

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

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Any views expressed in this paper do not necessarily represent those of the Federal Reserve System or its Staff.

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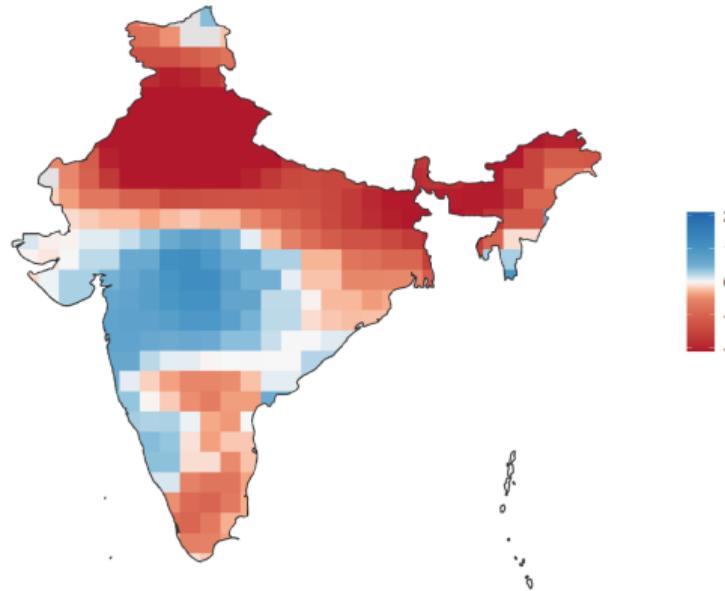
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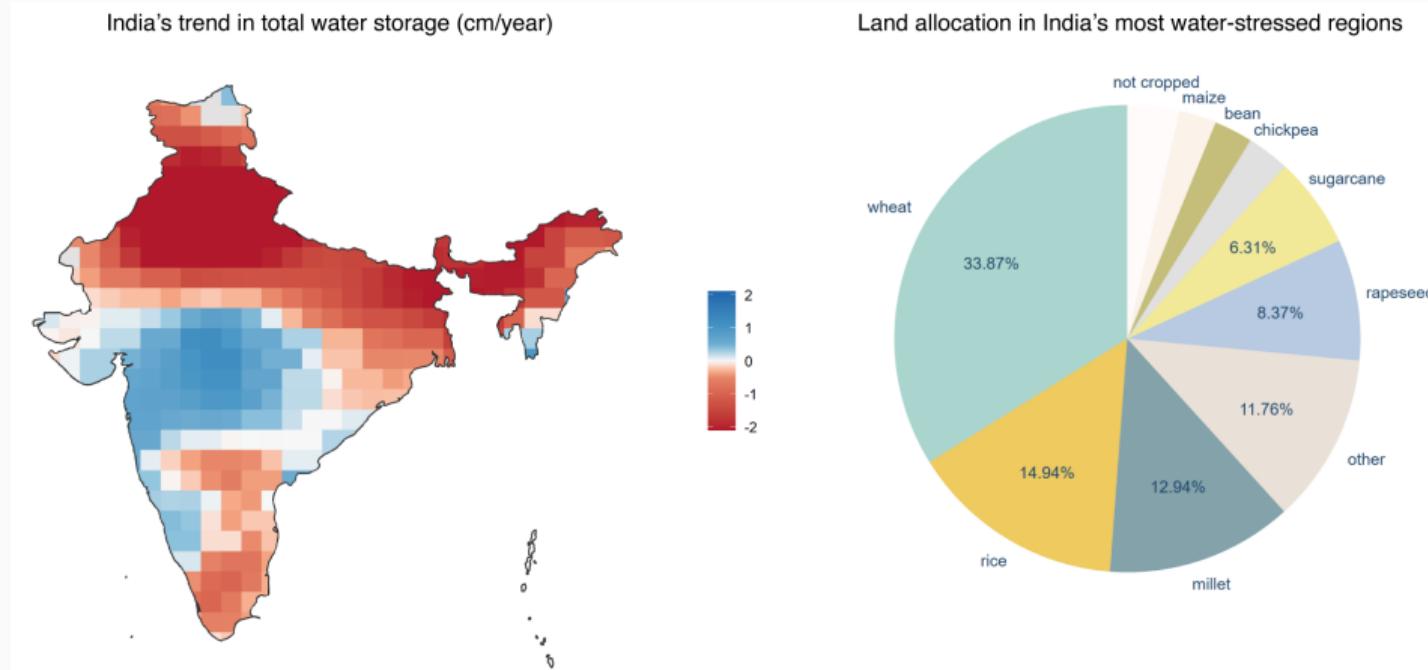
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- **~12 liters of water used to grow one almond**

Water-intensive production in water-scarce regions

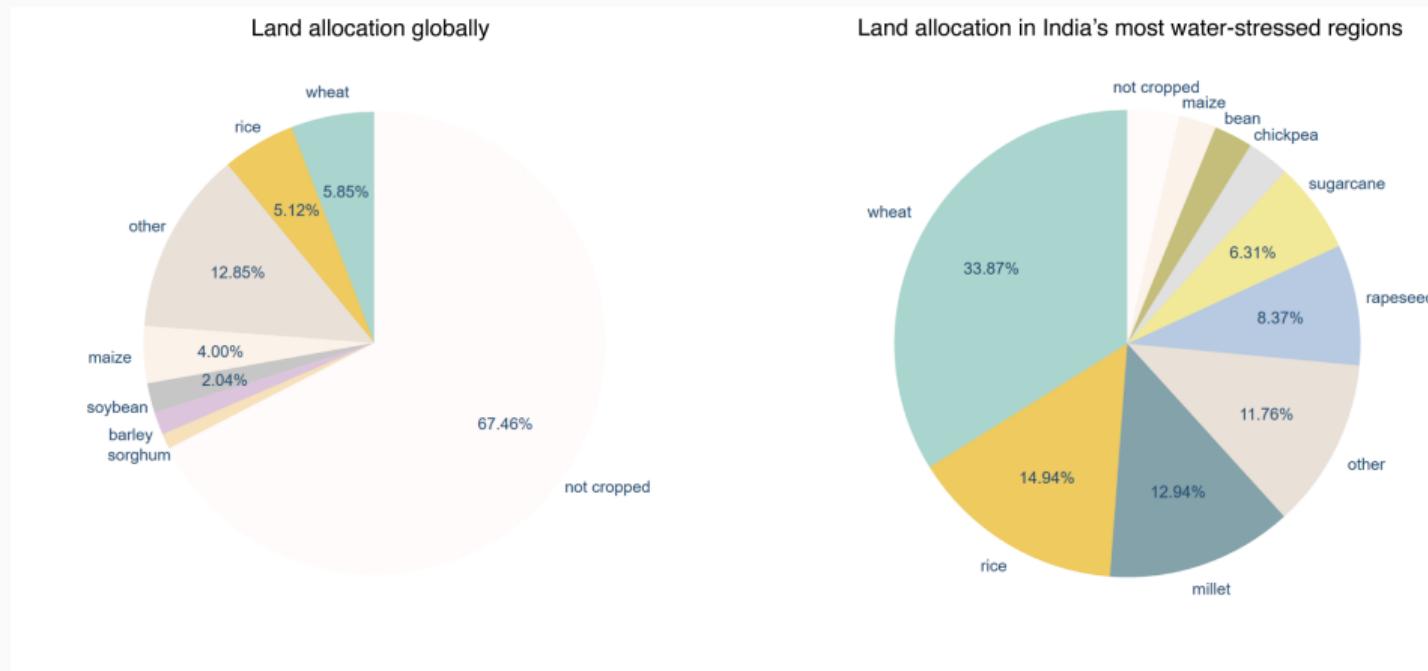
India's trend in total water storage (cm/year)



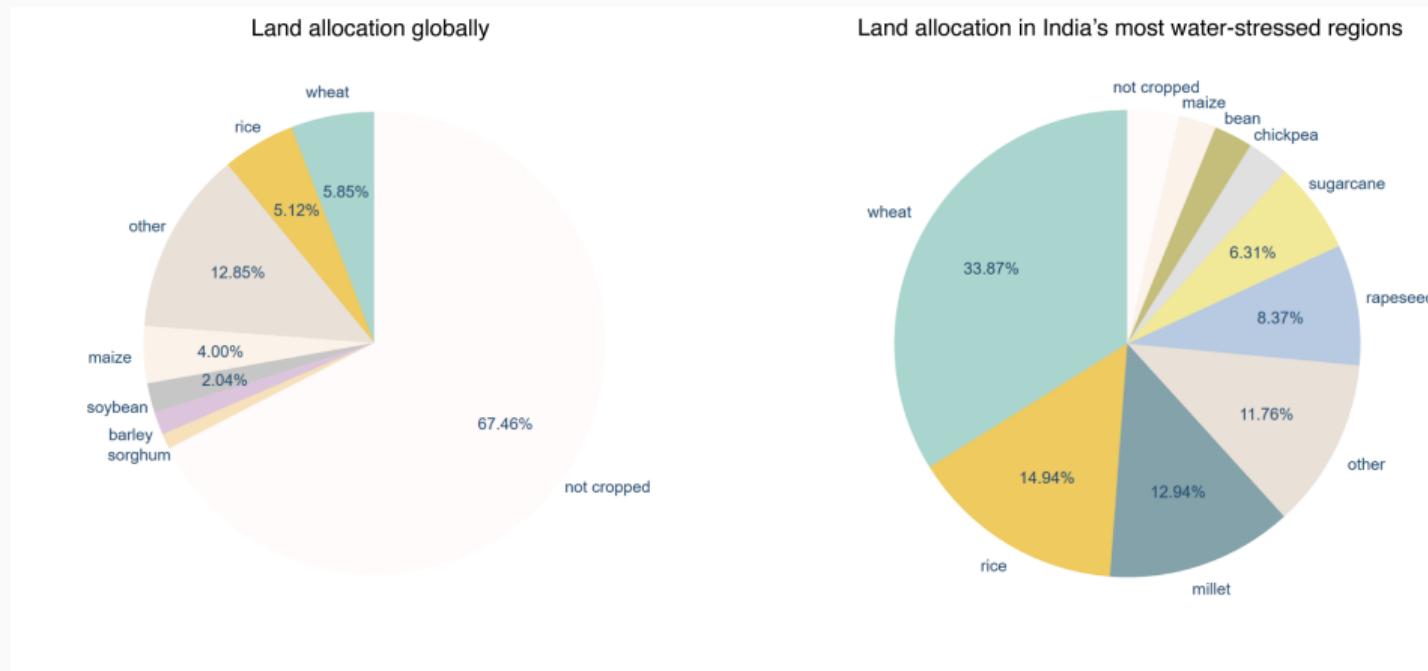
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Water-intensive production in water-scarce regions



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

Crop trade depletes global groundwater

Published online 6 April 2017

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

Nadia El-Awady

ENVIRONMENTAL RESEARCH LETTERS

LETTER • OPEN ACCESS

Global unsustainable virtual water flows in agricultural trade

Lorenzo Rosa¹ , Davide Danilo Chiarelli² , Chengyi Tu^{1,3}, Maria Cristina Rulli²  and Paolo D'Odorico¹ 

Published 22 October 2019 • © 2019 The Author(s). Published by

[Environmental Research Letters](#), Volume 14, Number 11

LETTER



News & Events  Multimedia

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

"The globalization of water through trade contributes to running rivers dry, an environmental externality commonly overlooked by trade policies"

--Rosa et al. (2019)

doi:10.1038/nature21403

700 | NATURE | VOL 543 | 30 MARCH 2017

Groundwater depletion embedded in international food trade

Carole Dalin¹, Yoshihide Wada^{2,3,4,5}, Thomas Kastner^{6,7} & Michael J. Puma^{3,4,8}

Research question

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:
 - 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
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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 → ag./trade spatial allocation ↔ long-run regional water availability

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

Preview of results

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

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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

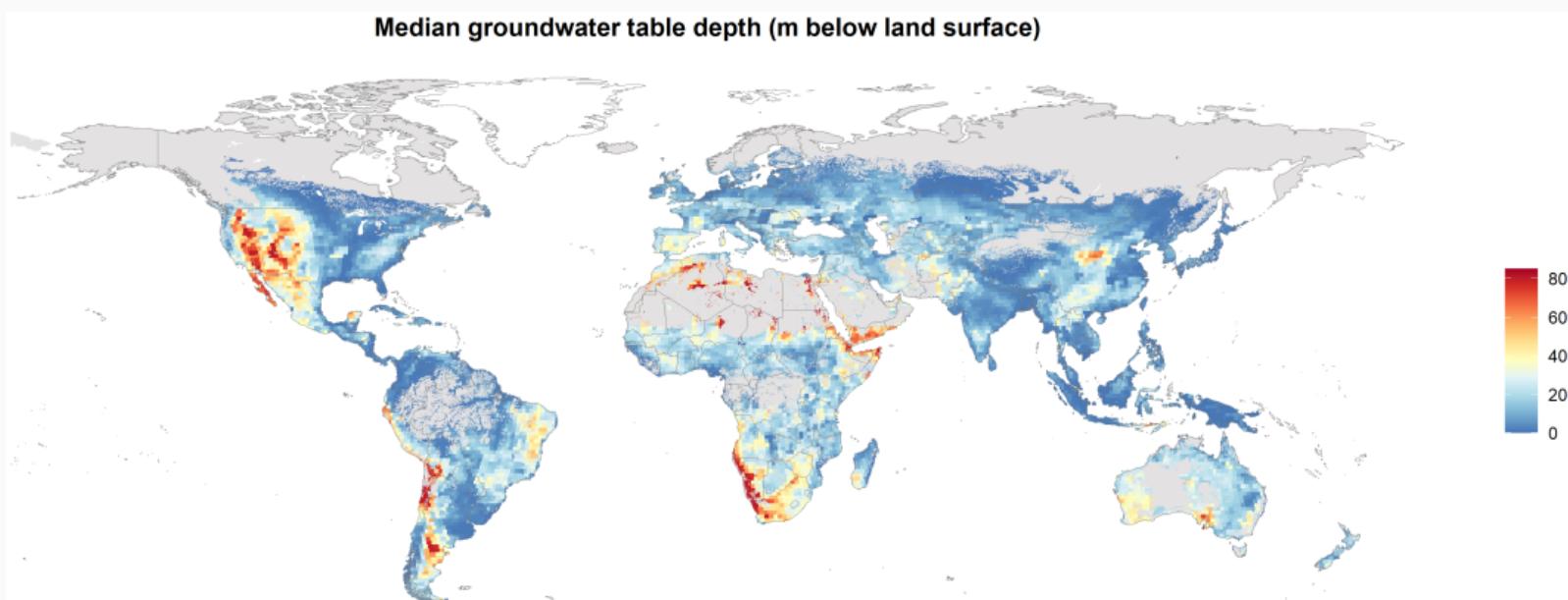
- Copeland, Shapiro, and Taylor (2022) review literature on globalization and the environment, but **little work on natural resources** [*lately*: Farrokhi et al. (2023)]
- Anderson, Rausser, and Swinnen (2013) review literature on ag. policy distortions, but **no investigation of environmental effects** [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**: $\Delta\text{Depth}_{qt} = \rho_q(\text{Consume}_{qt} - \text{Recharge}_{qt})$ given Depth_{q0}

