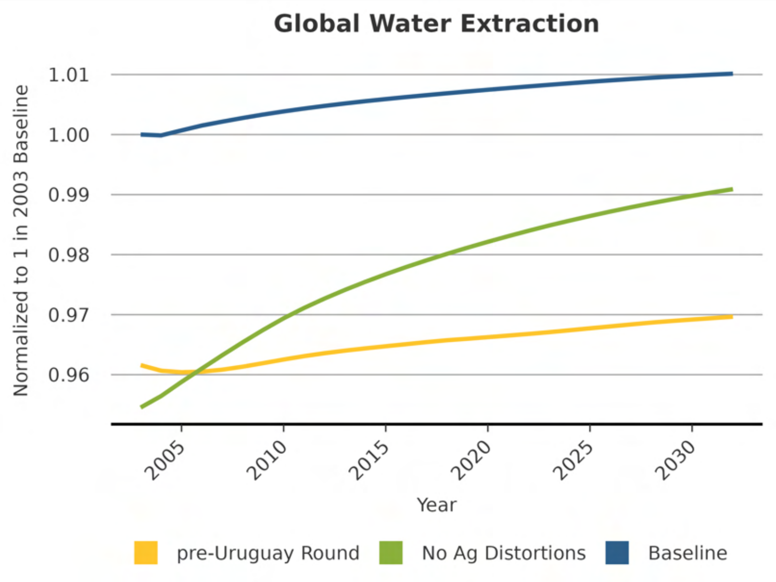
Removing current distortions lowers subsidies to ag. nearly everywhere



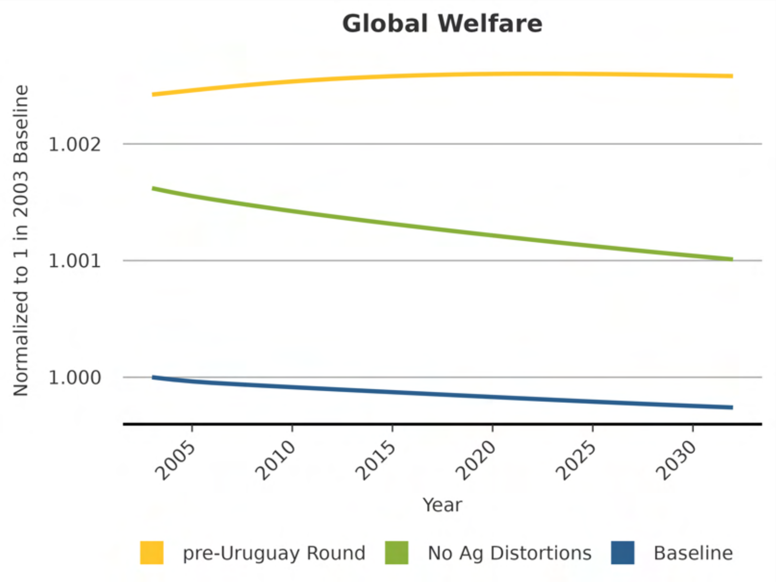
Removing current distortions lowers water extraction nearly everywhere



Global water extraction falls under both counterfactual policies



Global welfare rises under both counterfactual policies



Conclusion

Next steps

1. **Improve calibration**
   - Allow for double and triple-cropping (*currently running!*)
   - Incorporate heterogeneous ϕ_i^k water intensities
   - Allow fixed differences in water table depth within aquifer
   - Match non-ag 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 policy on water resources and long-run welfare **not ex ante obvious** with ubiquitous water property rights failures
- Comprehensive global data show water-intensive production **highly concentrated** in water-abundant locations
  - → Suggests a beneficial role for ag. trade in alleviating water stress
- Model counterfactuals show that **eliminating ag. trade causes global water depletion and declining welfare 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!

