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

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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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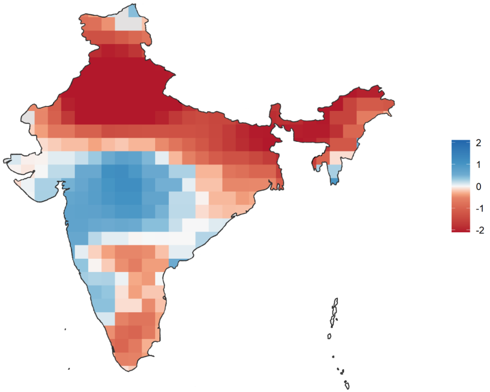
- Expansion coincides with **drought** and **land subsidence** due to groundwater extraction
- ∼**12 liters** of water used to grow **one** almond

Water-intensive production in water-scarce regions

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



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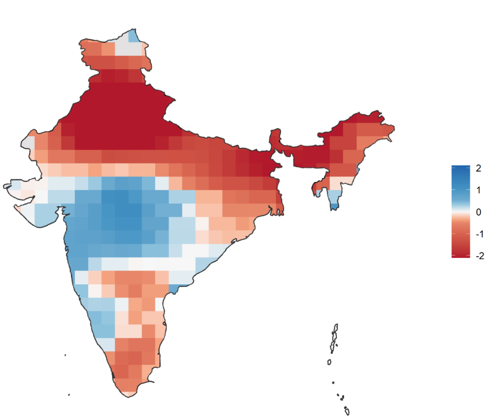
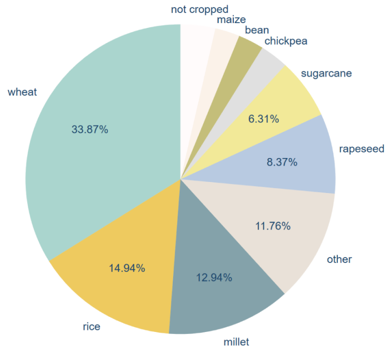


Land allocation in India's most water-stressed regions



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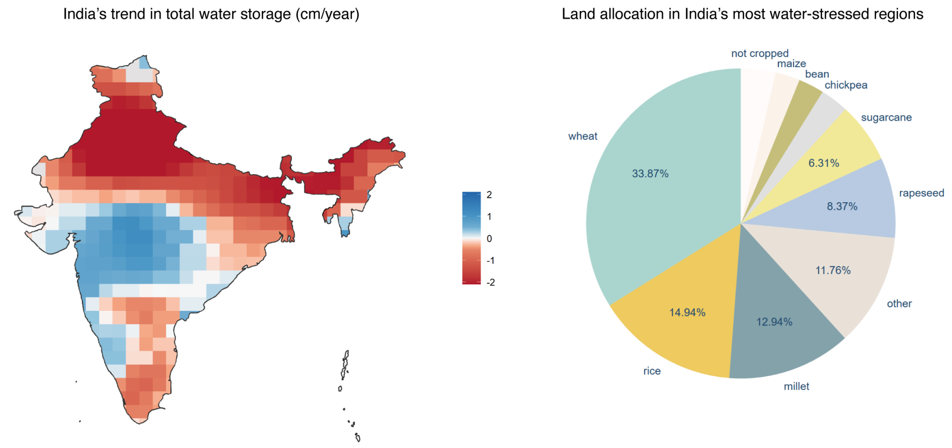

India is the world's leading exporter of rice

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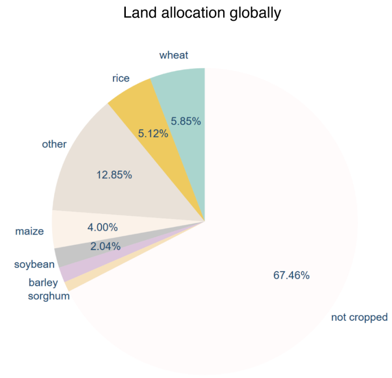

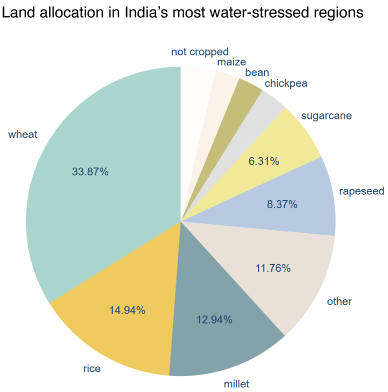

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Research questions

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

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With these in mind, we ask:

1. How does global **trade** in agriculture affect water resource **depletion**?
2. How do **existing** and **potential** ag./trade policies affect...
    - water resources,
    - agricultural production, and
    - welfare

   across space and **over time**?

This paper

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- Establish a **series of facts** about the allocation of water in global agricultural production:
    - Input market property right failures and agricultural market interventions are ubiquitous
    - Water-intensive crops concentrate *highly* in water-abundant locations, *but also* in a few locations losing water rapidly

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  - are there some *losers* from trade in the long run?
  - do ag./trade policies *exacerbate* or *mitigate* input market distortions?

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**

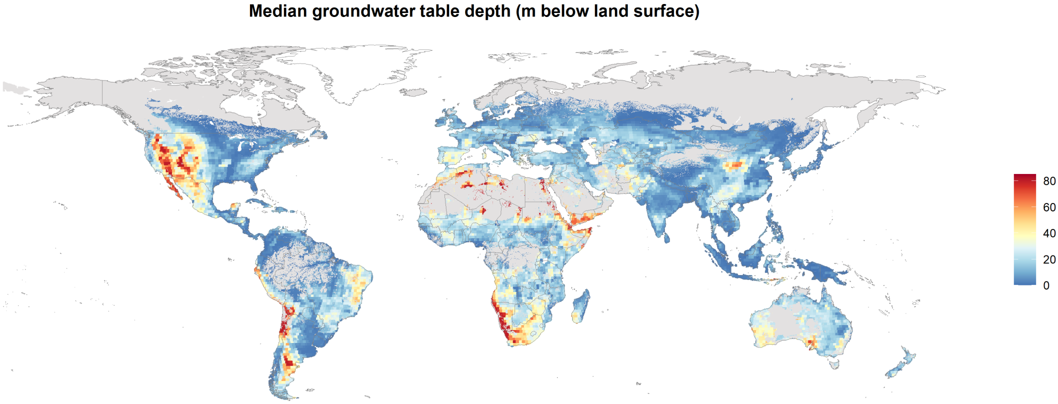
Data

Compilation of global water and agriculture data

	Source	Scale	Process
Hydrology & geology			
Water table depth	Fan et al. (2013)	1km	Hydrological model + 1.6 million wells
Change in water storage	GRACE	$\sim 1^\circ$	Satellite-derived
Precipitation	GMFD v3	0.25°	Reanalysis
Presence of surface water	Pekel et al. (2016)	30m	Satellite-derived
Soil type	Hengl et al. (2017)	250m	Machine learning + 150,000 soil samples
Specific yield	Loheide et al. (2005)	soil type	Literature meta-analysis
Water intensity of production	Mekonnen and Hoekstra (2011)	crop	Agronomic modeling
Agriculture			
Crop potential yields	FAO GAEZ	$\sim$10km	Agronomic modeling
Ag. land use	Monfreda et al. (2008)	$\sim$10km	Census data + remote sensing
Ag. production & trade	FAOSTAT & Comtrade	crop$\times$country	Direct reporting
Policy			
Distortions to ag. incentives	World Bank	crop$\times$country	Direct reporting + SOE model

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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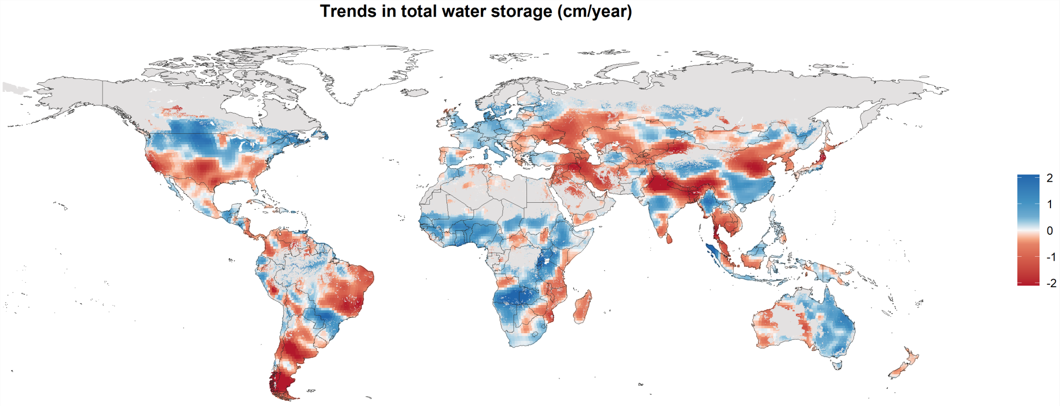

- Source: **GRACE**
- Resolution: Equal-area grid ($\sim 1^\circ \times 1^\circ$ at the equator) observed monthly over 2003–2016
- *How*: Variations in earth's gravity field—dominated by shifting water mass—change distance between two tandem satellites (Tapley et al., 2004)