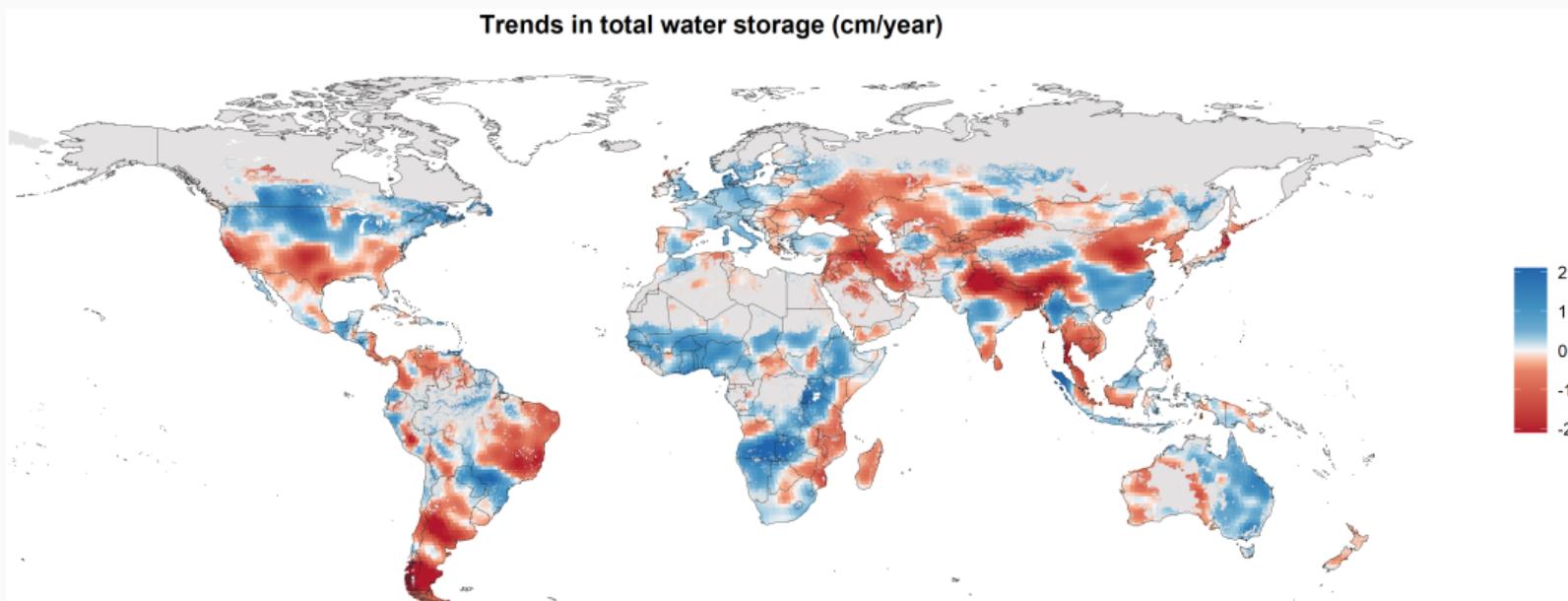
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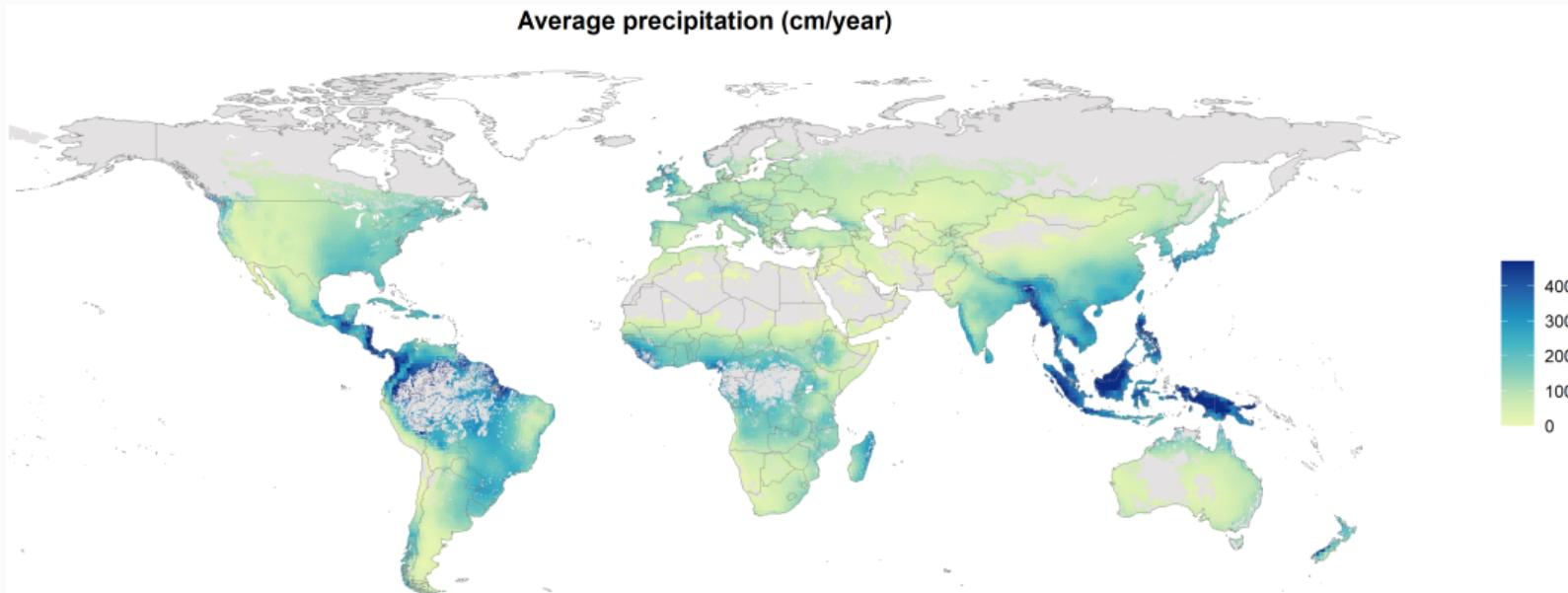
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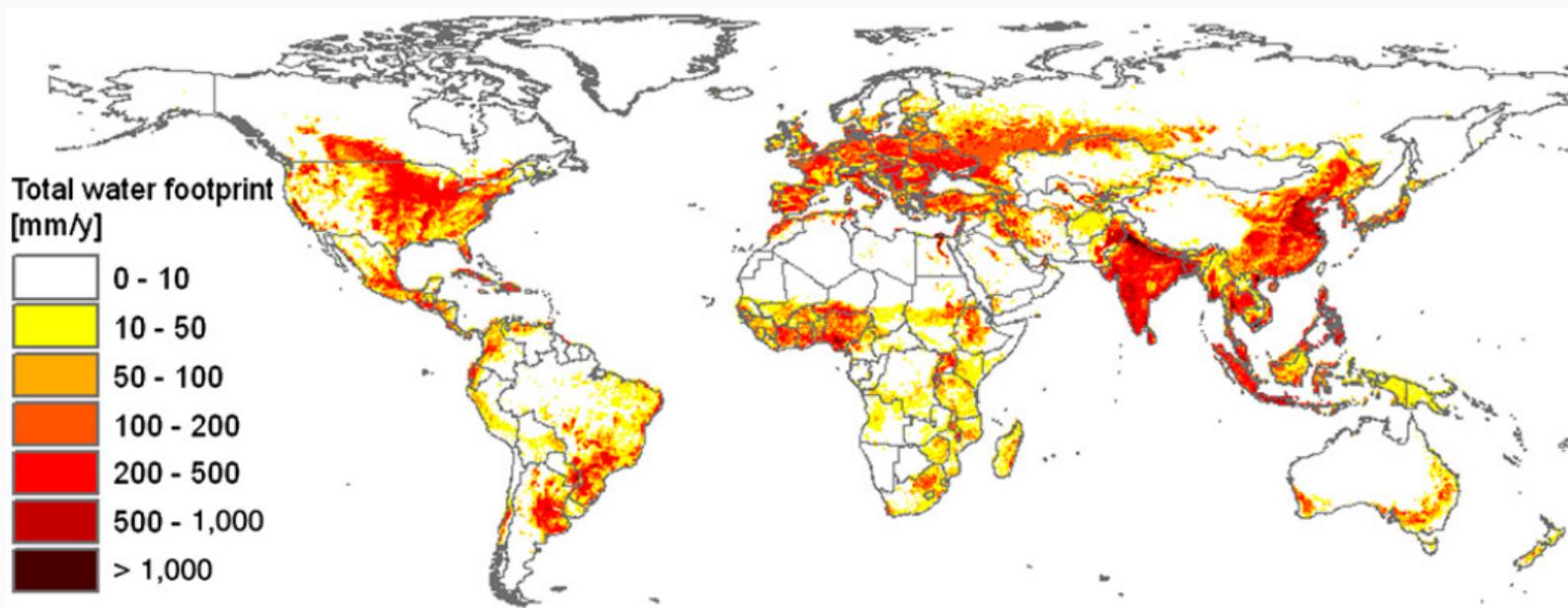
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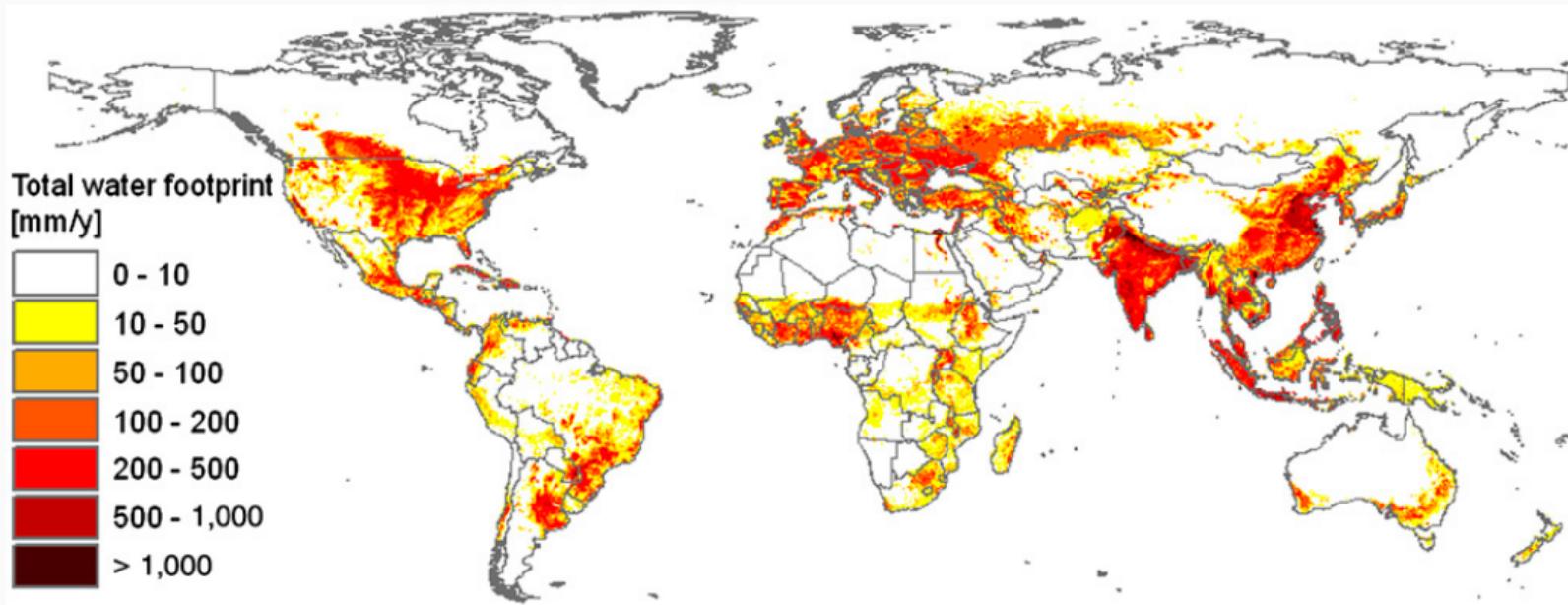
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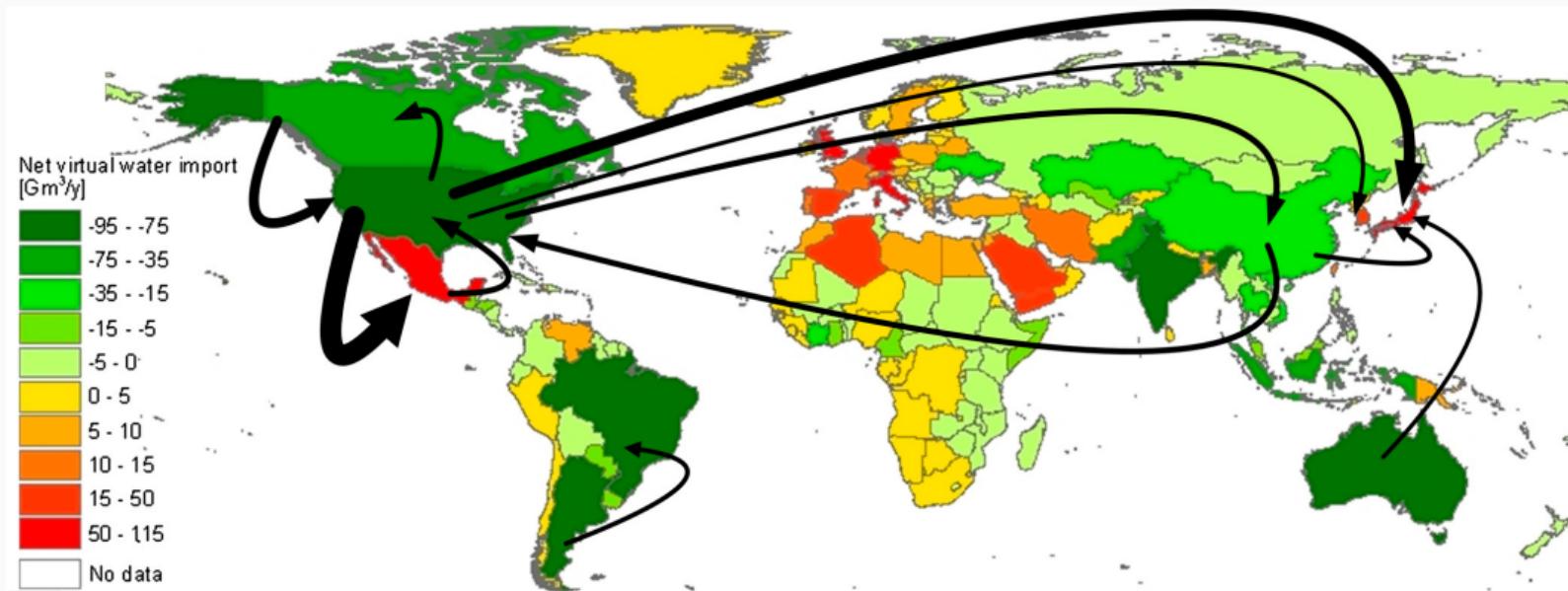
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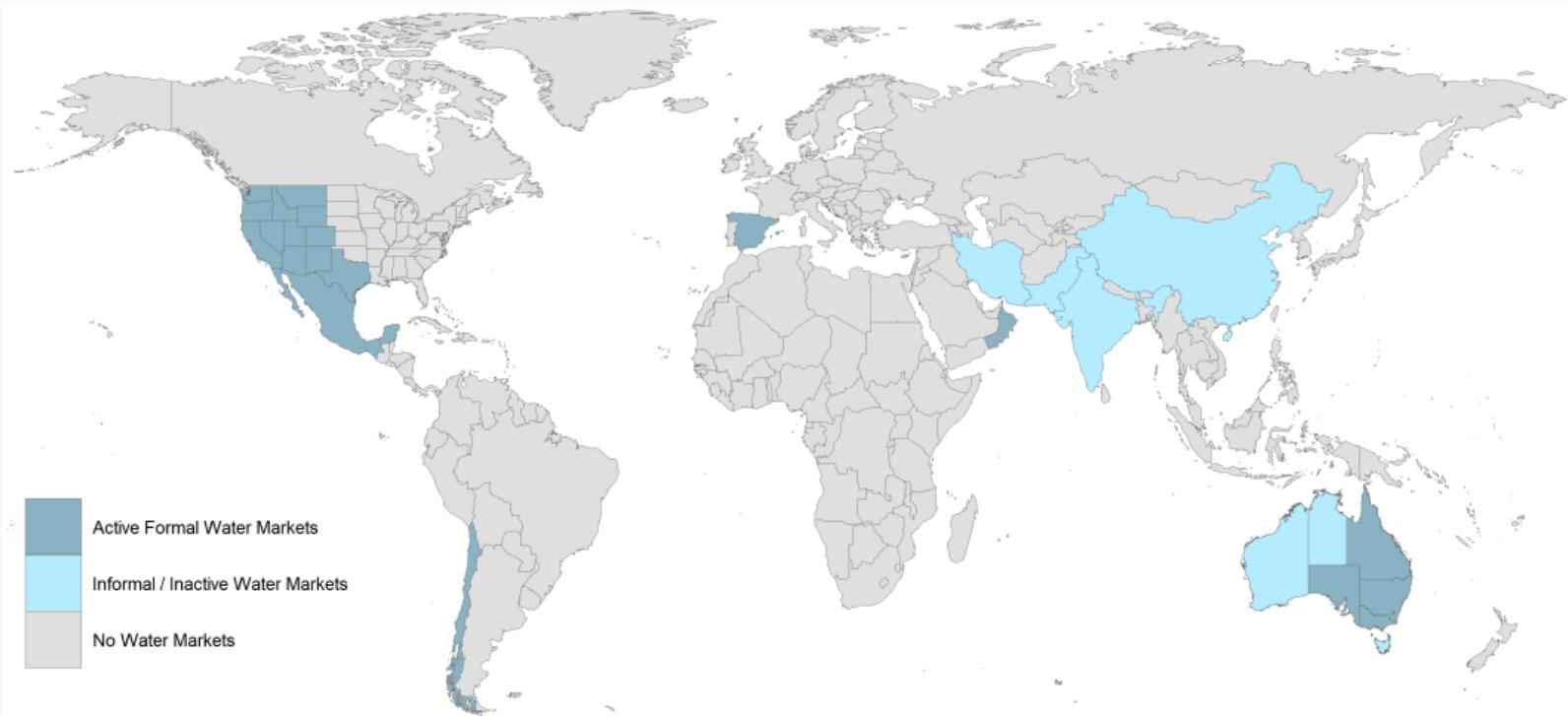
It's all about agriculture: $\sum_q \text{Consume}_{qt} \approx 90\%$ agricultural input use