lcrews@princeton.edu

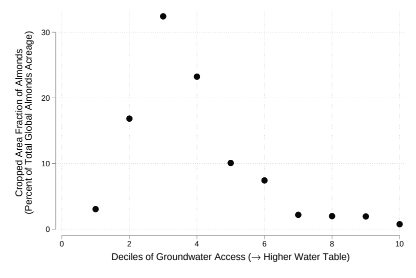
Appendix

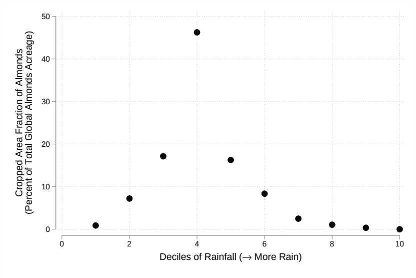
Fact 5: Water-intensive crops locate primarily in water-abundant regions . . .

Almonds

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

Almonds





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

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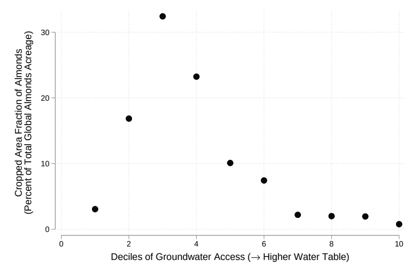
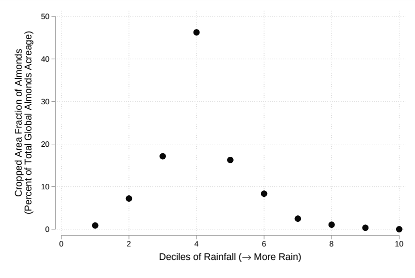
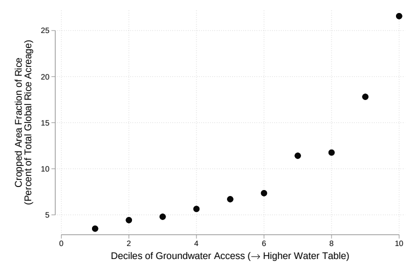
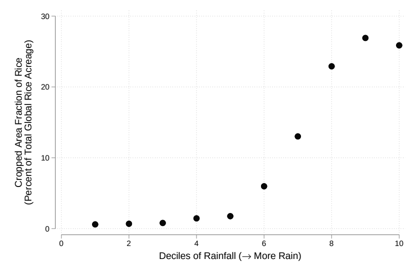




Rice





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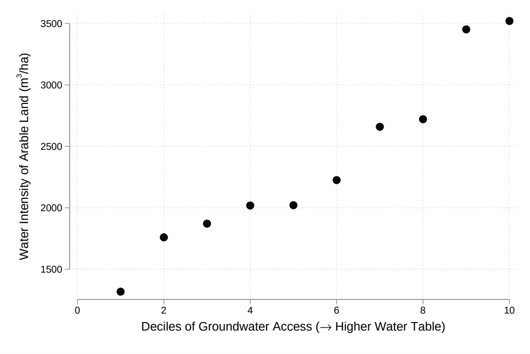
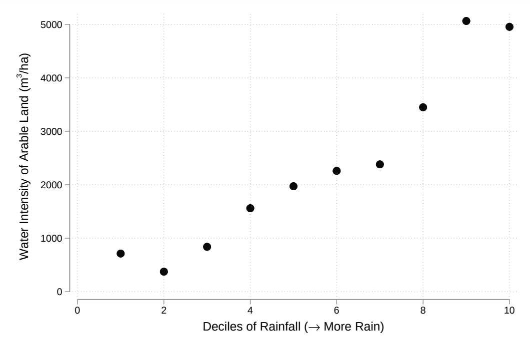
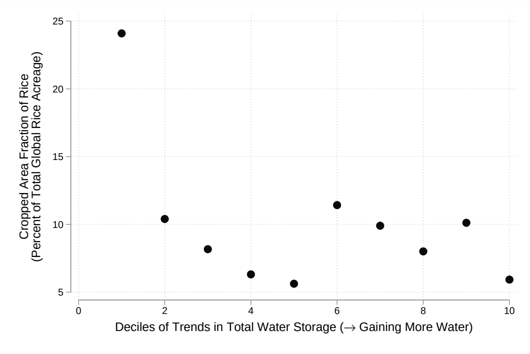