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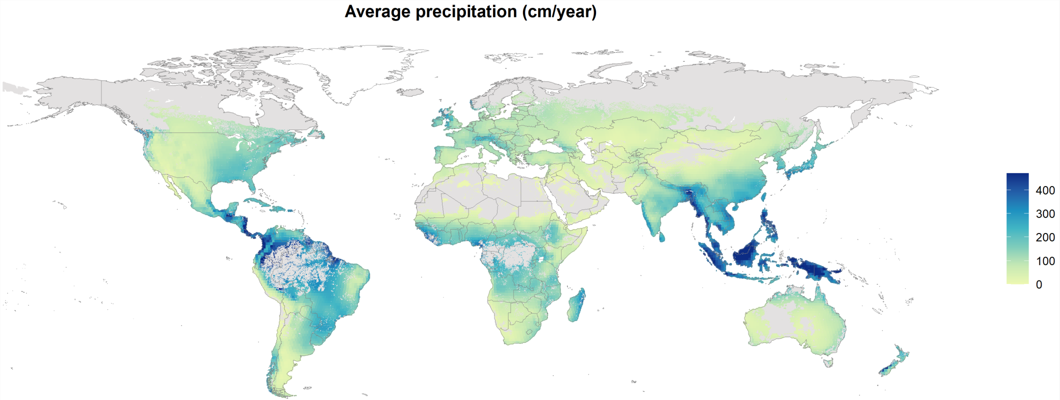
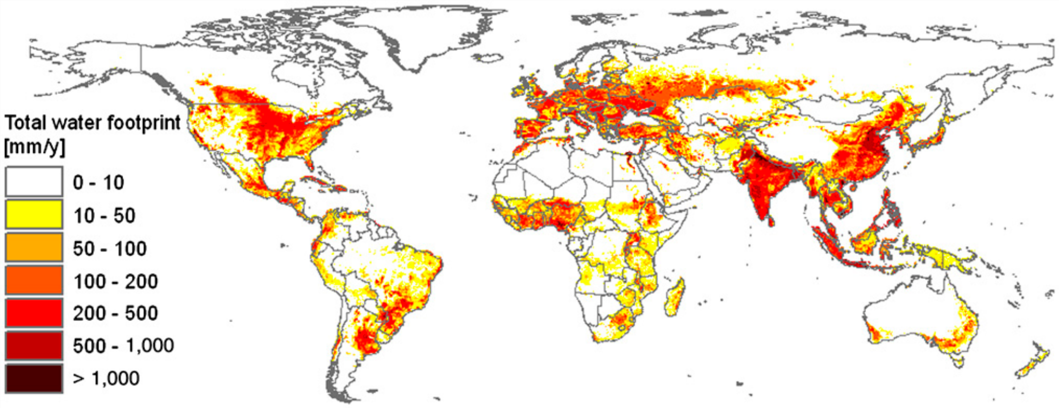


- Source: **Global Meteorological Forcing Dataset (GMFD) v.3**
- Resolution: 0.25° ($\sim$28km) observed daily over 1948–2010
- *How*: Observational data → weather model → downscaled (Sheffield, Goteti, and Wood, 2006)

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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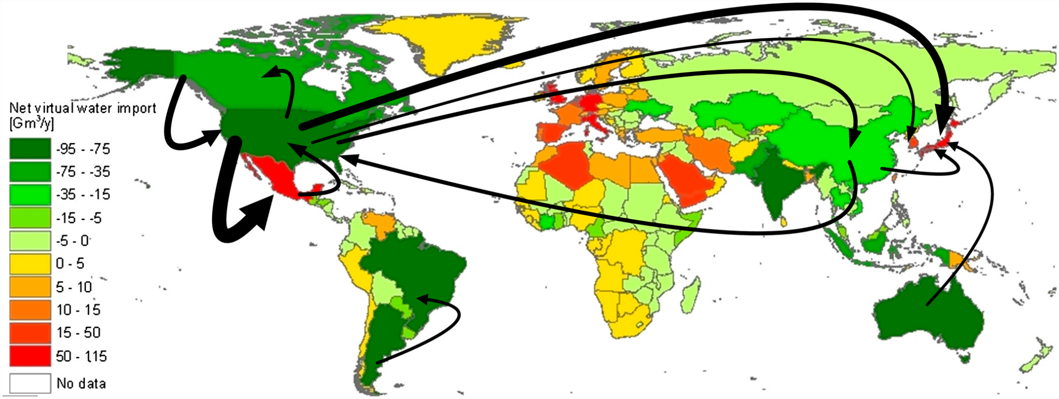
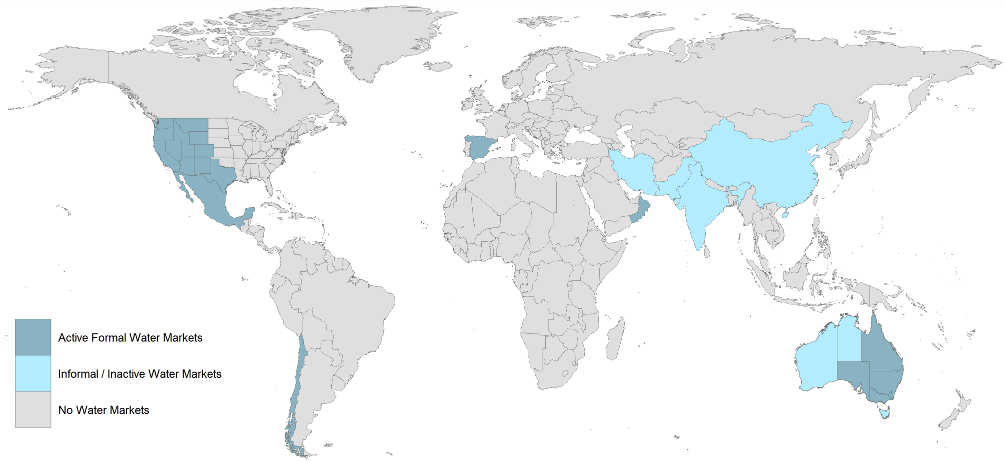


Agricultural *trade* embeds...

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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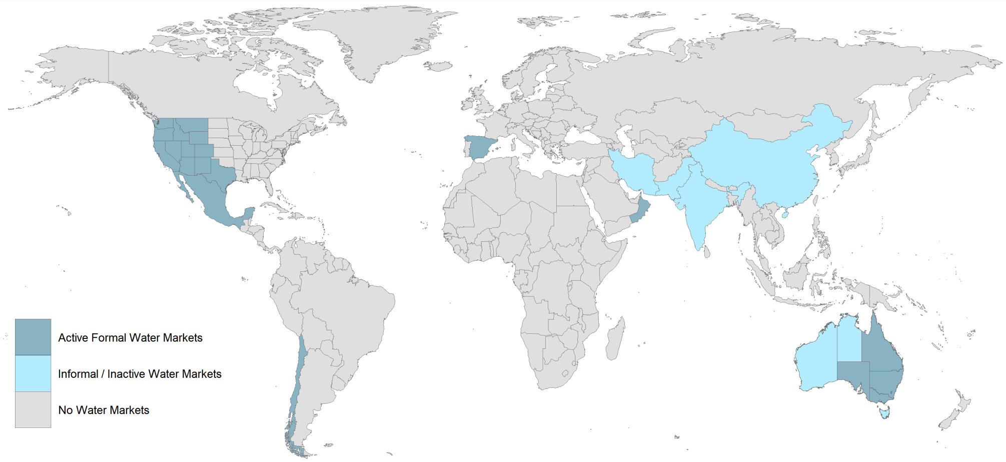
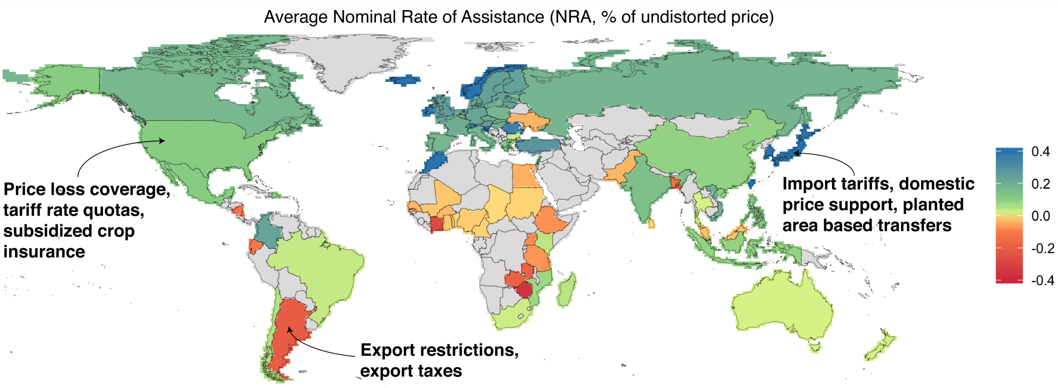


- $>$**93%** of global agricultural production occurs in regions with no formal water markets
- $>$**50%** of countries with "water-scarce" basins lack any regulatory control (Richter, 2016)

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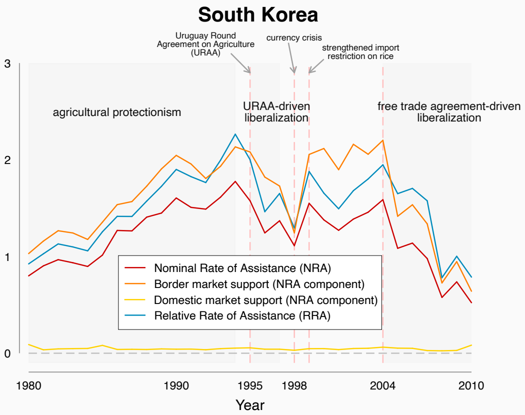
Direct evidence from Carleton (2021): increasing net agricultural subsidies **causes extremely large declines** in total water volumes