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



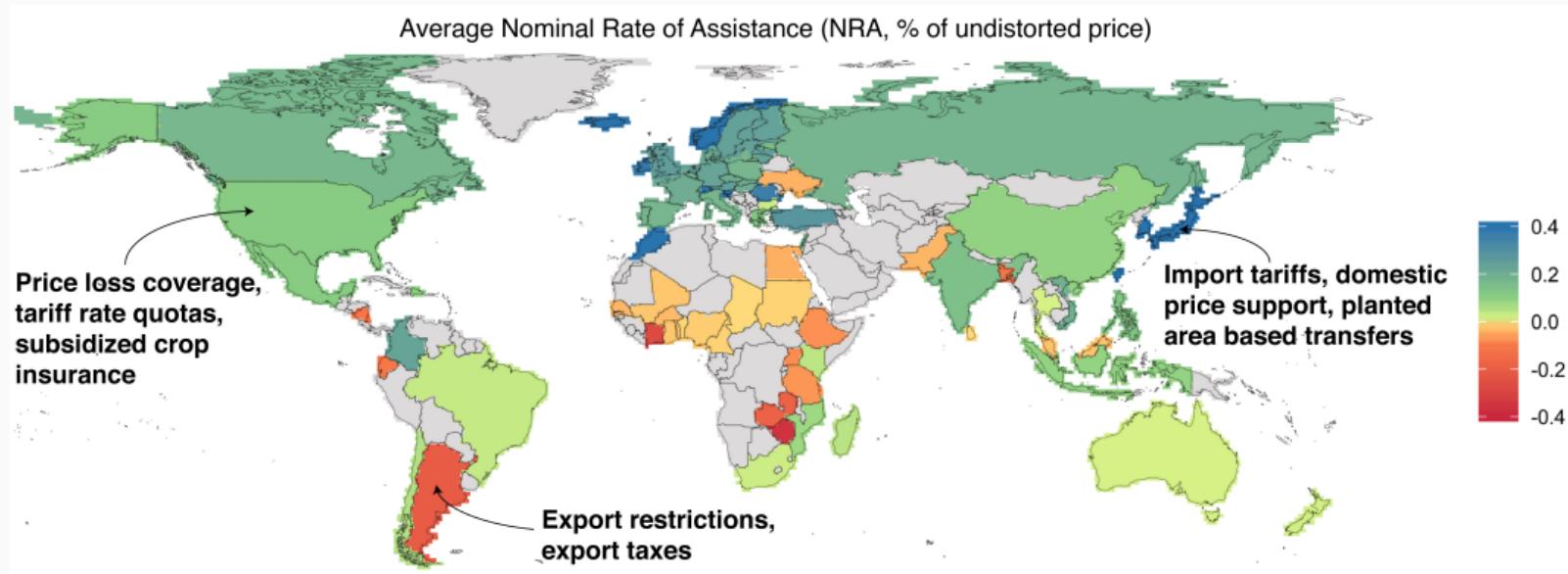
Ag. **trade** embeds **20–25%** of $\sum_q \text{Consume}_{qt}$ (Hoekstra and Mekonnen, 2012; Carr et al., 2013)

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

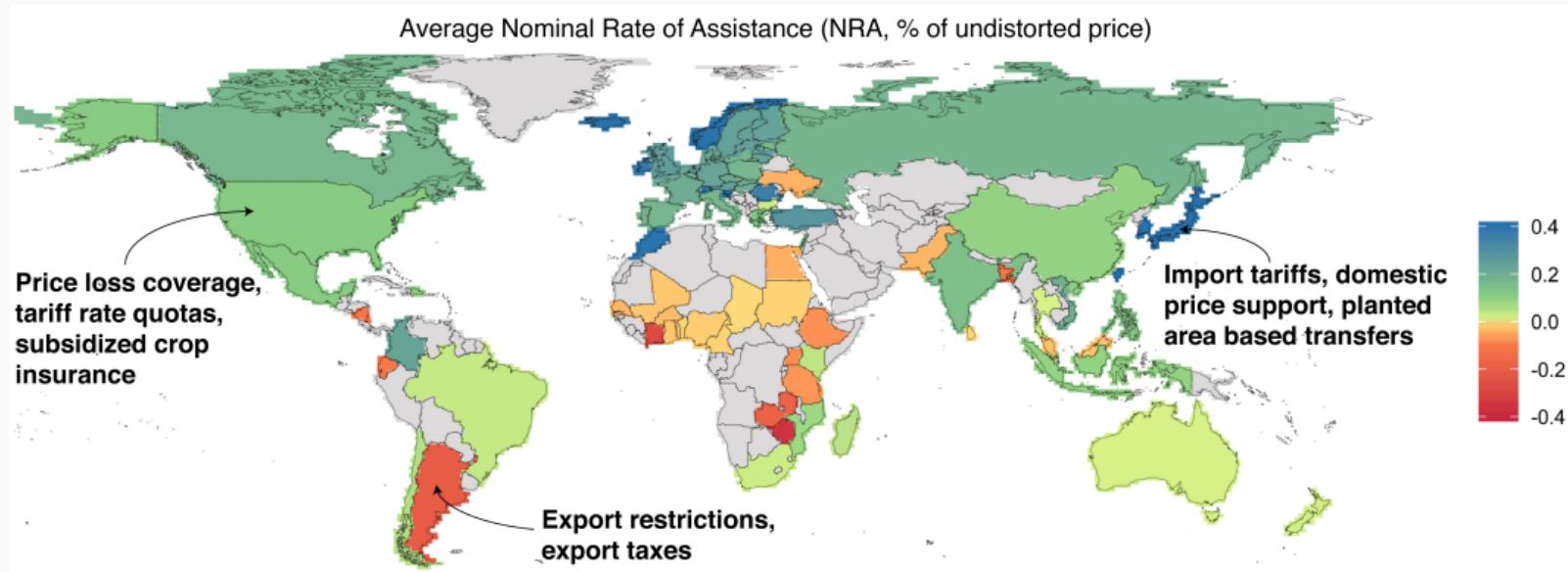


>93% of global agricultural production occurs in regions with no formal water markets

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

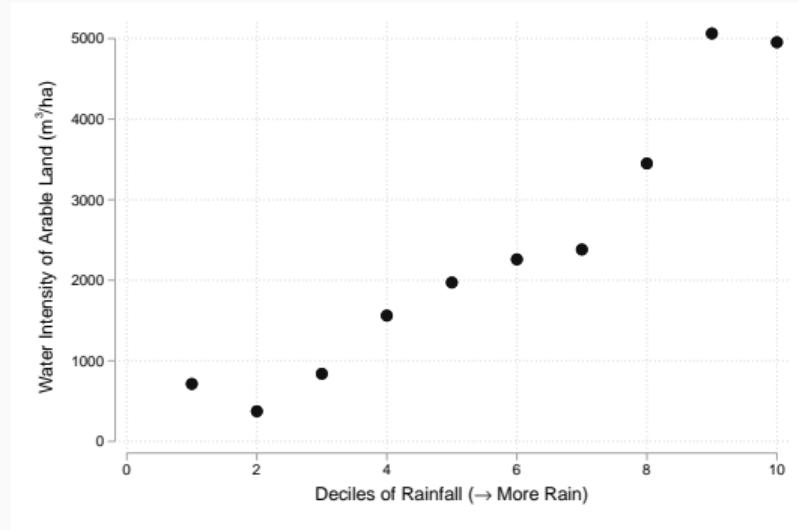
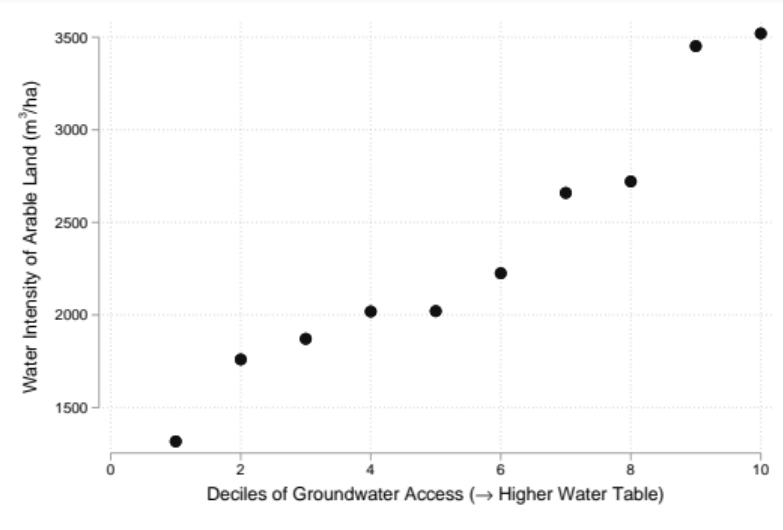


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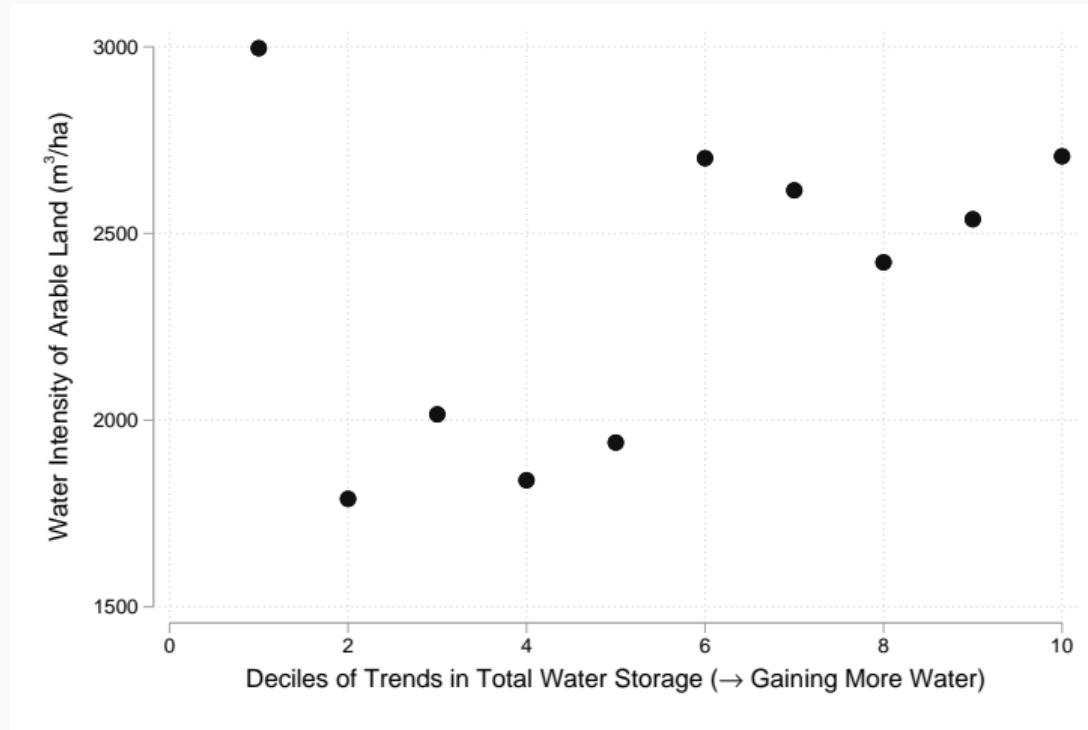
10pp inc. in net ag. subsidy → ΔDepth_{qt} from 50th to 75th pctl (Carleton, 2021)