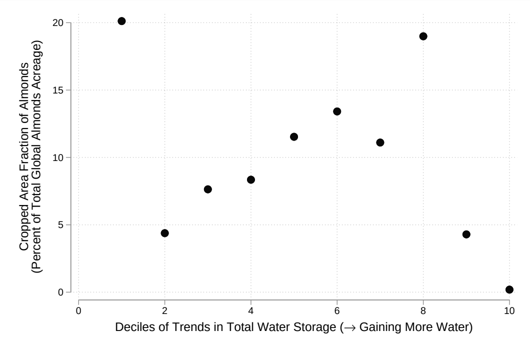
$$\text{Water Intensity of Arable Land } (\mathrm{m}^3/\mathrm{ha}) = \frac{\sum_{k \in \mathcal{K}} \text{hectares}^k \times \left(\frac{\text{water } (\mathrm{m}^3)}{\text{hectare}}\right)^k}{\sum_{k \in \mathcal{K}} \text{hectares}^k + \text{pasture}}$$

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

Rice Acreage by Water Trends



Almond Acreage by Water Trends



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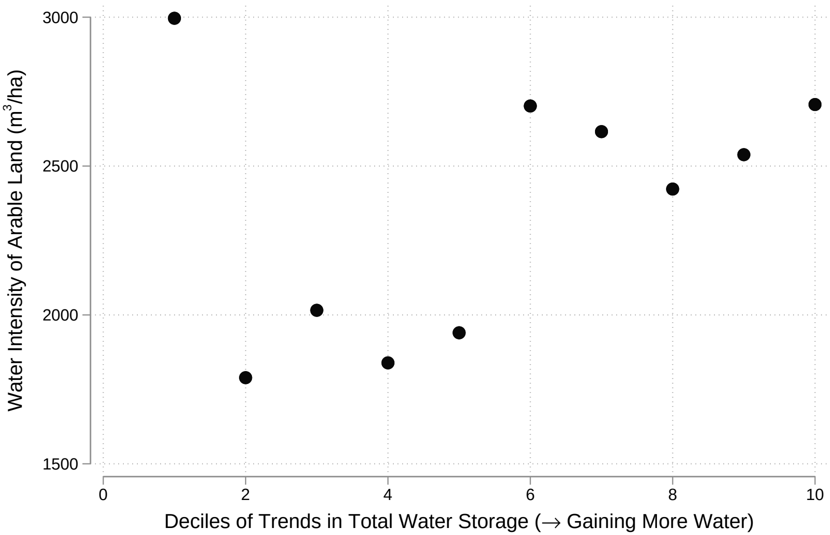
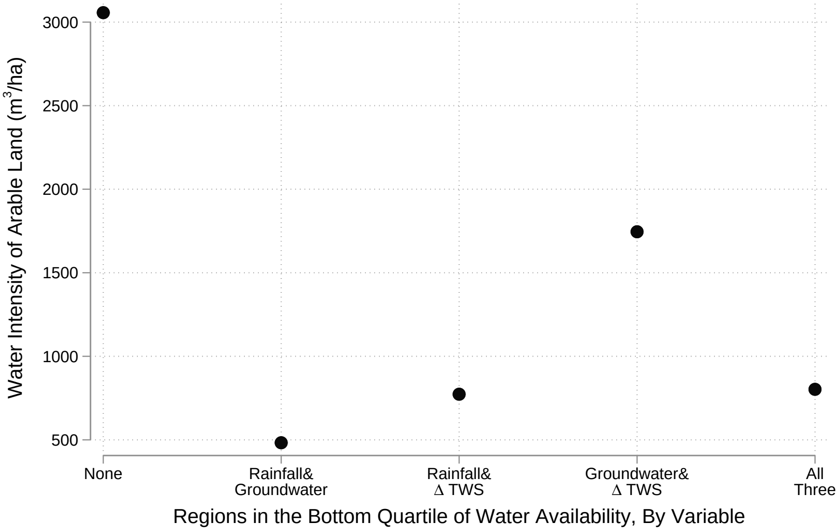
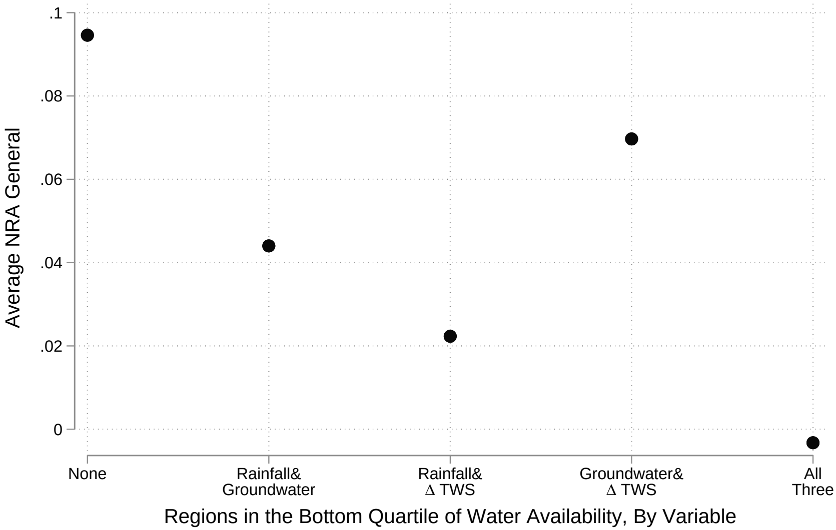