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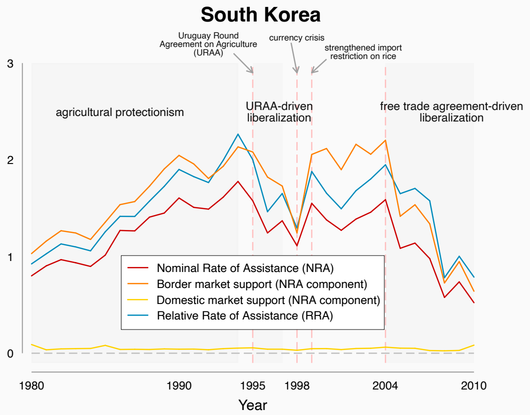
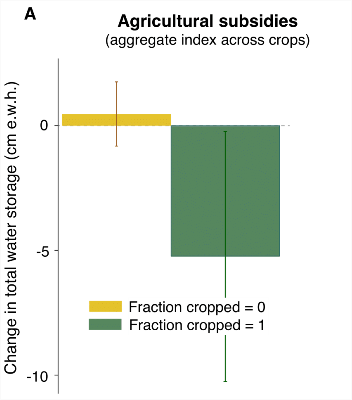
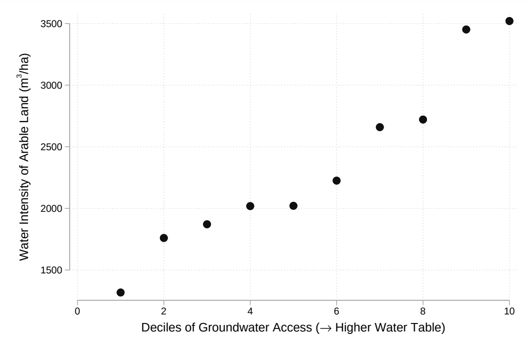
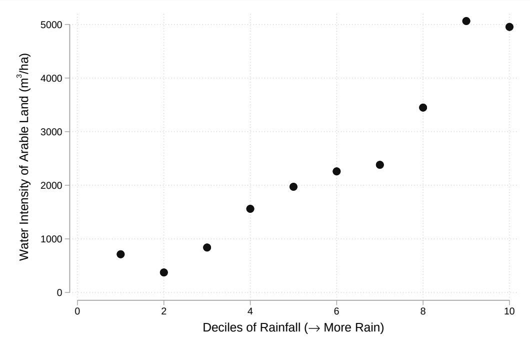




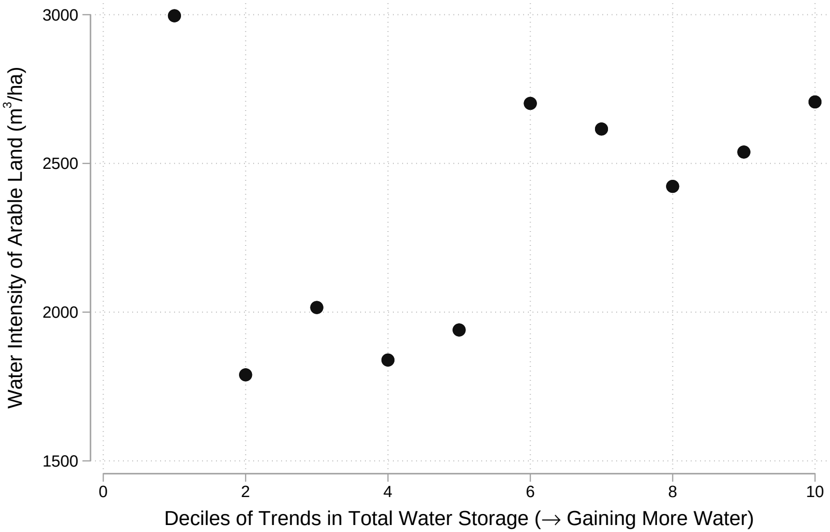
Fact 5: Water-intensive crops locate primarily in water-abundant regions...





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

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



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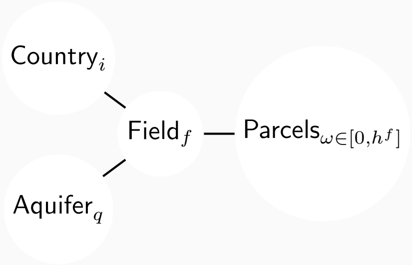
3. Local markets for water rarely exist $\rightarrow$ **spatial & temporal externalities**
4. Agricultural policy greatly affects water use $\rightarrow$ **maybe it hurts, but maybe it can help**
5. Water-intensive crops primarily locate in water-abundant regions, but also in some water-losing regions $\rightarrow$ **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**: $p_{jit}^k = \delta_{ji}^k p_{jt}^k$
  - **NRA** τ_{jt}^k 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

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;
- 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

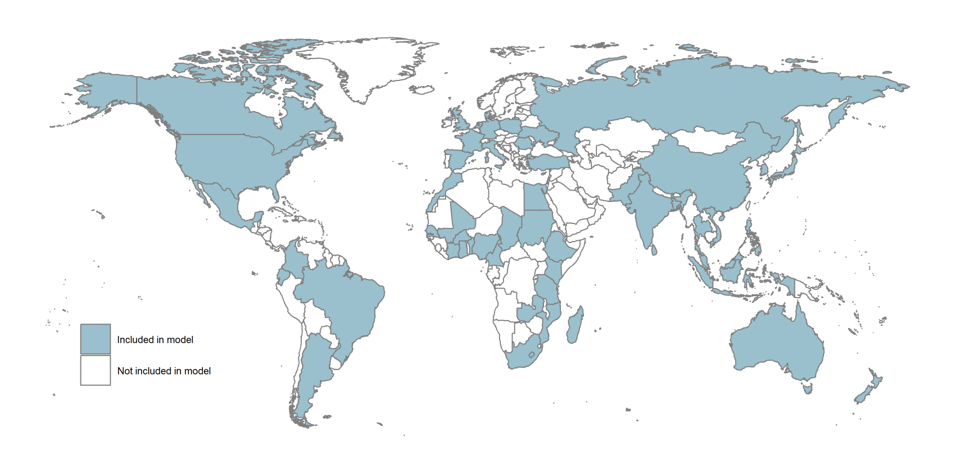
Include countries in the **top 40** globally in any of...

(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

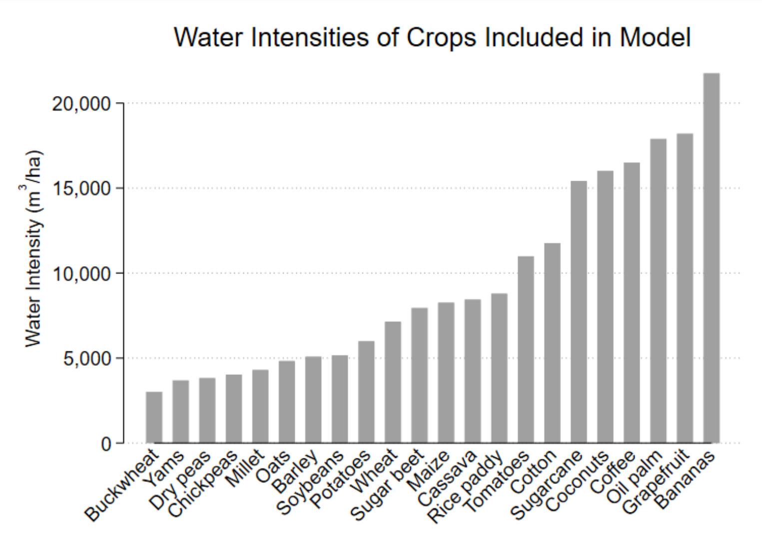
Include **high-value** and **staples** (global *and* regional) + **span** water intensities | in GAEZ (38)

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

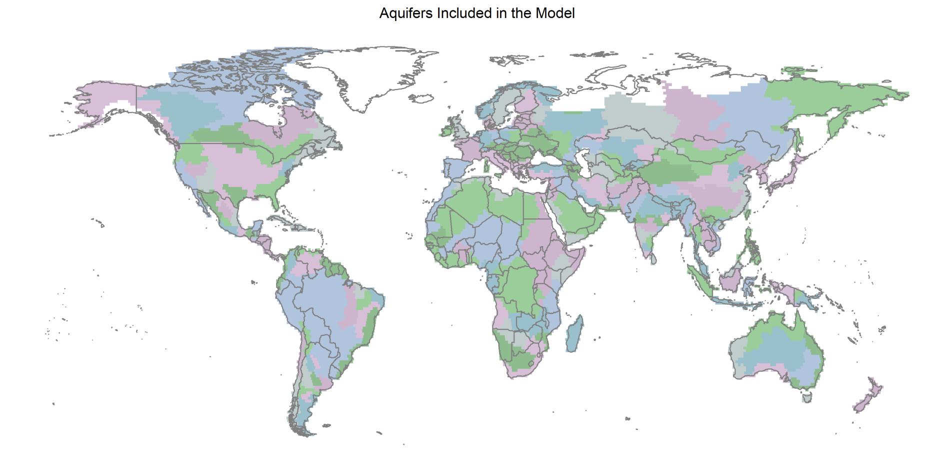


Sample selection: Aquifers

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 ($\sim$**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
☐	$\{A_i^o\}$	mean labor prod. in outside sector
☐	ψ	return flow rate
☐	$\{\rho_q\}$	specific yield
☐	$\{R_q\}$	natural recharge
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☑ calibrated: lit. & data

☑ estimated: follow **CDS (2016)**

Parameters to be calibrated/estimated

☑ (blue)	σ, κ	demand elasticities
☑ (blue)	$\{\zeta_j, \zeta_j^k, \zeta_{ij}^k\}$	demand shifters
☑ (blue)	$\{\delta_{ij}^k\}$	bilateral crop-specific trade costs
☑ (gray)	α	labor share in crop production
☑ (gray)	$\{\phi^k\}$	crop-specific water intensity
☑ (orange)	θ	technological heterogeneity
☑ (orange)	$\{A_i^o\}$	mean labor prod. in outside sector
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☑ (gray)	$\{\rho_q\}$	specific yield
☑ (gray)	$\{R_q\}$	natural recharge
☑ (orange)	$\{\Upsilon_q\}$	scale of extraction productivity
☑ (gray)	υ	elasticity of extraction productivity