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

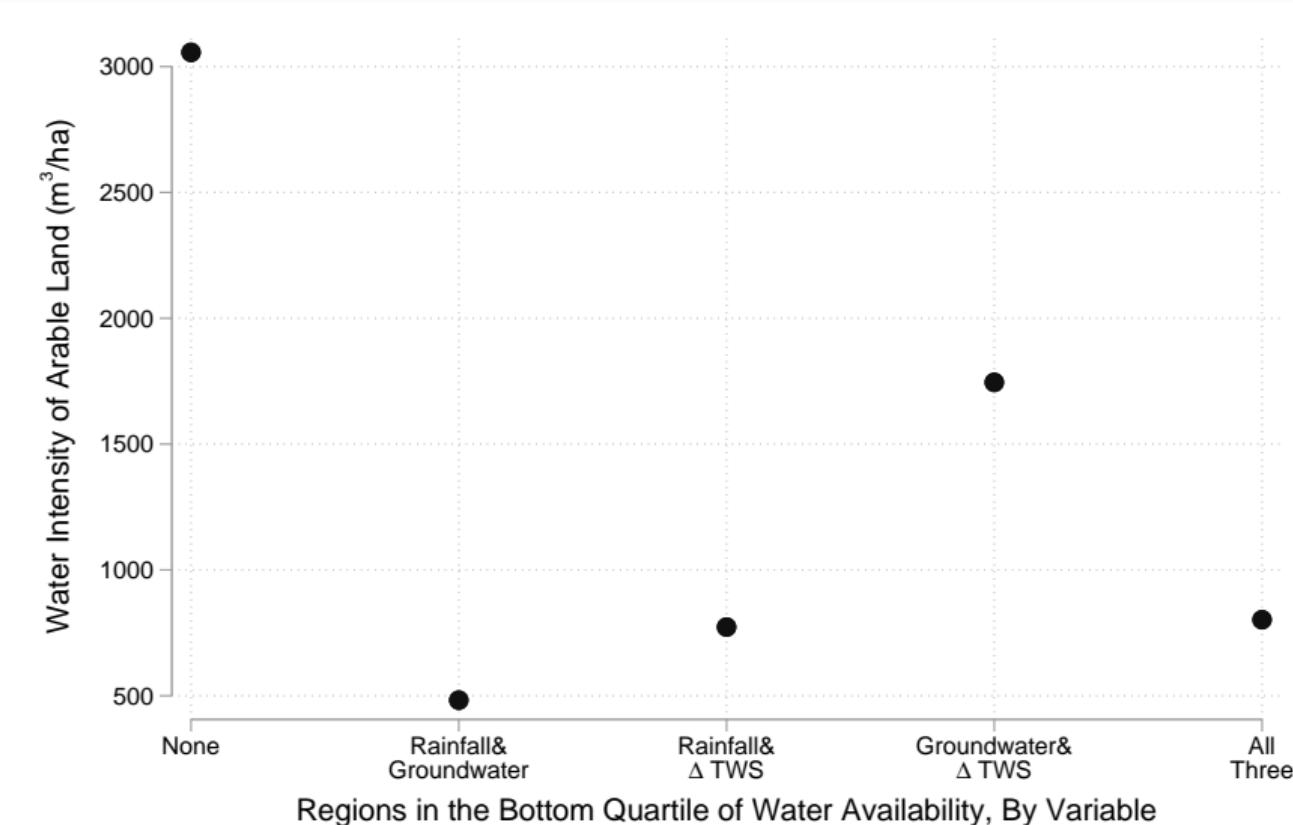


$$\text{Water Intensity of Arable Land (m}^3/\text{ha}) = \frac{\sum_{k \in \mathcal{K}} \text{hectares}^k \times \left(\frac{\text{water (m}^3)}{\text{hectare}} \right)^k}{\sum_{k \in \mathcal{K}} \text{hectares}^k + \text{pasture}}$$

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



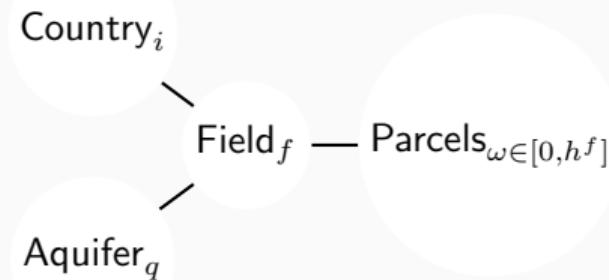
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Model

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:

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

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 $A_q^w(D) = \Upsilon_q D^{-v}$.

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

$$\max_H Q_t^{fk}(\omega) = \mathbf{A}^{fk}(\omega) \mathbf{M}(\phi^k, \mathbf{D}_{qt})$$

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 :

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

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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

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

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

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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, $\{C_{jxit}^k\}$, 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:

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

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

- depths obey their law of motion.

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

Quantification

Data

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

- Field-level (f): from **GAEZ** and **SAGE** at 5-arc minute level ($\sim 1.9\text{mil grid cells}$)
 - 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
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- α non-land share in crop production
 - $\{\phi^k\}$ crop-specific water intensity
 - θ technological heterogeneity
 - $\{A_i^o\}$ mean labor prod. in outside sector
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- ψ return flow rate
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estimated: follow **CDS (2016)**



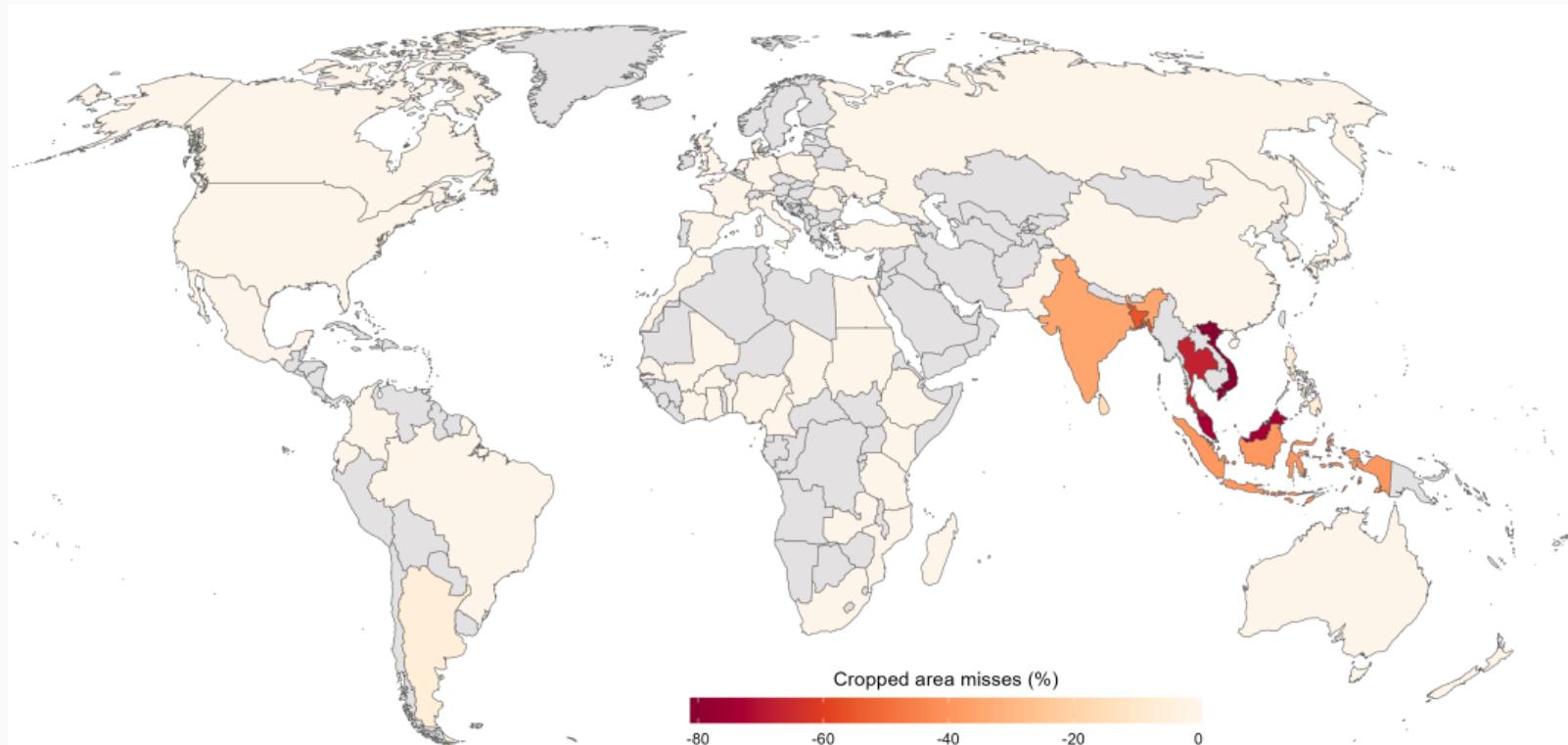
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<input checked="" type="checkbox"/>	$\{\rho_q\}$	specific yield
<input checked="" type="checkbox"/>	$\{R_q\}$	natural recharge
<input checked="" type="checkbox"/>	$\{\Upsilon_q\}$	scale of extraction productivity
<input checked="" type="checkbox"/>	v	elasticity of extraction productivity

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



Model fit: Cropped area



Counterfactuals

Menu of counterfactuals

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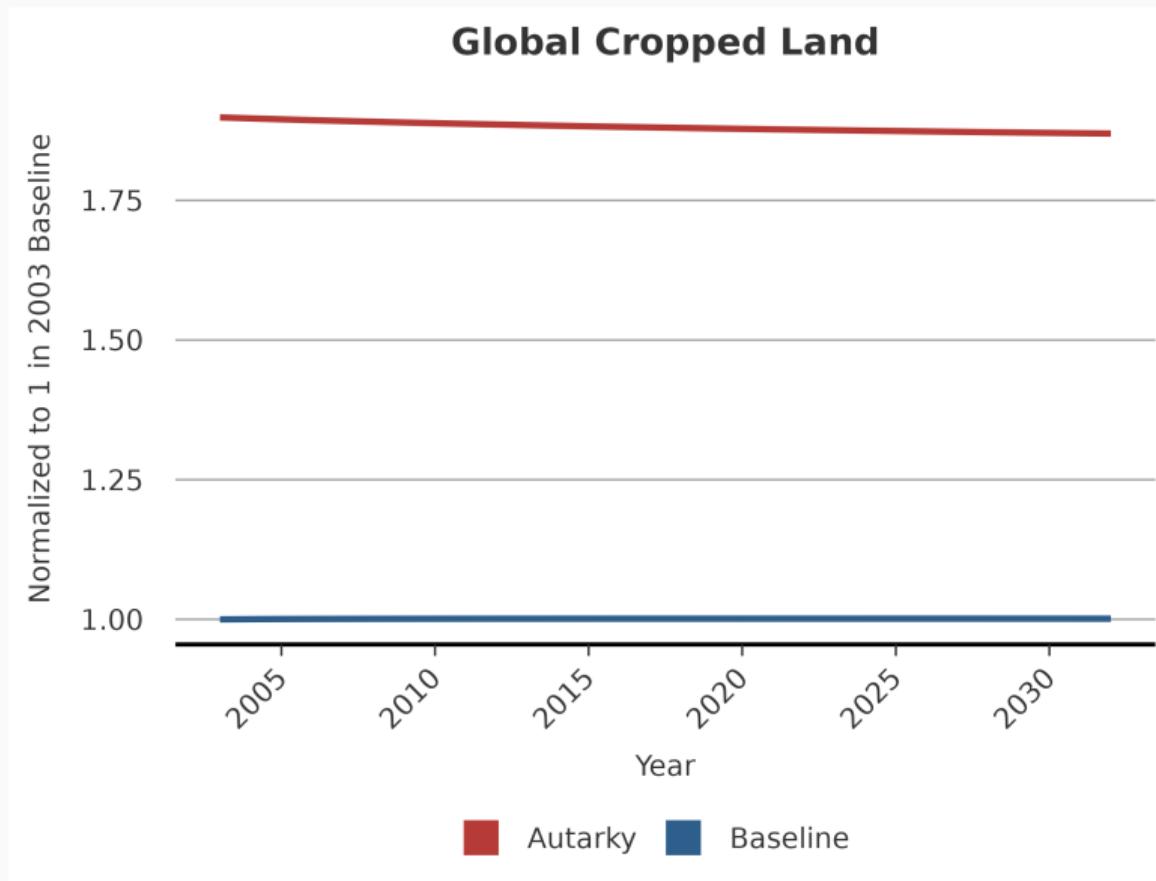
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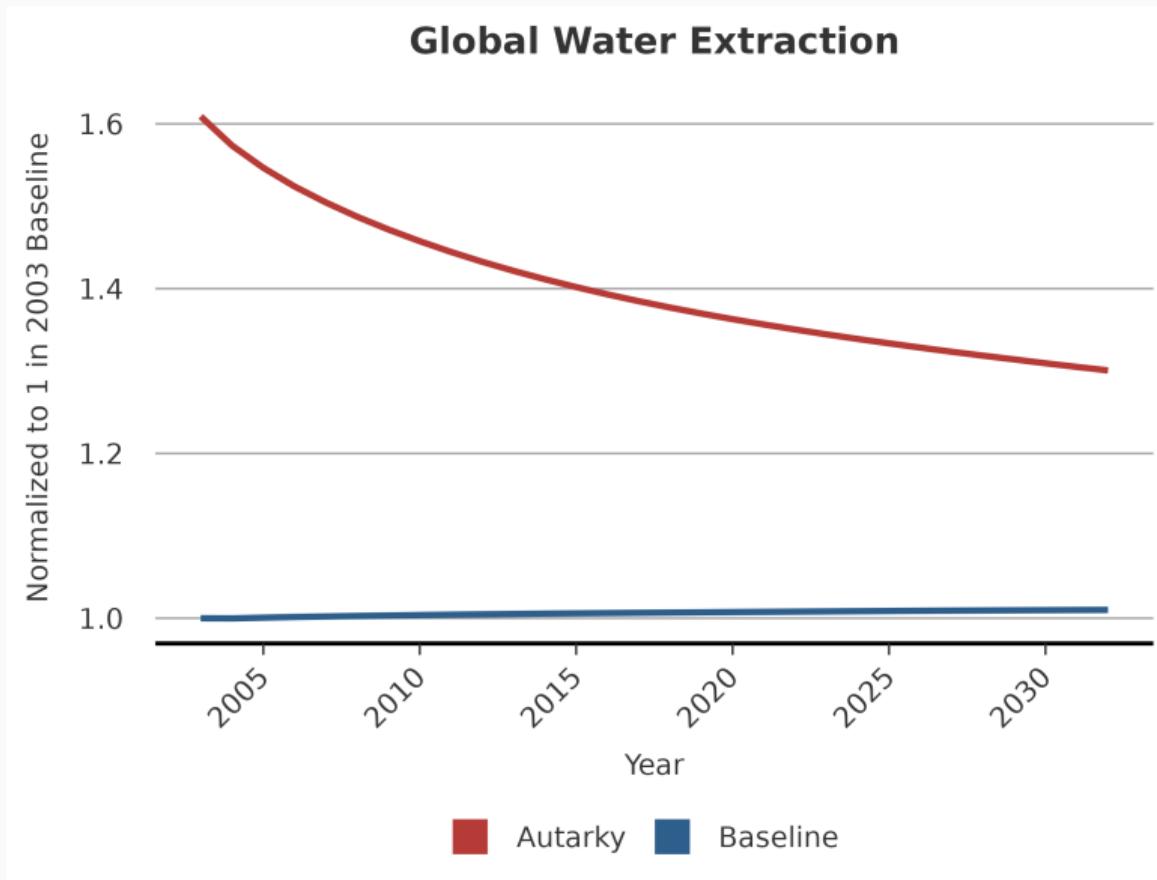
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4. **Unilateral country policy changes**—e.g. rice export ban in India, EU import restrictions from certain countries, etc.