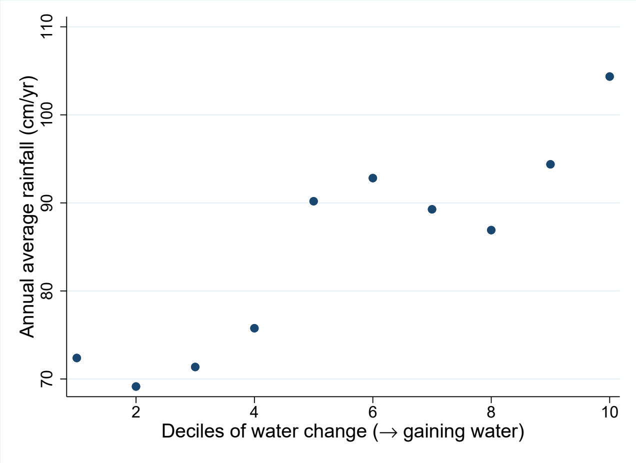
Fact 5: ... but also in some regions losing water rapidly



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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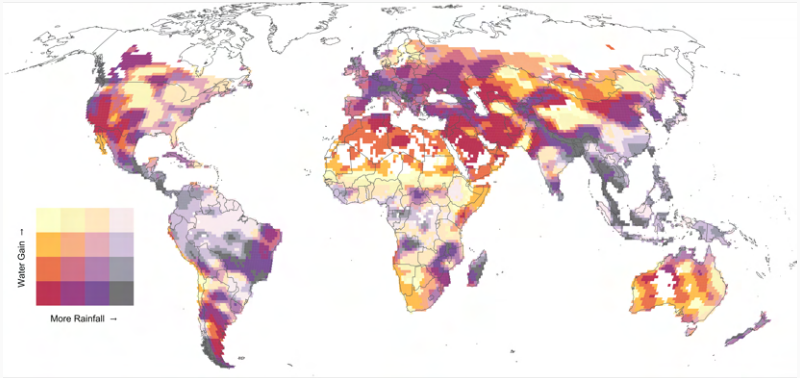