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

Intuition for estimating the supply side

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

- **Share of non-cultivated land** $\leftrightarrow$ non-agricultural labor productivity $\{A_i^o\}$
- **Water extracted** $\leftrightarrow$ labor productivity of extraction $\{\Upsilon_q\}$
- **Cross-crop dispersion in output** $\leftrightarrow$ cross-parcel dispersion in productivity θ

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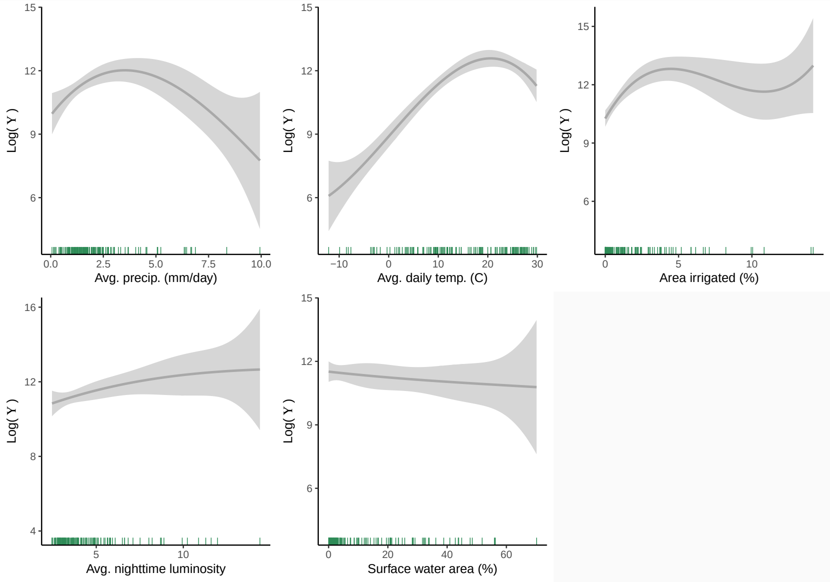
Importantly, this implies...

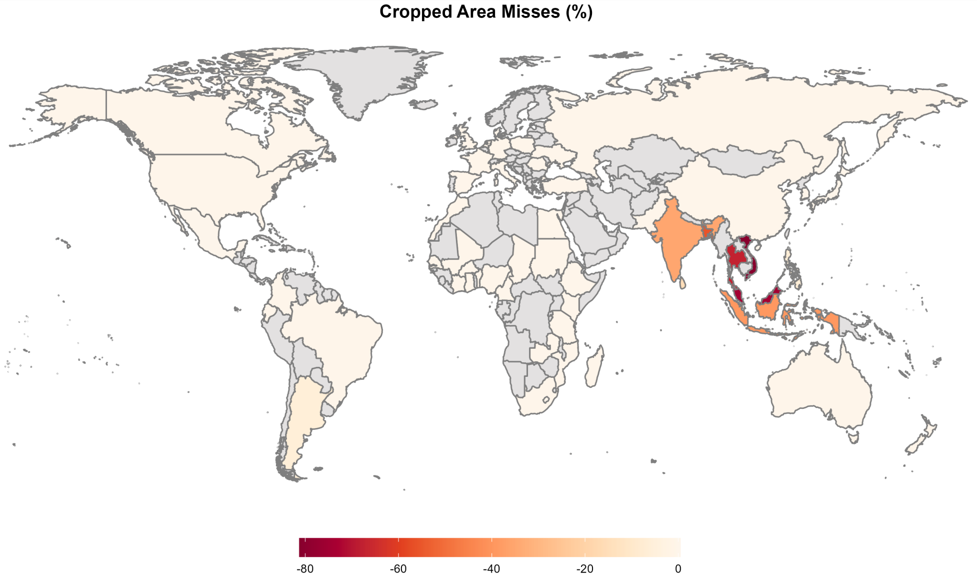
- Aquifer-level costs of water extraction estimated based on **revealed preference** of farmer crop allocations
- These costs can be driven by water availability (e.g., rainfall), technology (e.g., irrigation), institutions (e.g., formal regulatory regime), etc.

Model validation: Water extraction productivity

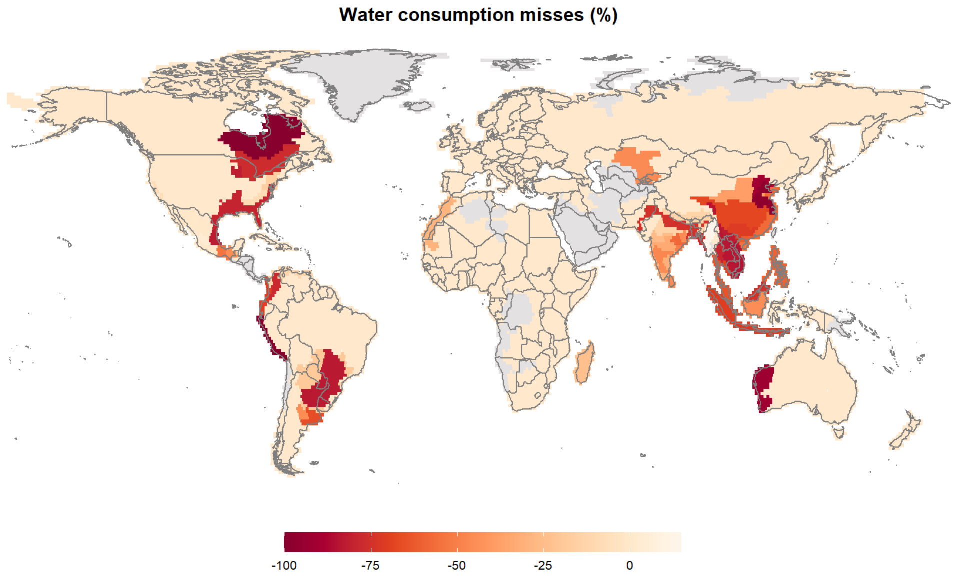


These factors explain **56%** of the variation in Υ across aquifers

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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   - Do *all* observed agricultural market interventions exacerbate input market failures?

Menu of counterfactuals

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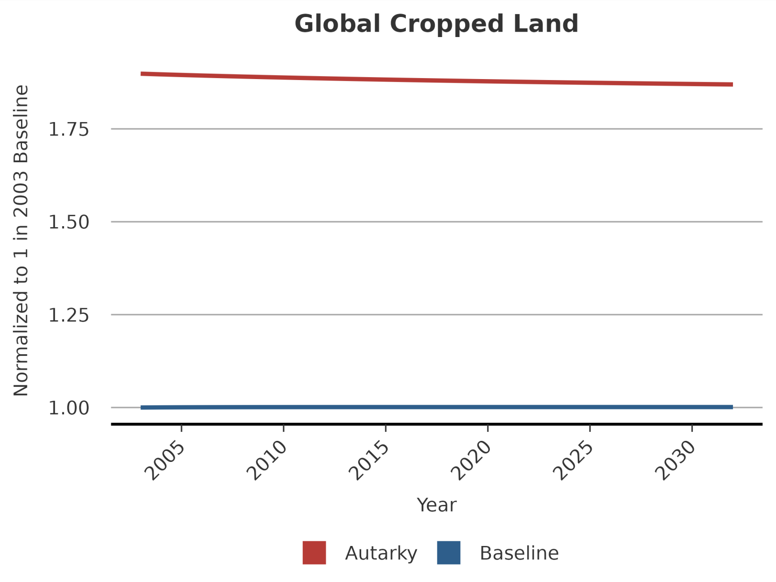
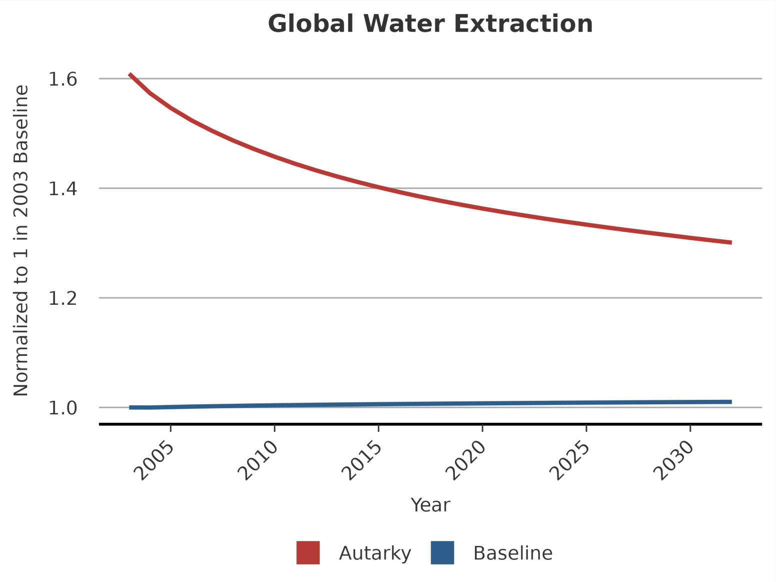
4. **Unilateral country policy changes**—e.g. rice export ban in India, EU import restrictions from certain countries, etc.