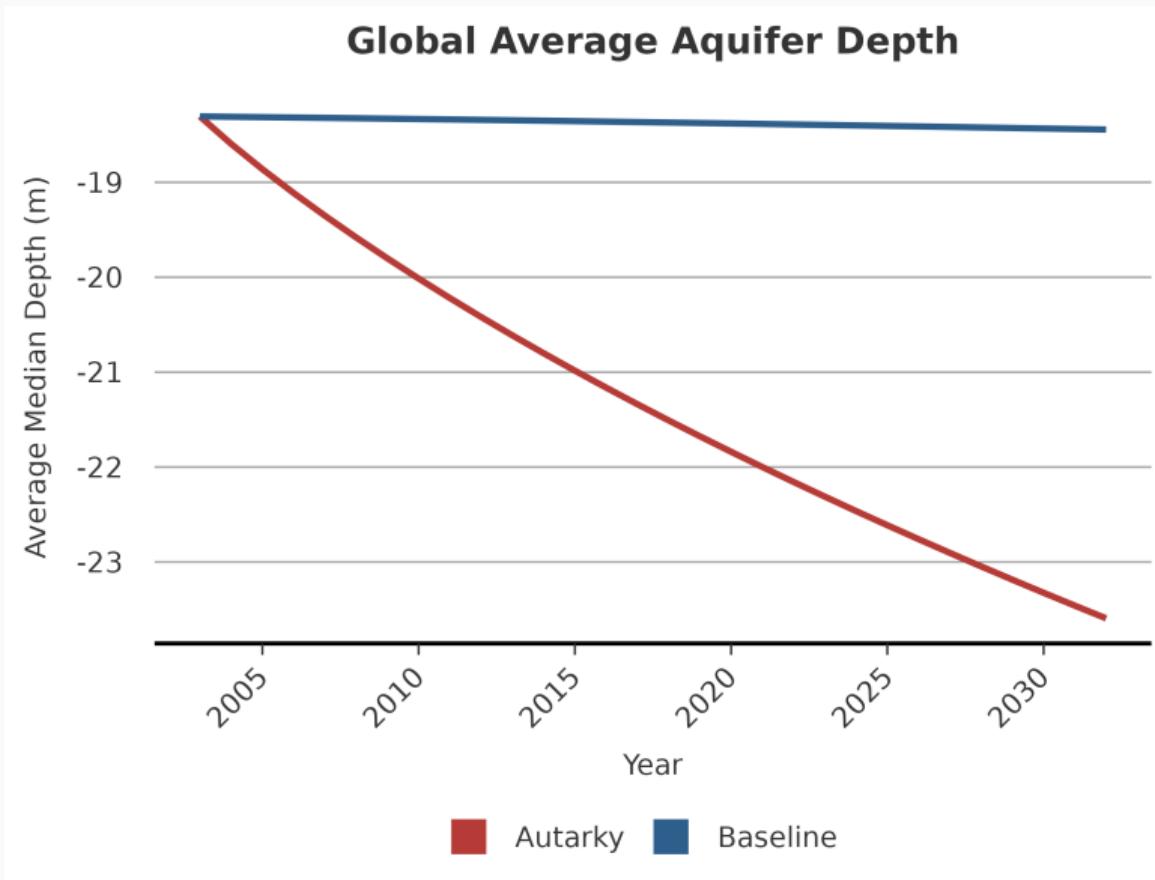
Global cropped area more than doubles in autarky



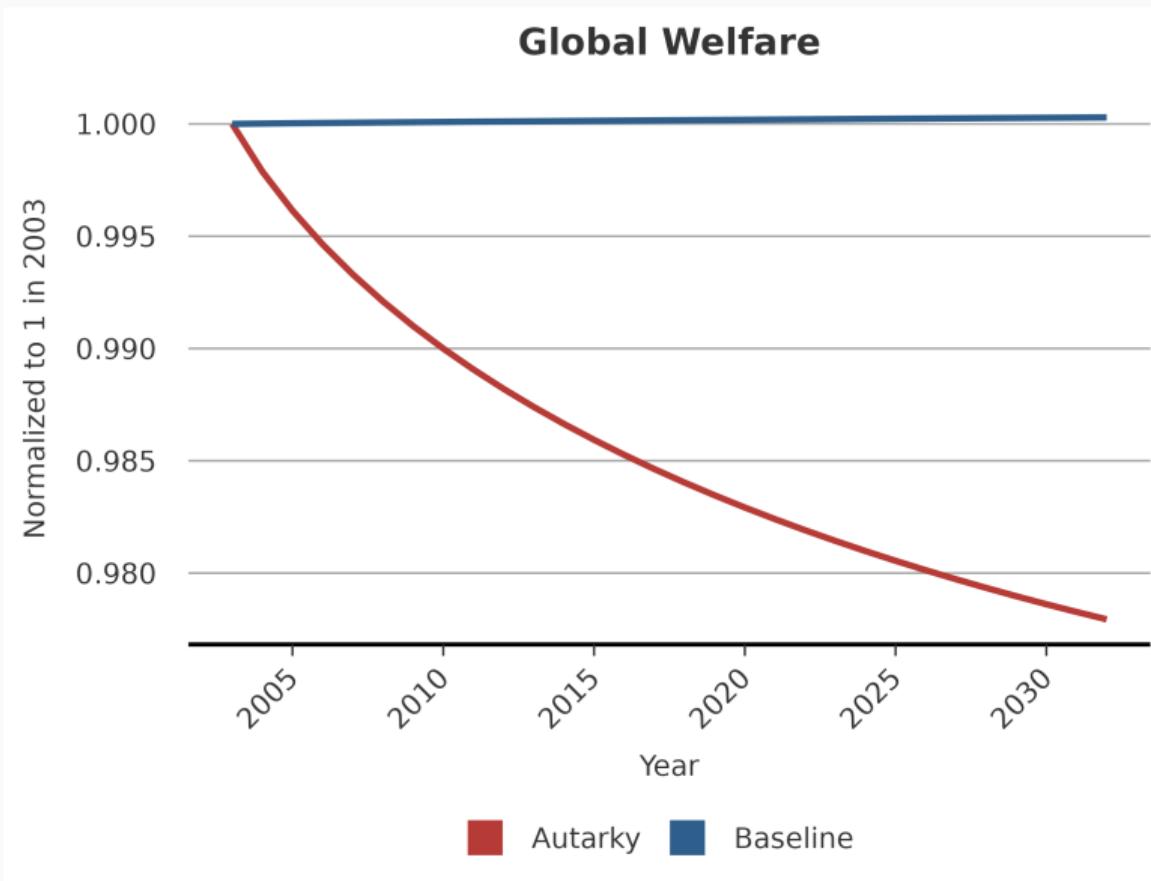
Total global water use much higher in autarky



Allowing trade prevents global aquifer depletion

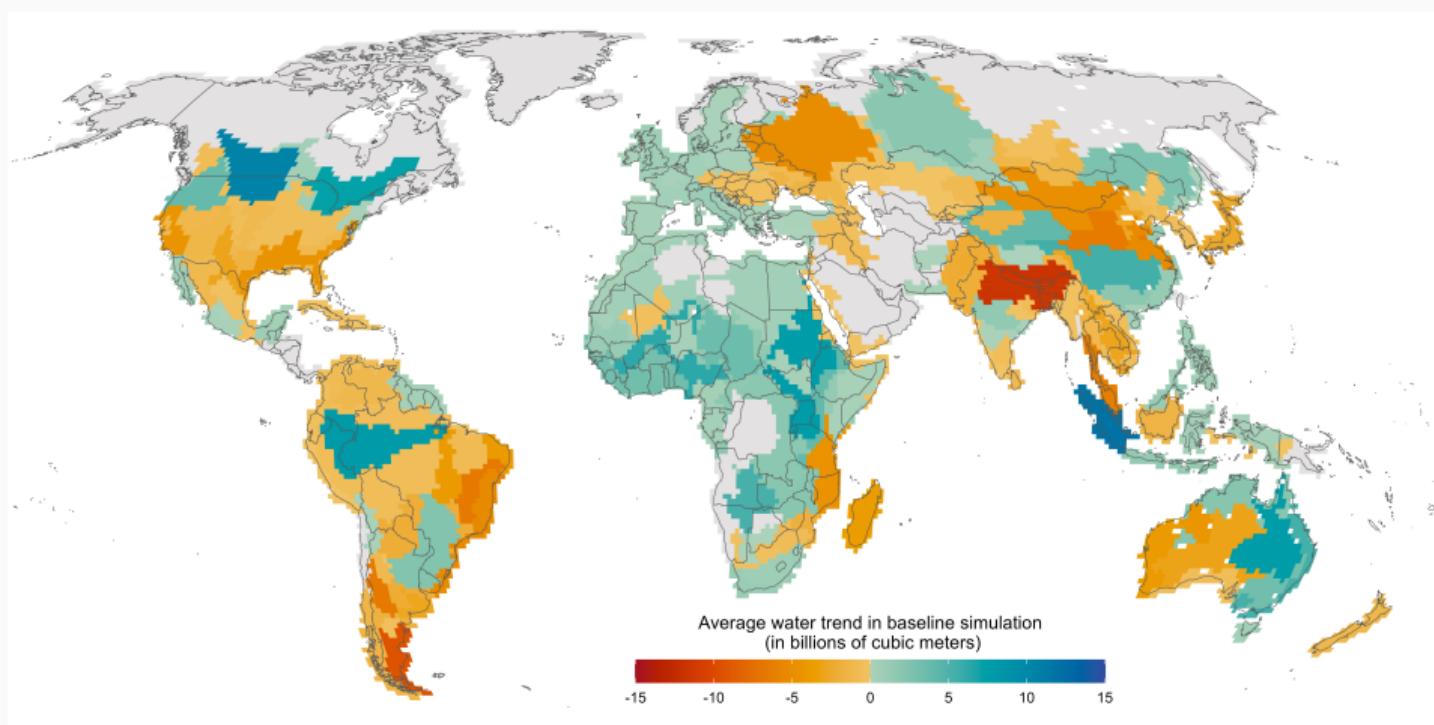


Welfare declines over time in autarky as aquifers deplete



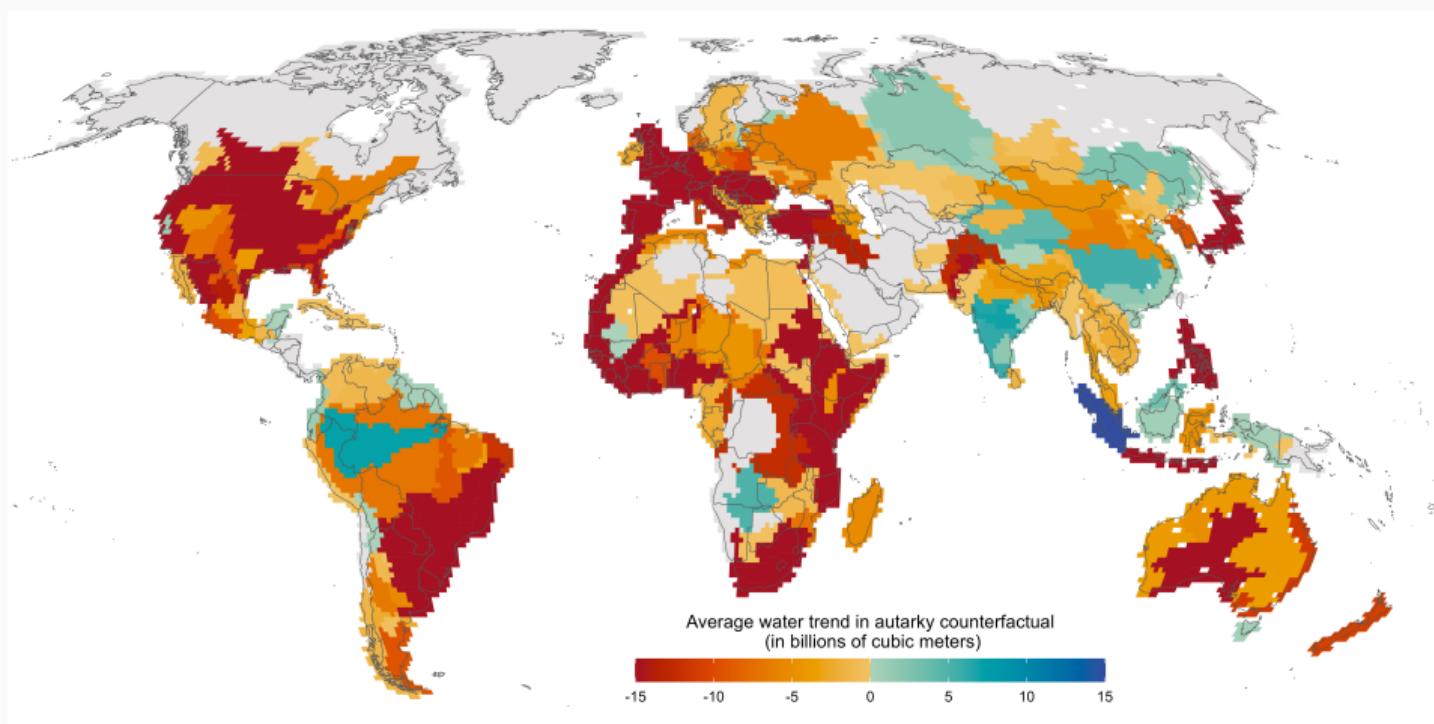
Allowing trade prevents extreme regional depletion . . .

Trends in local water resources - baseline



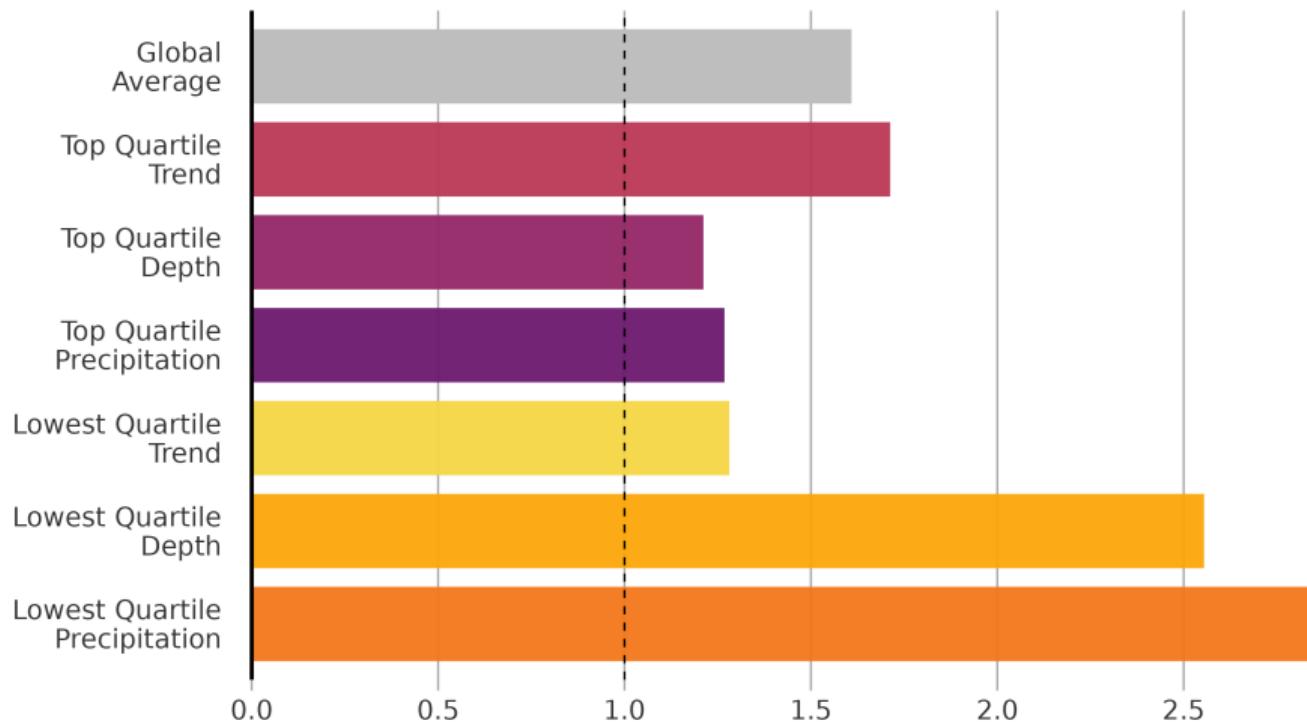
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Trends in local water resources - autarky