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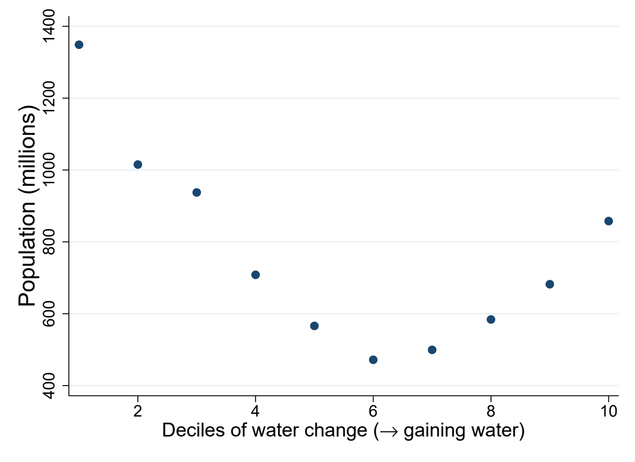

Regions losing water rapidly are very **highly populated**

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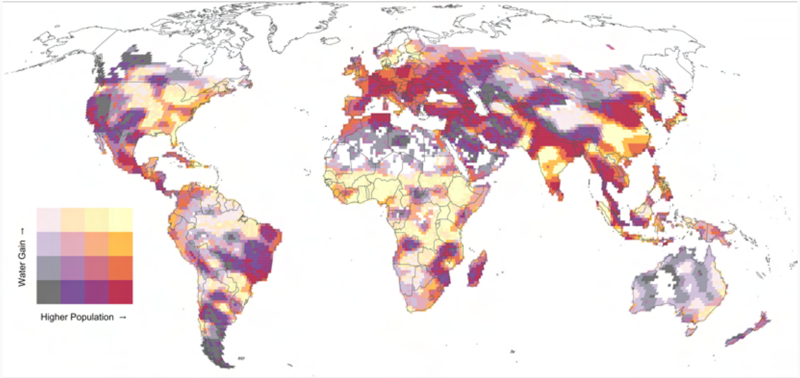

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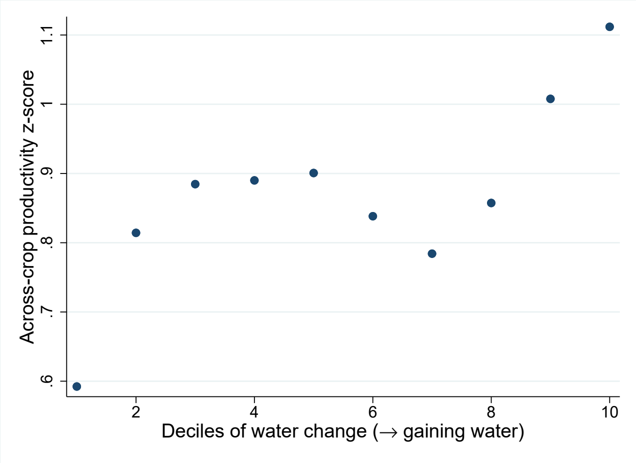

Regions losing water rapidly have **low suitability for crops**

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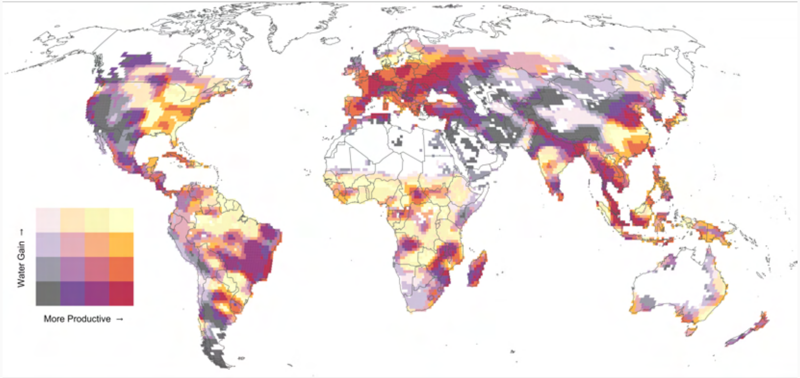

Regions losing water rapidly have **low suitability for crops**

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

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

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

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

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

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
☐	α	labor share in crop production
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☐	$\{\Upsilon_q\}$	scale of extraction productivity $A_q^w(D) = \Upsilon_q D^{-\upsilon}$
☐	υ	elasticity of extraction productivity