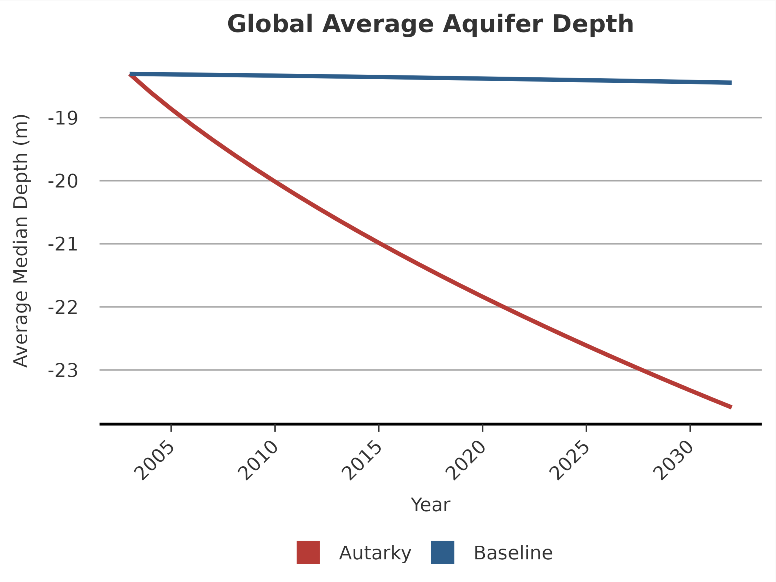
Global cropped area more than doubles in autarky



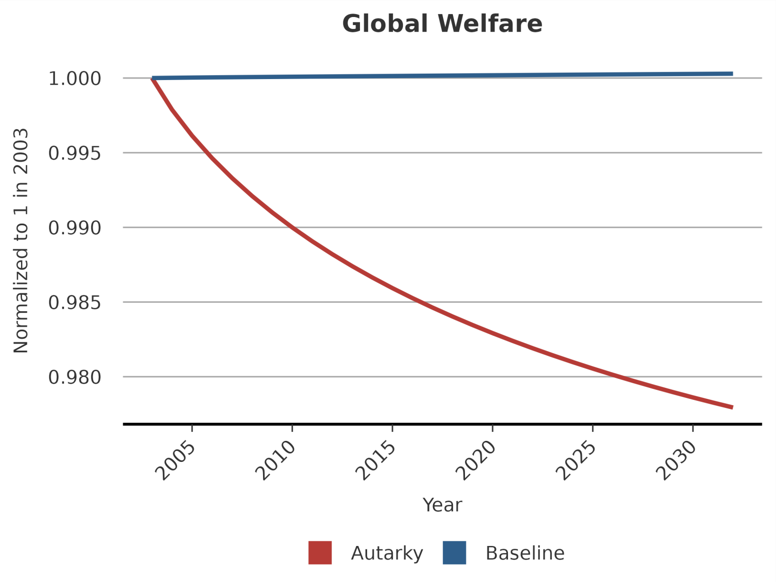
Total global water use much higher in autarky



Allowing trade prevents global aquifer depletion



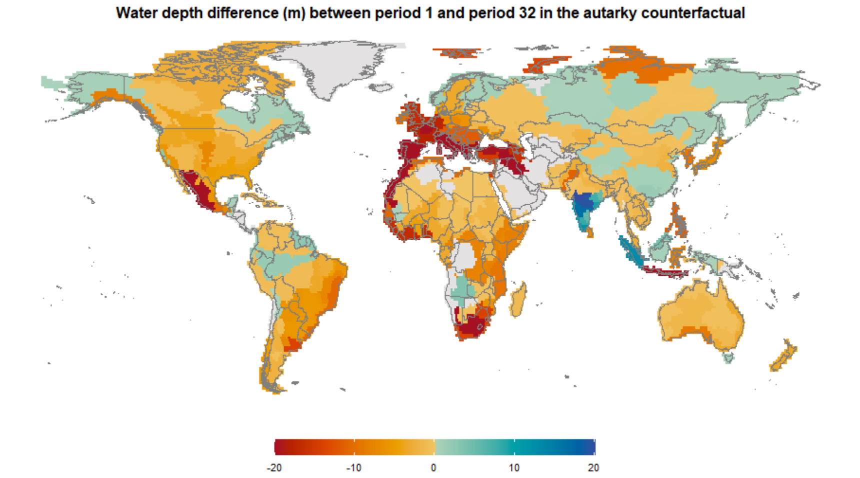
Welfare declines over time in autarky as aquifers deplete



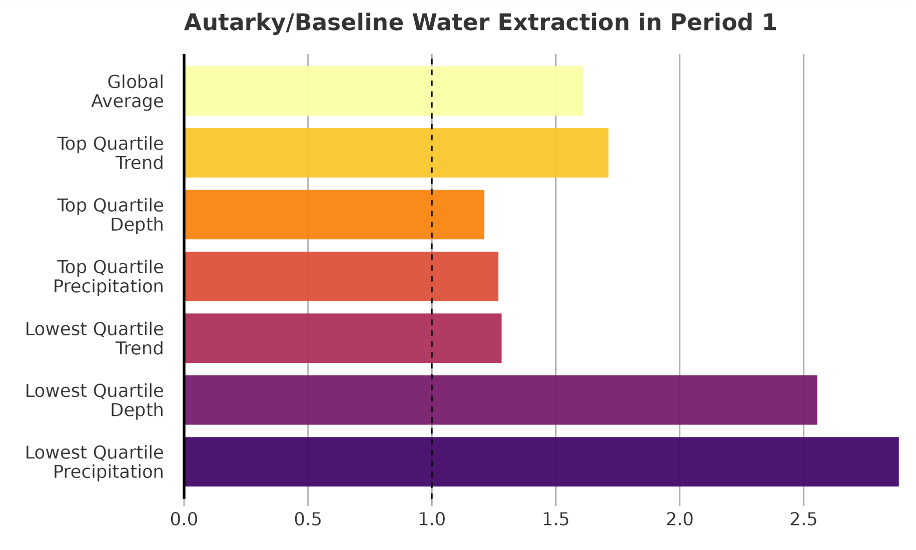
Mechanisms for declining welfare over time

- As water tables decline, **yields fall**
- **Higher prices** of food
- More agricultural land required, **less production of outside good**

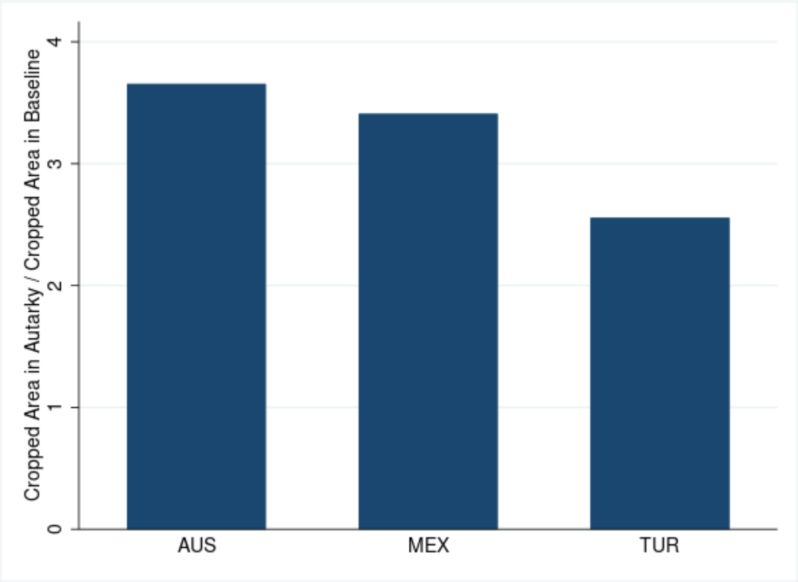
Allowing trade prevents extreme regional depletion . . .



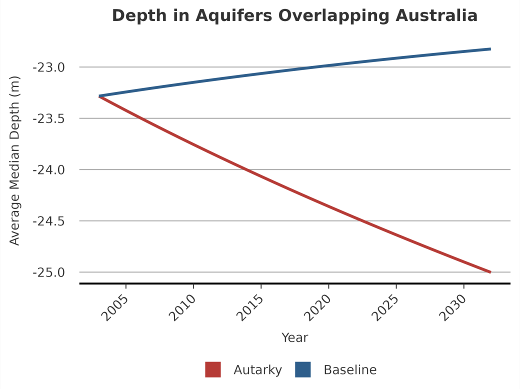
. . . by lowering water use in water-stressed regions

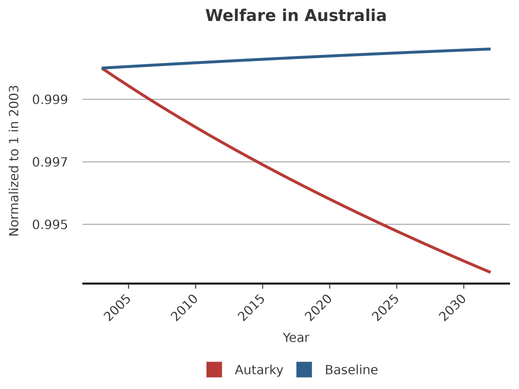


Large cropped area increases under autarky in current food importers . . .