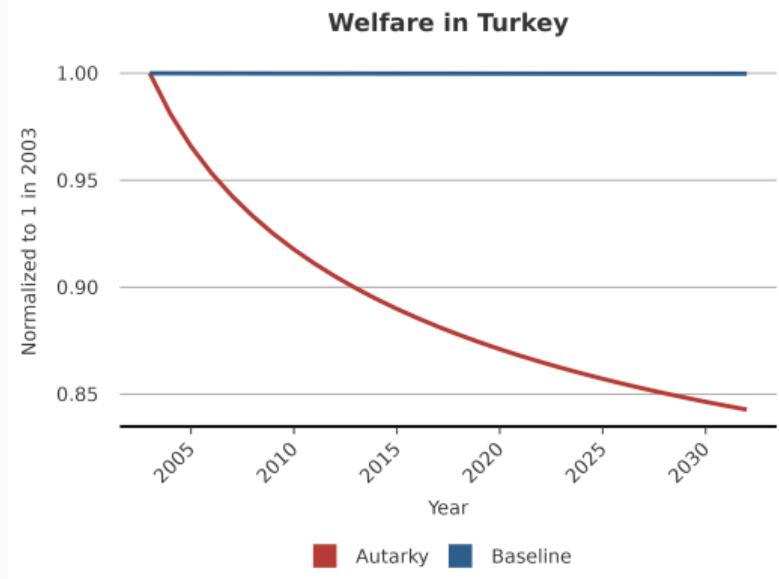
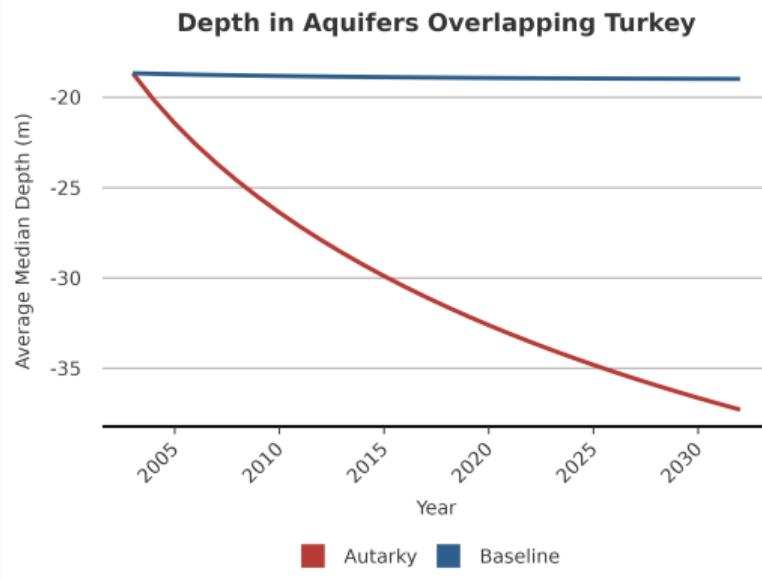


...by lowering water use in water-stressed regions

Autarky/Baseline Water Extraction in Period 1



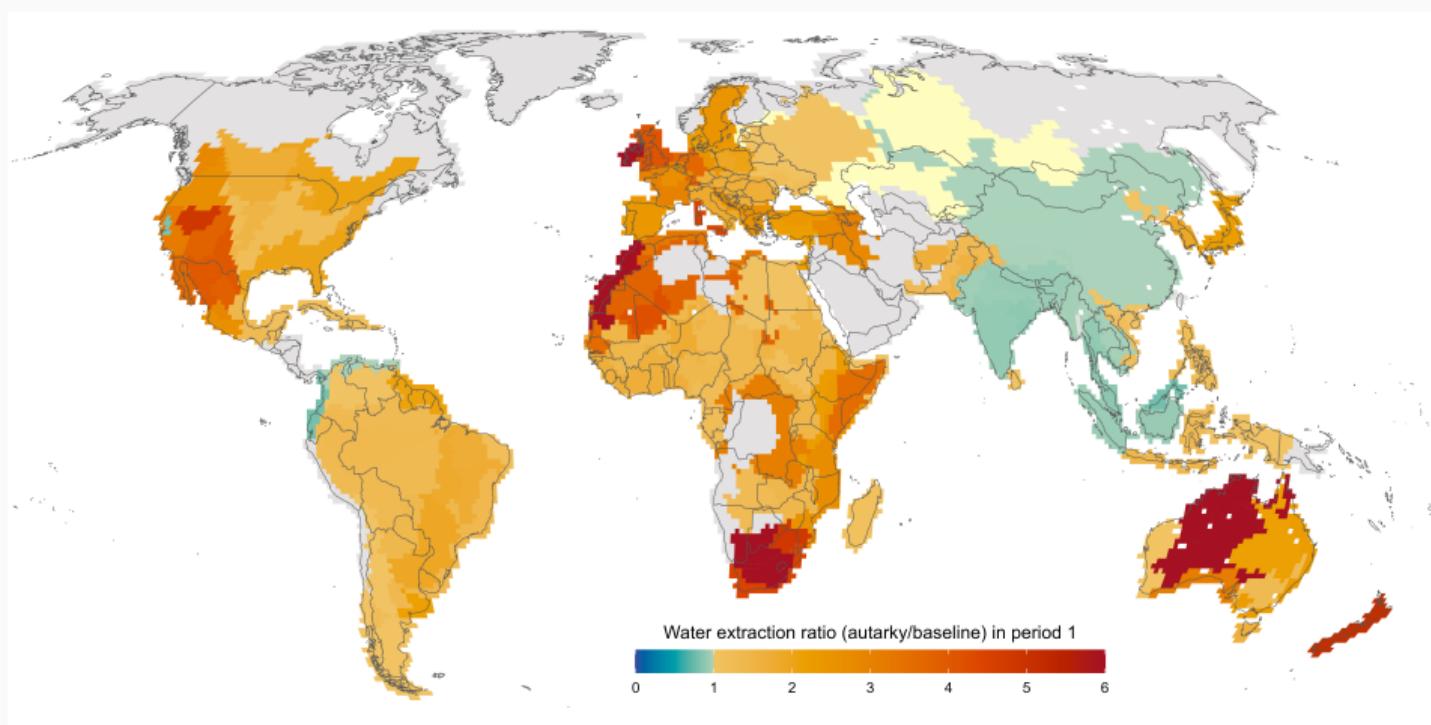
Autarky causes severe water depletion for some food importers



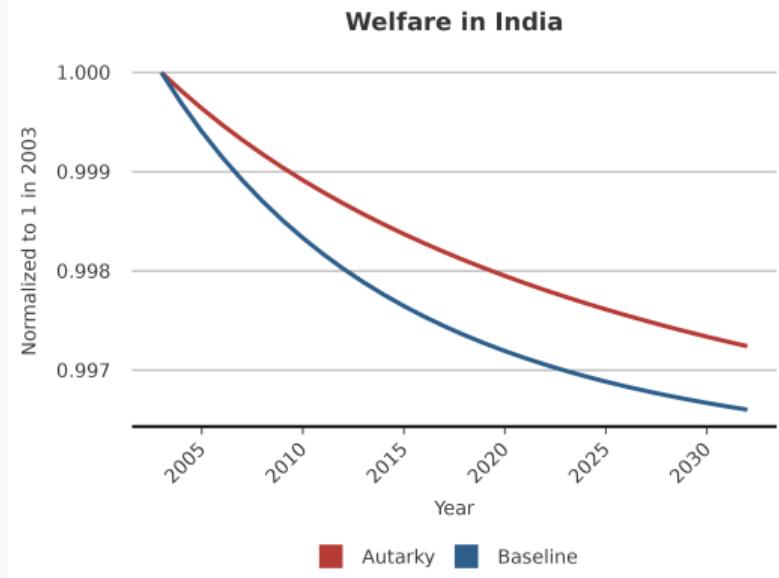
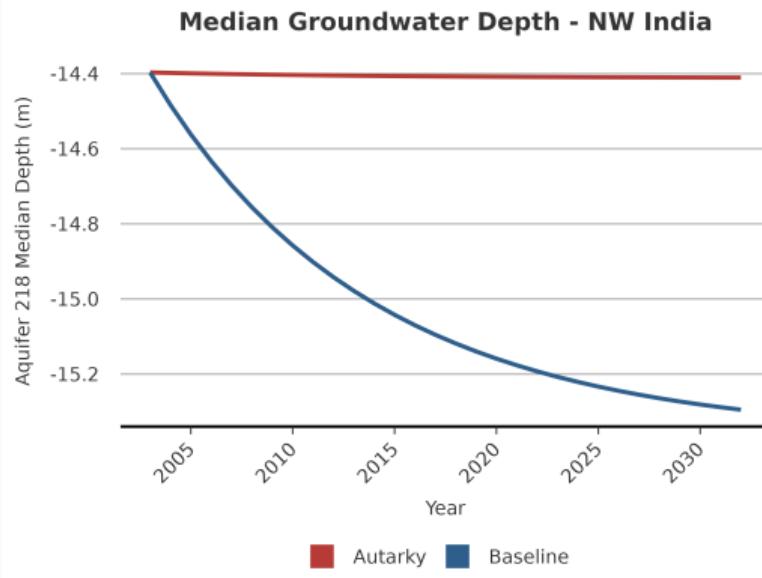
→ Cropped area increases >250% in autarky in Turkey

But, autarky prevents severe depletion for some food exporters

Water extraction *ratio* between autarky and baseline



But, autarky prevents severe depletion for some food exporters



→ Autarky prevents continued water depletion in the region currently losing water fastest



1. **Eliminate trade in agriculture**—set $\delta_{ji}^k = \infty$ for all i, j, k with $i \neq j$
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 - **Liberalizing agricultural markets can raise or lower water extraction and welfare**

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 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

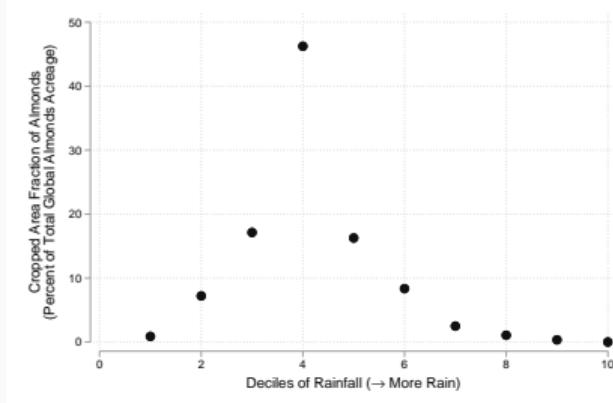
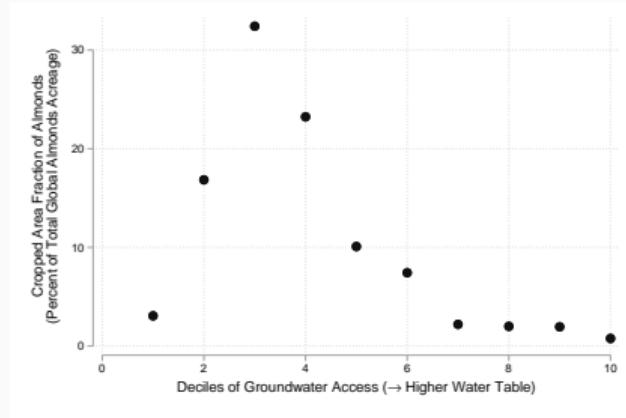
Appendix

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

Almonds

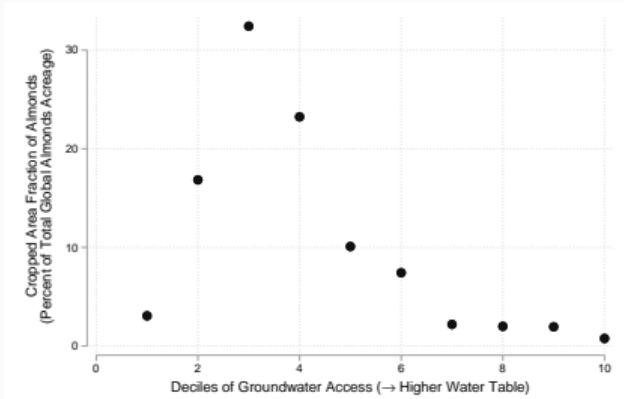
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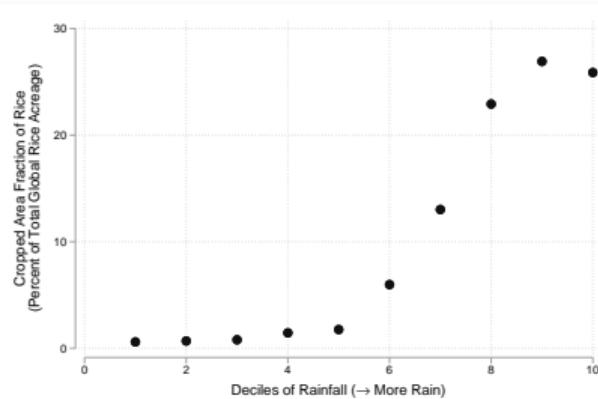
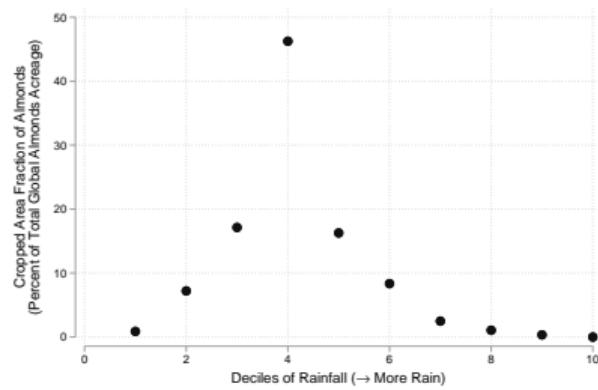
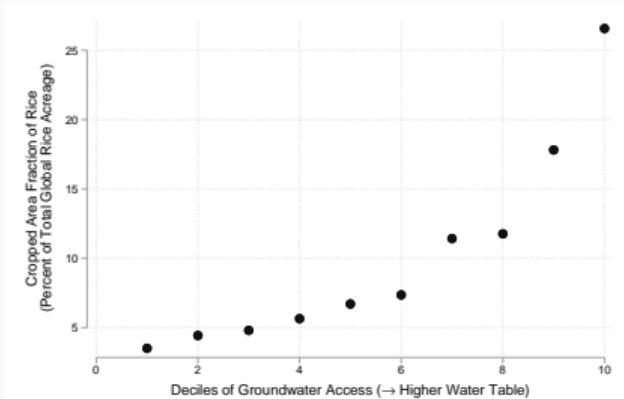