Calibrating technological and hydrological parameters

Parameter		Value	Source
labor share	α	0.75	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)

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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 σ, 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 κ and construct ζ_j^k, using Z_j^k to instrument for P_j^k

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

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Estimating the supply side

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

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

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

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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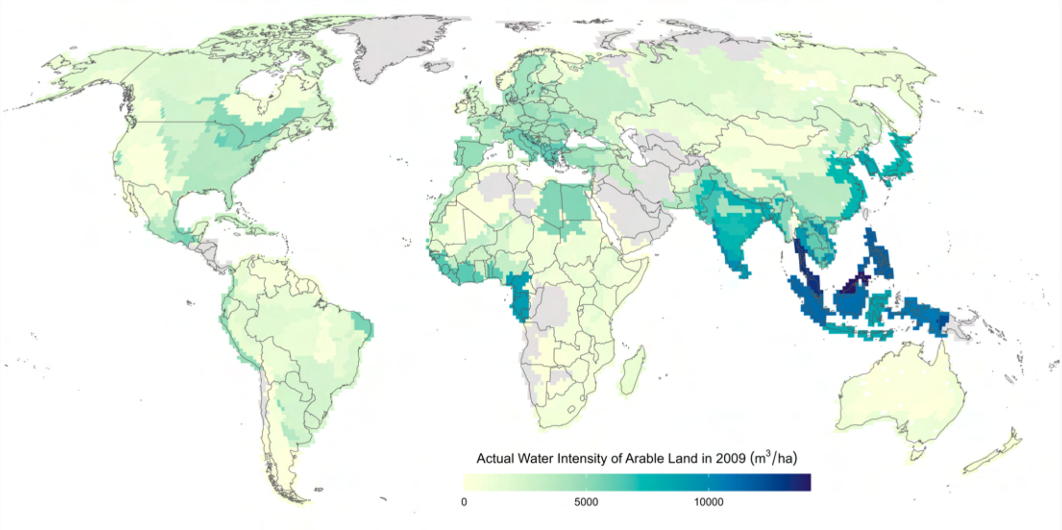
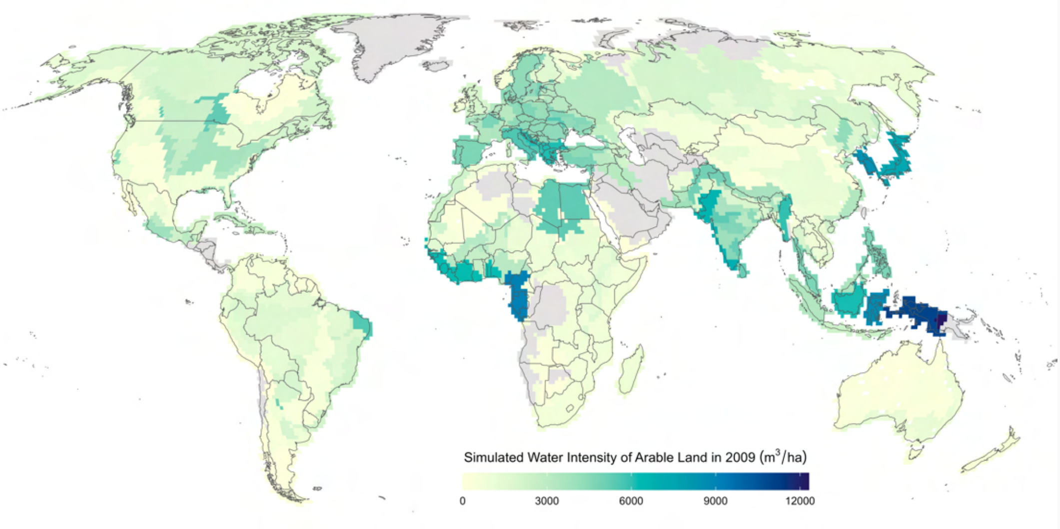
Model fit: Agricultural water extraction (Target)



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

References

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