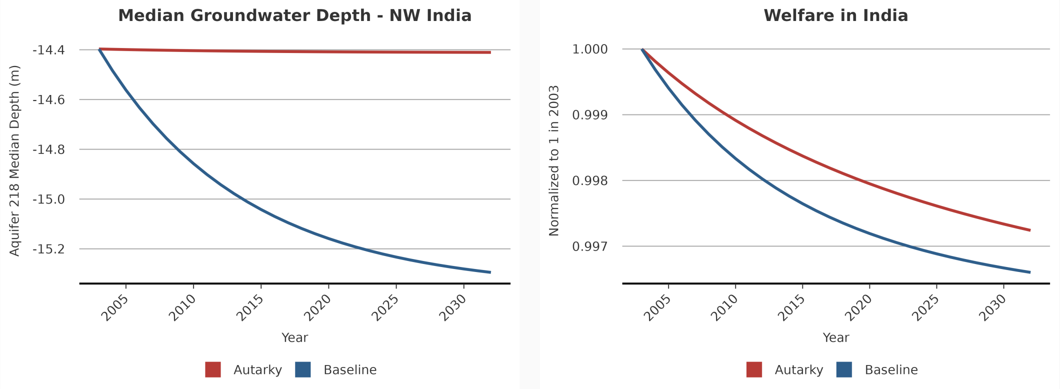


. . . causing severe water depletion and lowering welfare





But, autarky prevents severe depletion for some food exporters

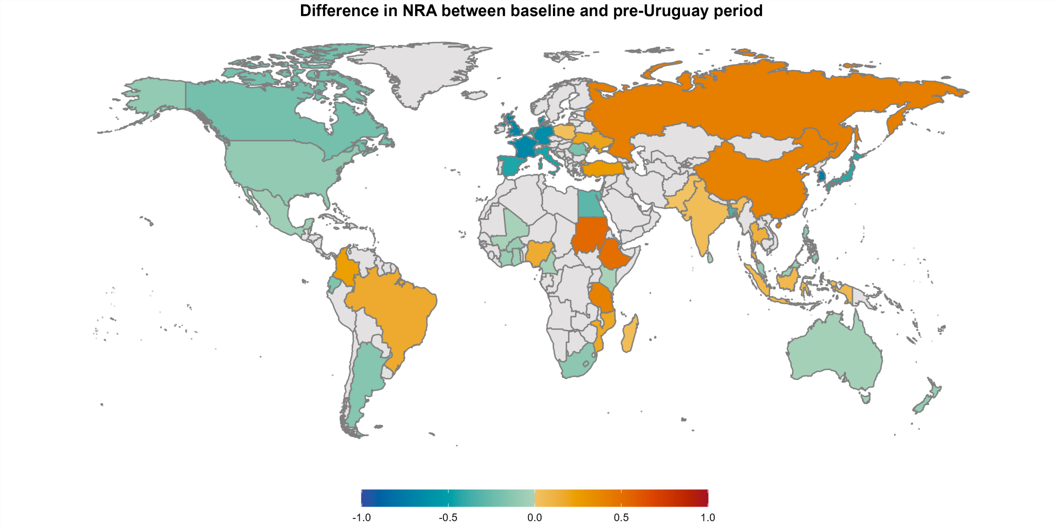


Alternative policy counterfactuals

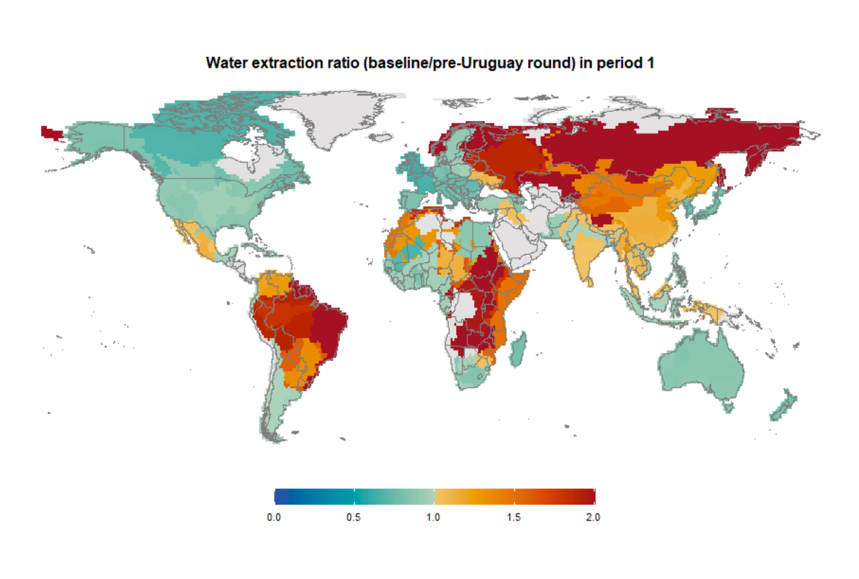
2. **1994 Uruguay Round of WTO Negotiations:** Largest global ag. liberalization
    - Prior trade agreements (GATT) largely excluded agriculture
    - "Tariffication" of non-tariff barriers to agricultural trade with maximum tariff rates imposed
    - *Implementation:* set $\tau_i^k = 1+$ avg. from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

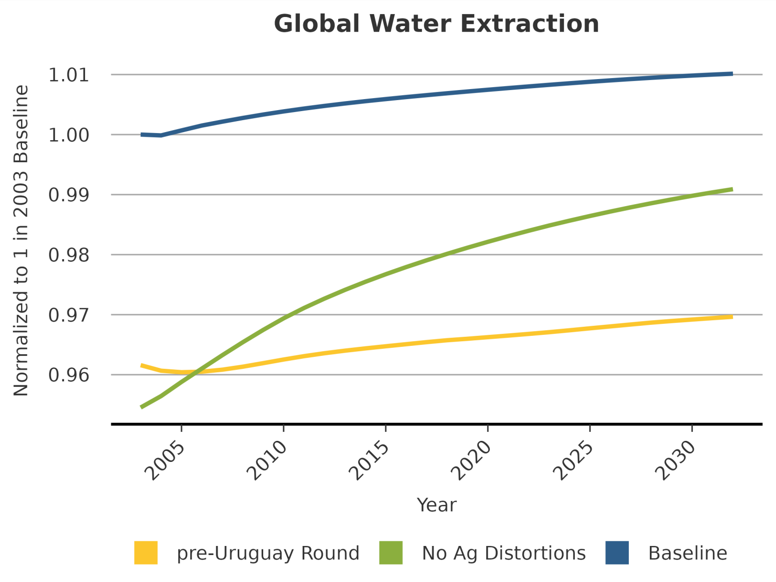
Uruguay Round lowered subsidies in the north, raised them in the south



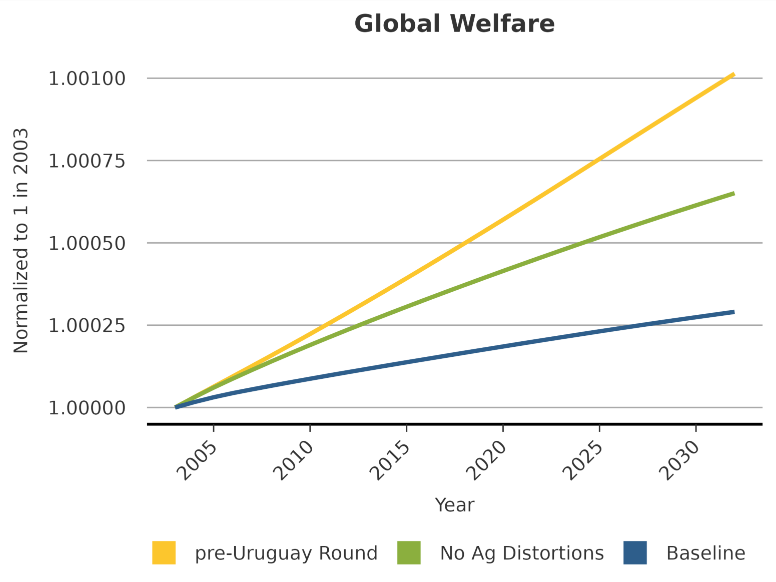
Uruguay Round increased water extraction in the south



Global water extraction falls under both counterfactual policies



Global welfare rises under both counterfactual policies



Conclusion

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 shows water-intensive production **highly concentrated** in water-abundant locations
- Preliminary model counterfactuals: 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 regions lose from trade

Thank you!

tcarleton@ucsb.edu

Appendix

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

Almonds

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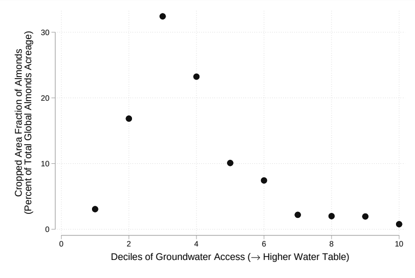
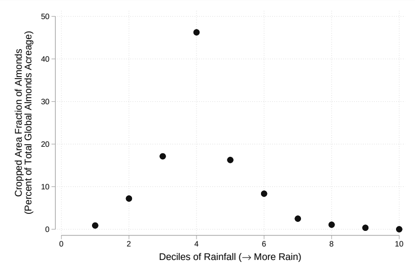
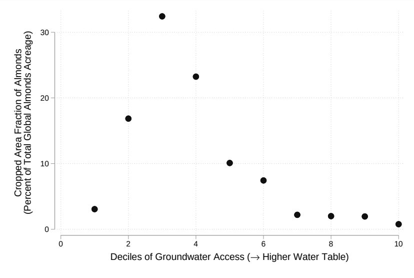
Almonds

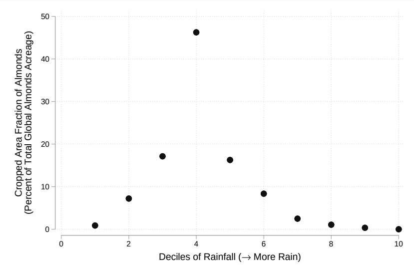




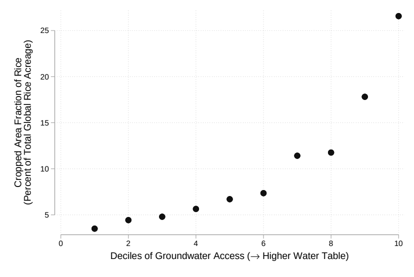
Fact 5: Water-intensive crops locate primarily in water-abundant regions . . .