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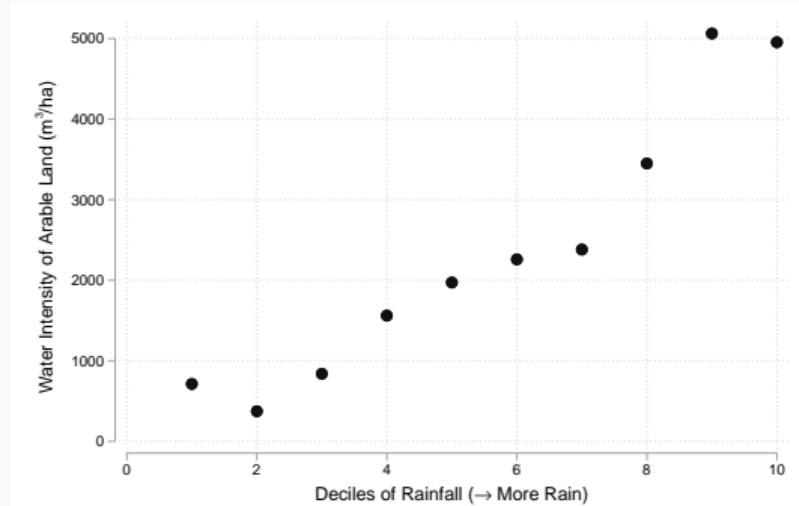
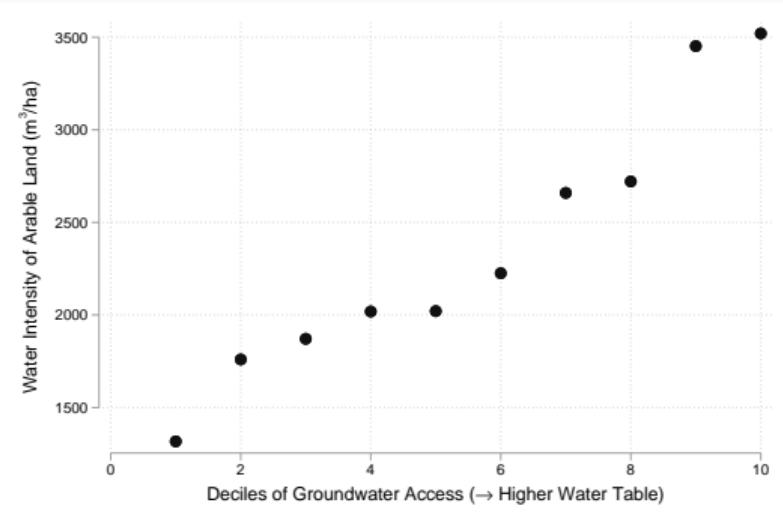
Almonds



Rice



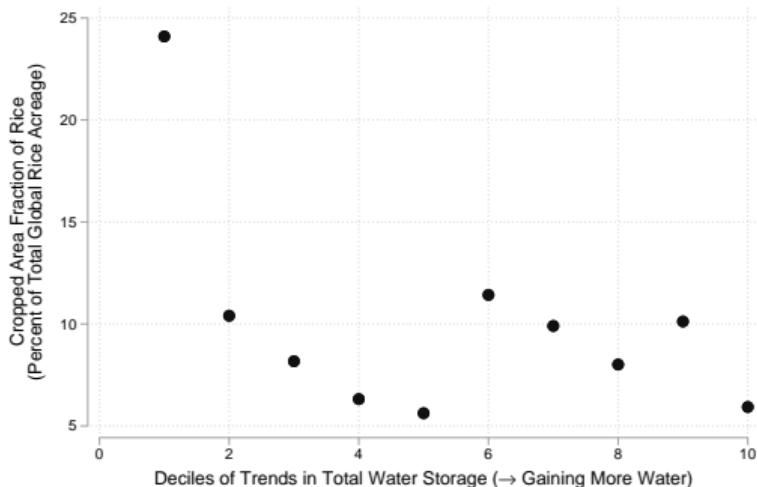
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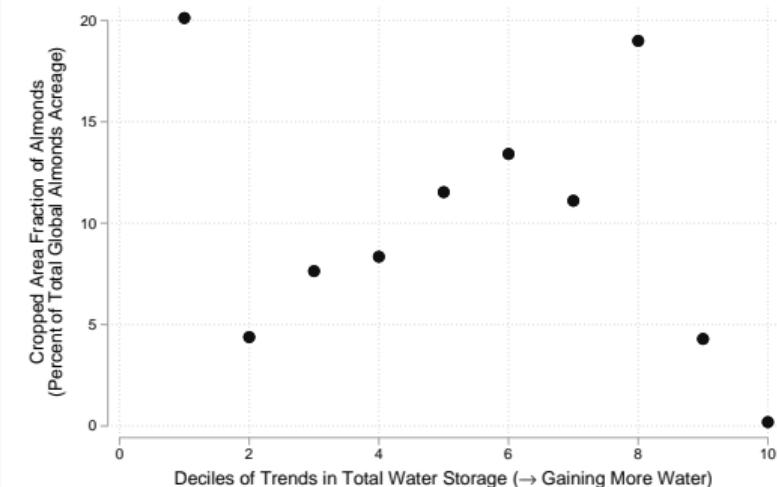
$$\text{Water Intensity of Arable Land } (m^3/\text{ha}) = \frac{\sum_{k \in \mathcal{K}} \text{hectares}^k \times \left(\frac{\text{water } (m^3)}{\text{hectare}} \right)^k}{\sum_{k \in \mathcal{K}} \text{hectares}^k + \text{pasture}}$$

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

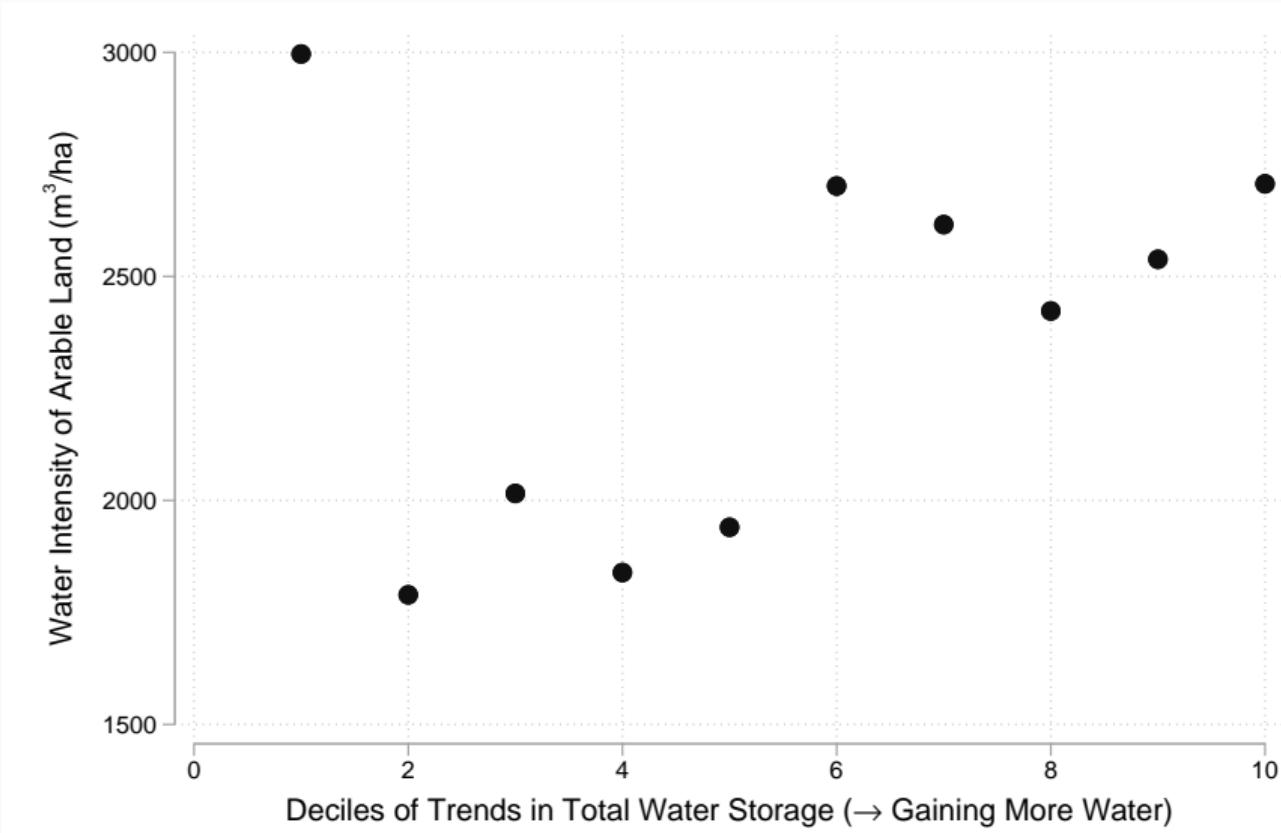
Rice Acreage by Water Trends



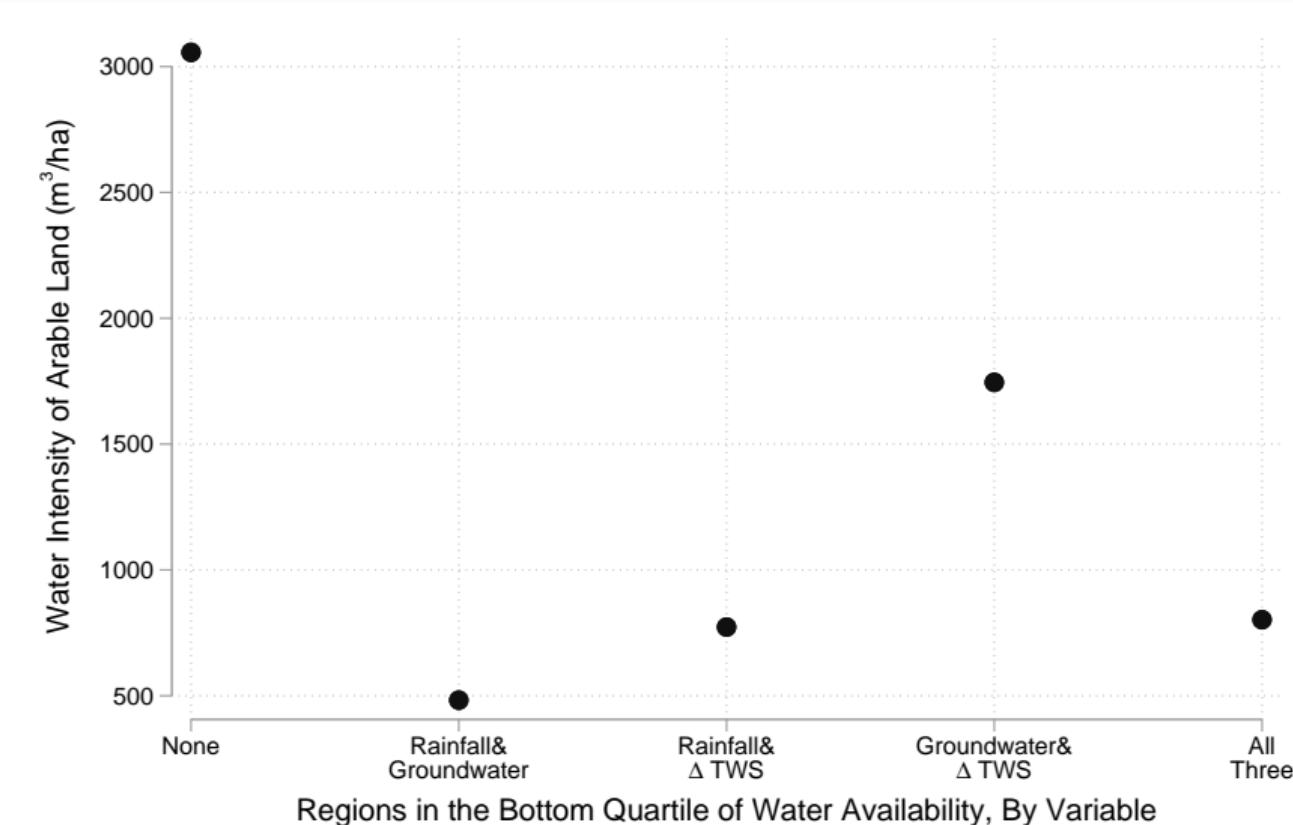
Almond Acreage by Water Trends



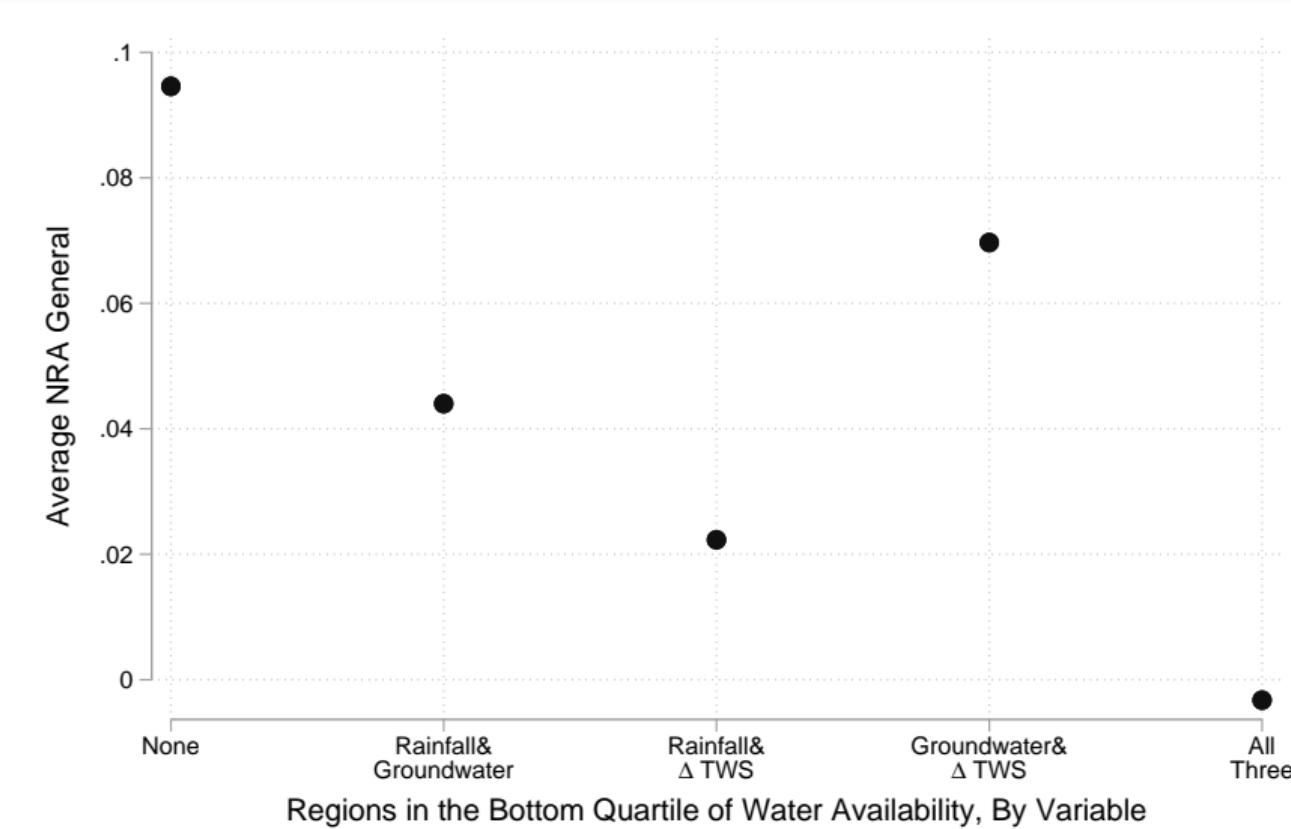
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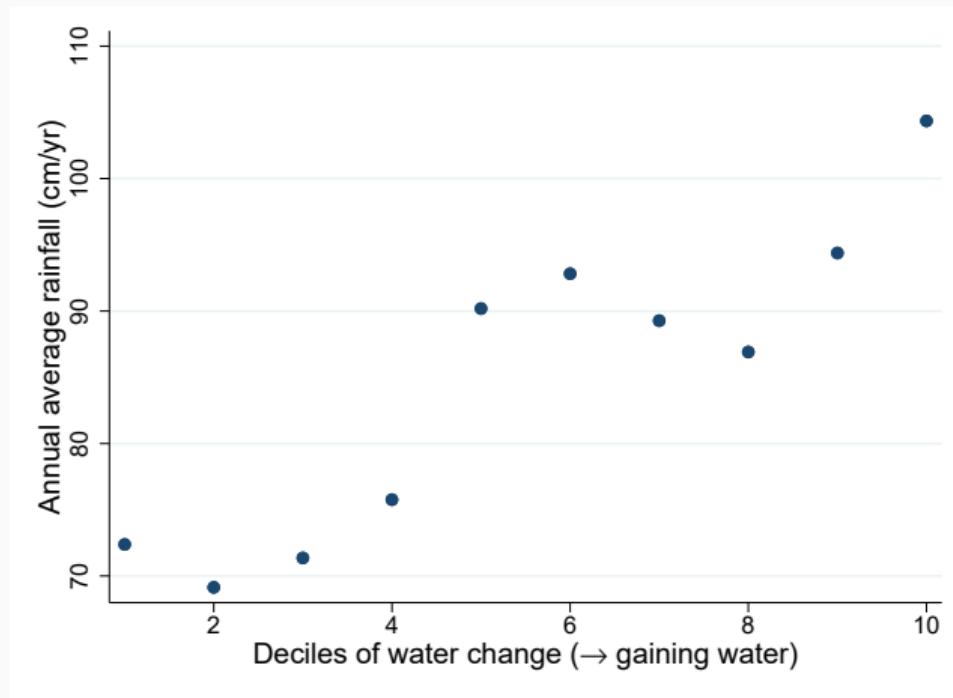
Fact 5: . . . but also in some regions losing water rapidly