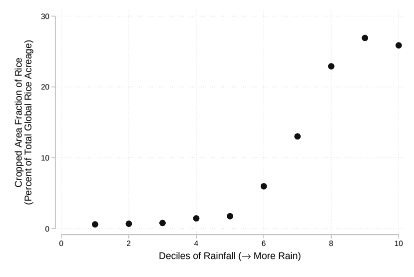
Almonds





Rice





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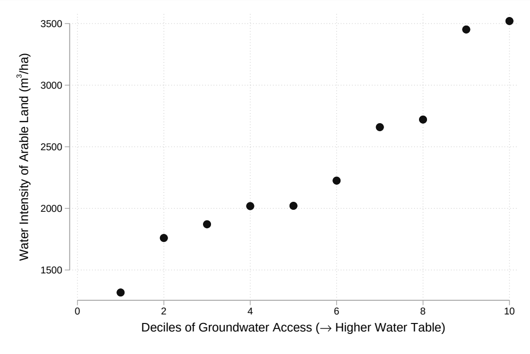
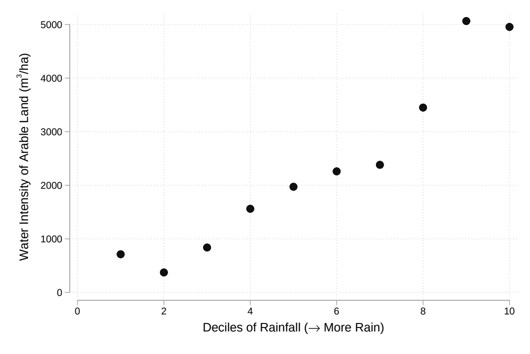
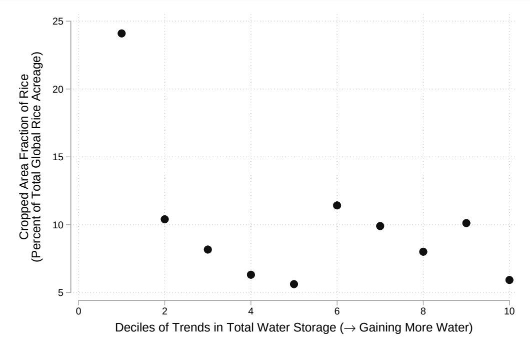




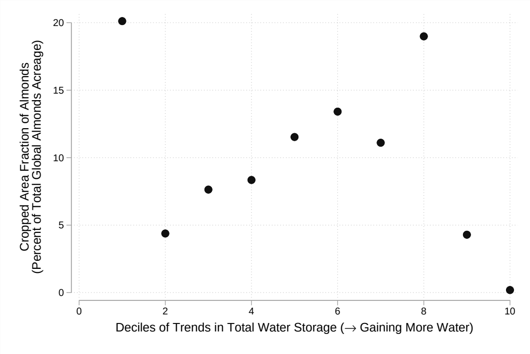
$$\text{Water Intensity of Arable Land } (\text{m}^3/\text{ha}) = \frac{\sum_{k \in \mathcal{K}} \text{hectares}^k \times \left(\frac{\text{water } (\text{m}^3)}{\text{hectare}}\right)^k}{\sum_{k \in \mathcal{K}} \text{hectares}^k + \text{pasture}}$$

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

Rice Acreage by Water Trends



Almond Acreage by Water Trends



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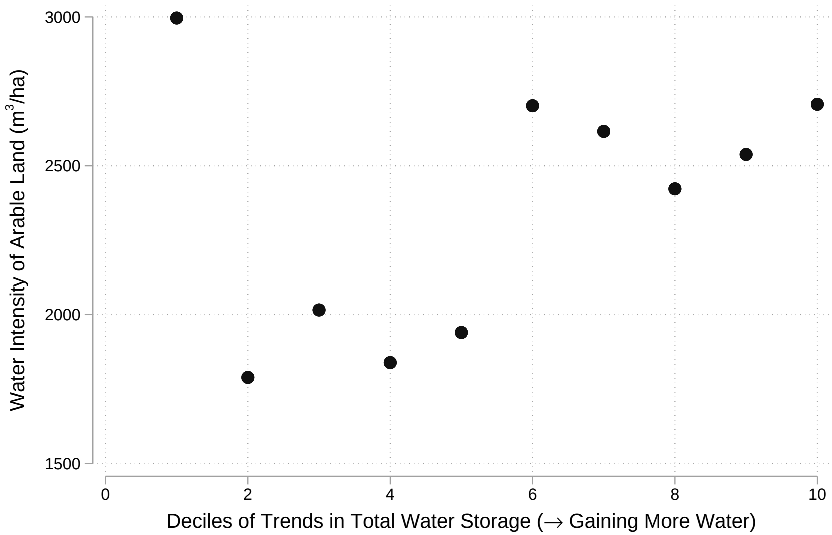
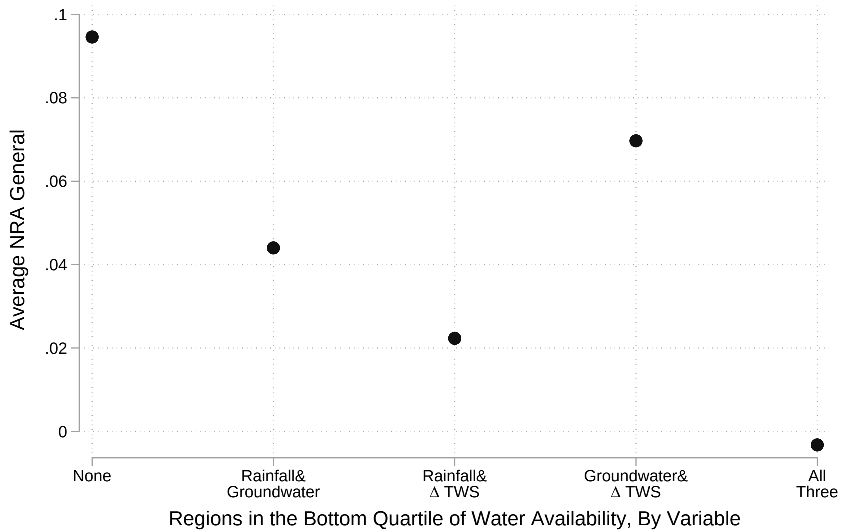


Fact 5: Similar patterns in water intensity and agricultural policy



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

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

Parameters to be calibrated/estimated

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☐	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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☑	α	labor share in crop production
☑	$\{\phi^k\}$	crop-specific water intensity
☐	θ	technological heterogeneity (Fréchet shape parameter)
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☐	$\{\Upsilon_q\}$	scale of extraction productivity $A_q^w(D) = \Upsilon_q D^{-\upsilon}$
☑	υ	elasticity of extraction productivity

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

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
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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

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
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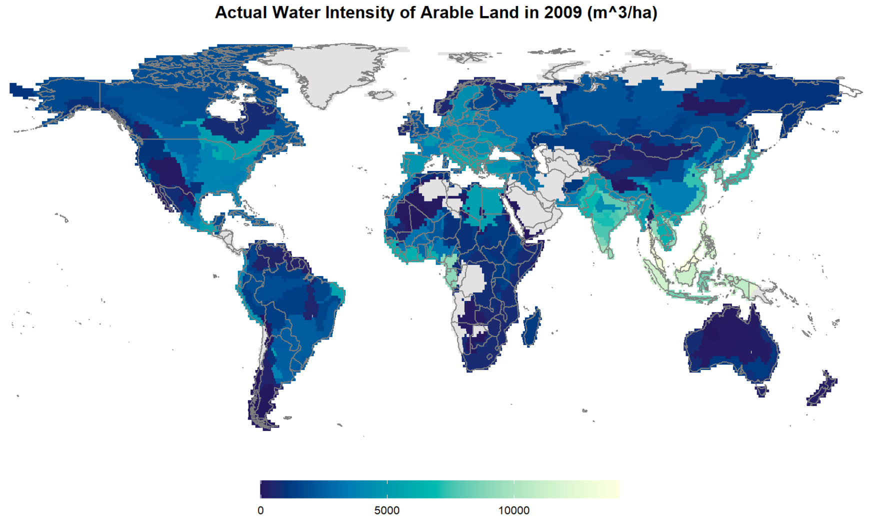
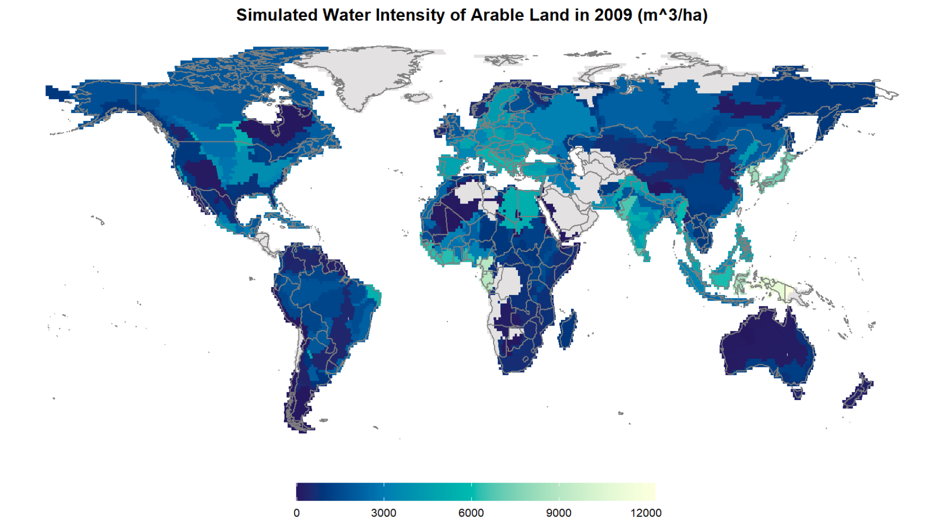
Model fit: Agricultural water extraction (Target)



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 ($A_q^w(D_{qt})$)

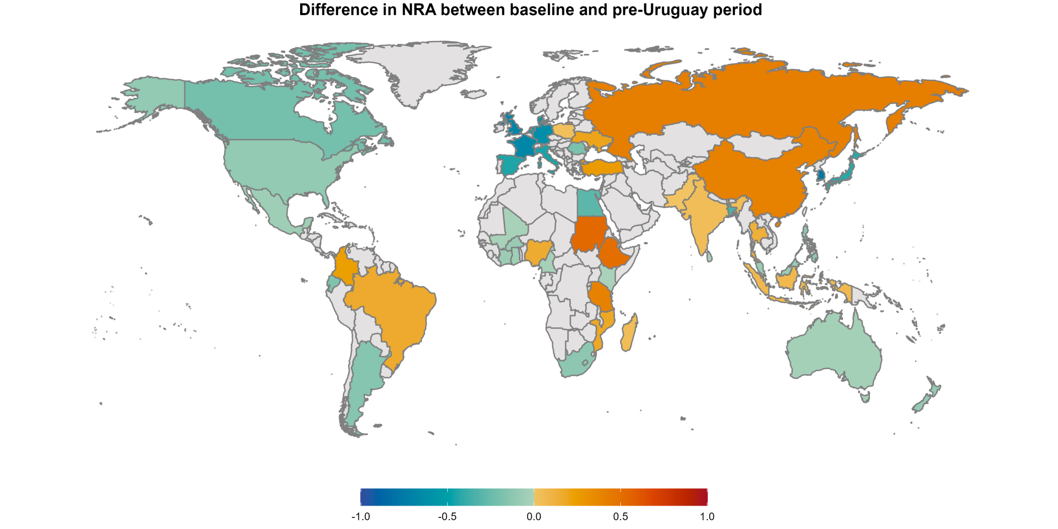
	Dependent Variable	
	log(Υ)	log($A_q^w(D_{qt})$)
Precipitation	0.64**	0.54*
	(0.25)	(0.28)
Precipitation^2	-0.11**	-0.08**
	(0.03)	(0.03)
Temperature	0.26***	0.17***
	(0.04)	(0.05)
Temperature^2	-0.004***	-0.003*
	(0.001)	(0.002)
Area irrigated (%)	0.10*	0.10*
	(0.05)	(0.05)
Nighttime luminosity	0.20***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

Alternative policy counterfactuals

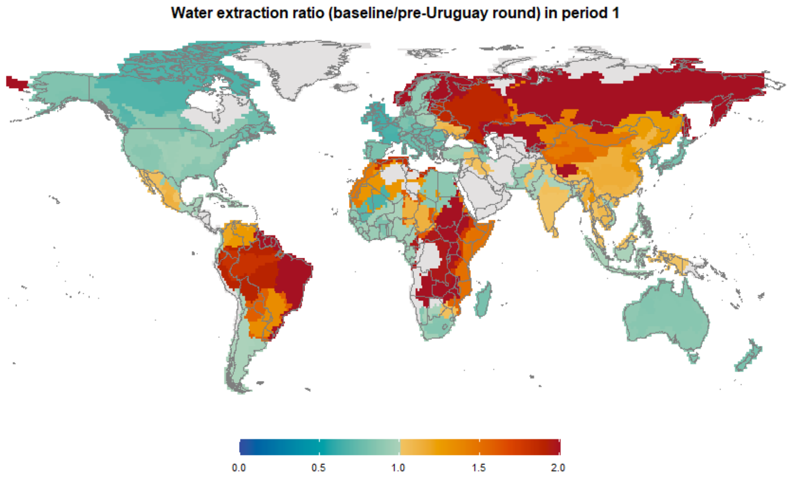
2. **1994 Uruguay Round of WTO Negotiations:** Largest global ag. liberalization
    - Prior trade agreements (GATT) largely excluded agriculture
    - "Tariffication" of non-tariff barriers to agricultural trade with maximum tariff rates imposed
    - *Implementation:* set $\tau_i^k = 1+$ avg. from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

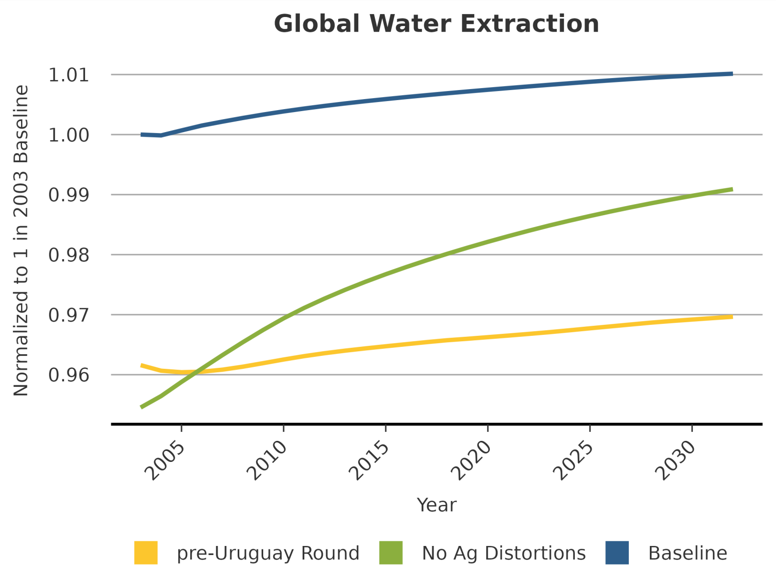
Uruguay Round lowered subsidies in the north, raised them in the south



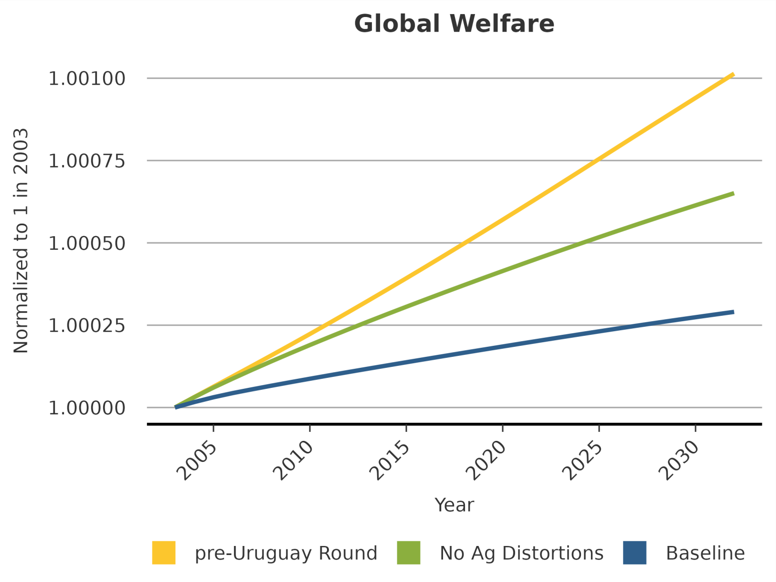
Uruguay Round increased water extraction in the south



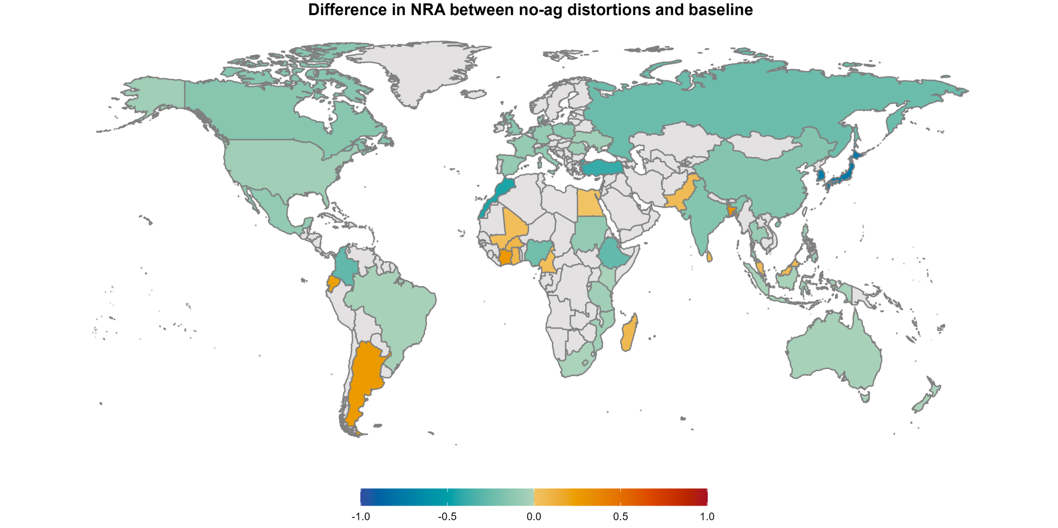
Global water extraction falls under both counterfactual policies



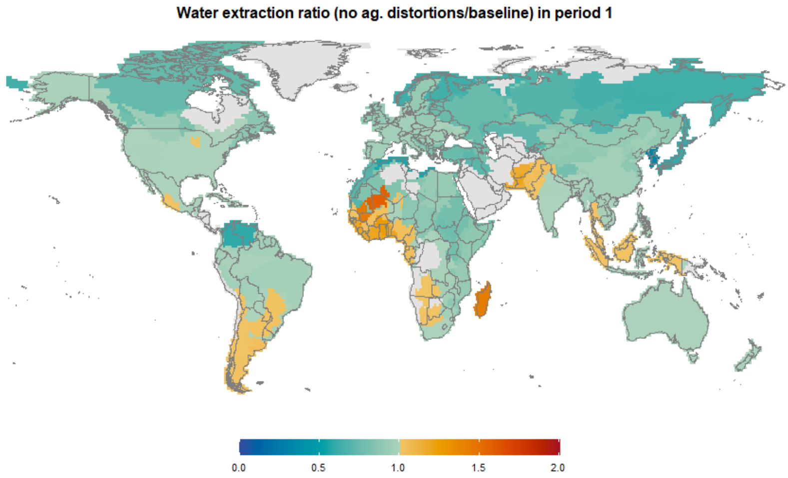
Global welfare rises under both counterfactual policies



Removing current distortions lowers subsidies to ag. nearly everywhere



Removing current distortions lowers water extraction nearly everywhere



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