Fact 5: Similar patterns in water intensity and agricultural policy

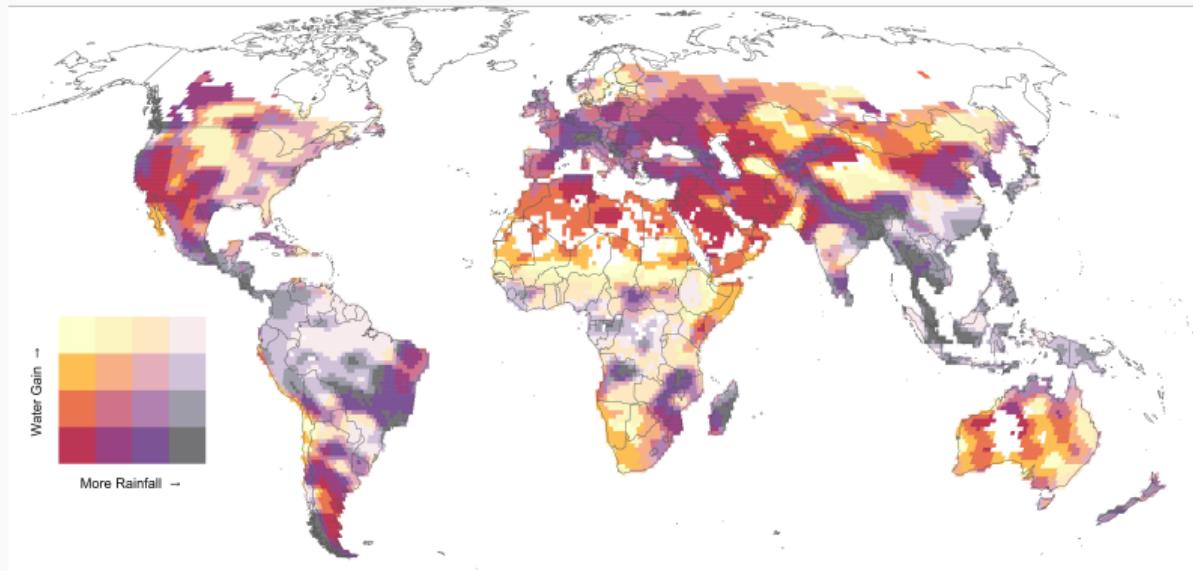


Fact Aside: Characteristics of depleting regions (AEA P&P 2024)



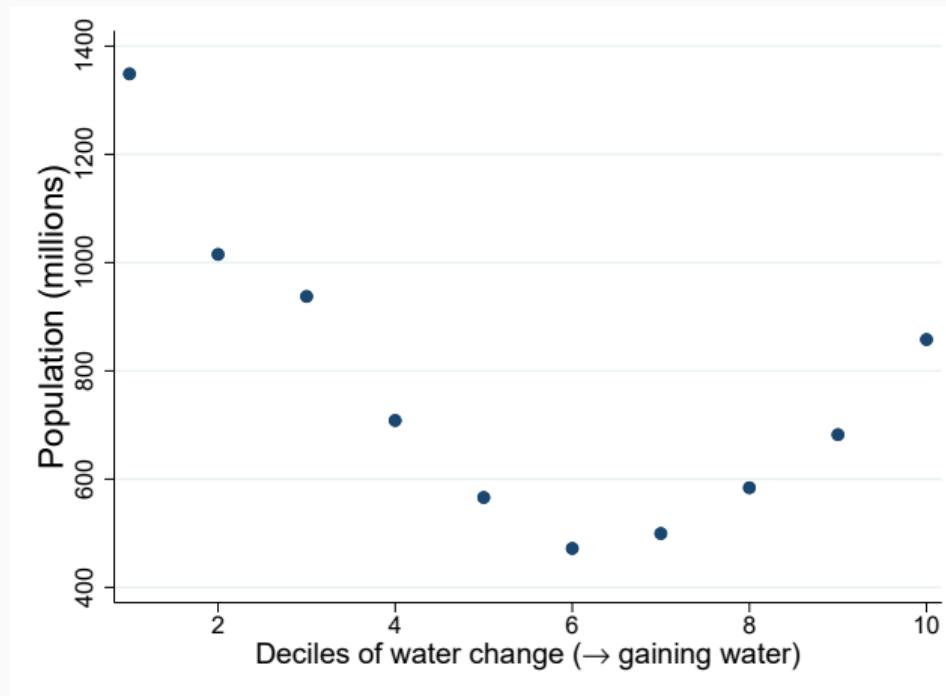
Regions losing water rapidly are disproportionately **already water-scarce**

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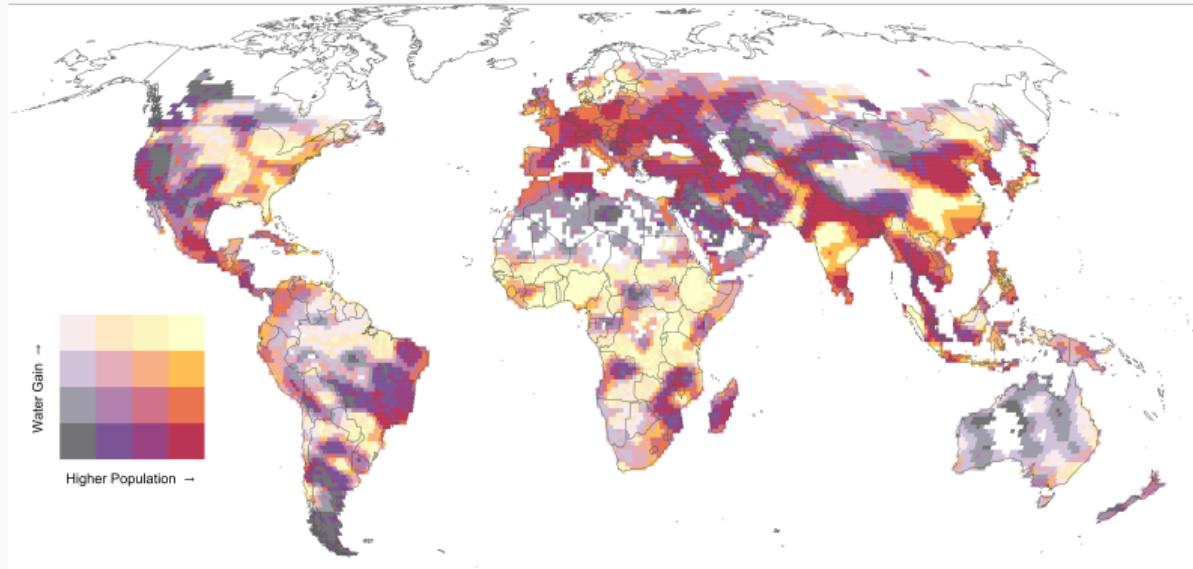
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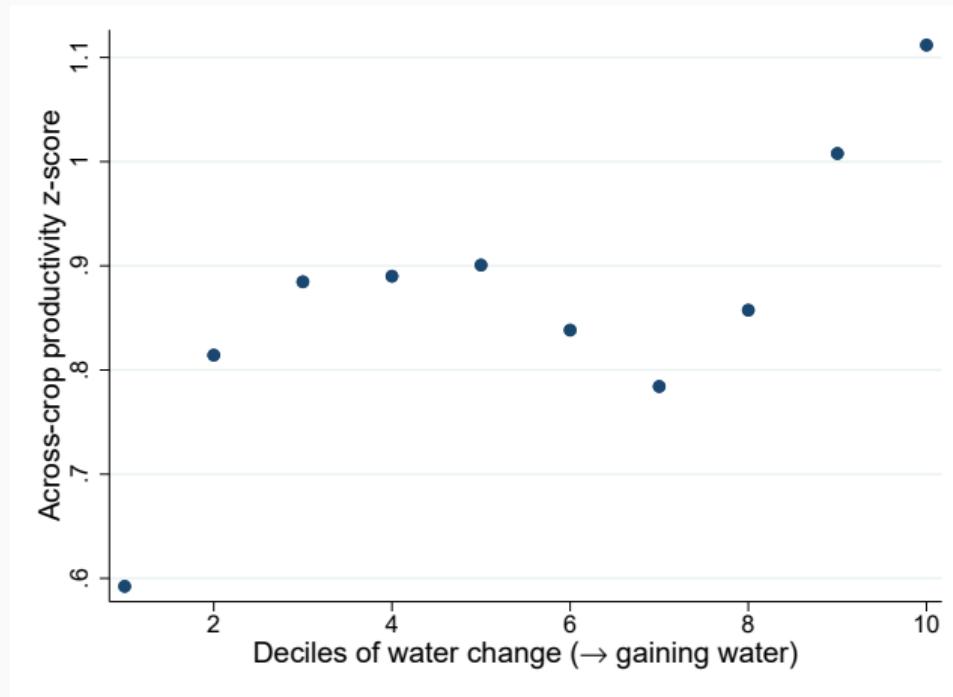
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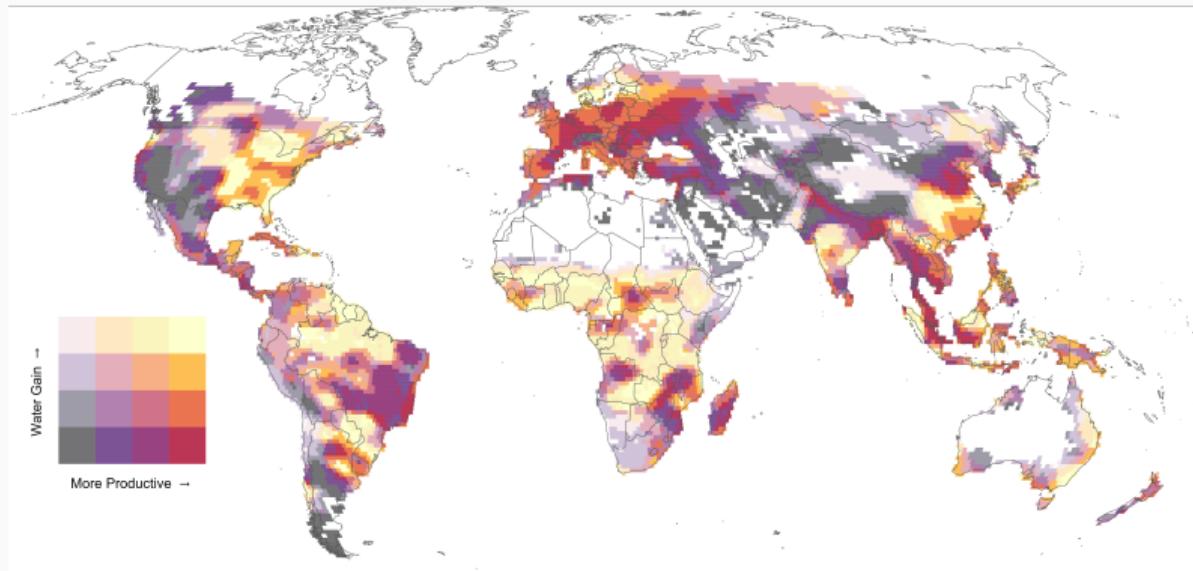
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Regions losing water rapidly have **low suitability for crops**

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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

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

where

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

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

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

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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- **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

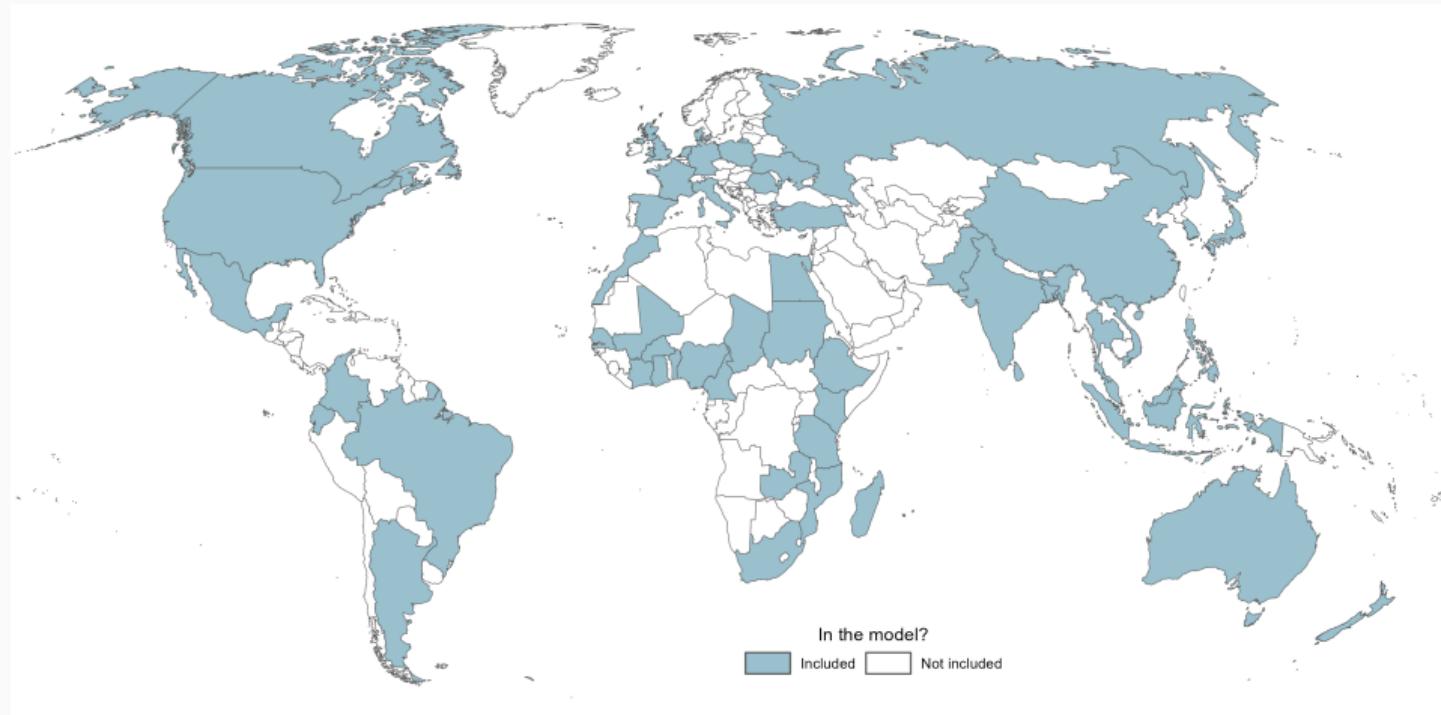
Include countries in the **top 40** globally in any of...

- (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)

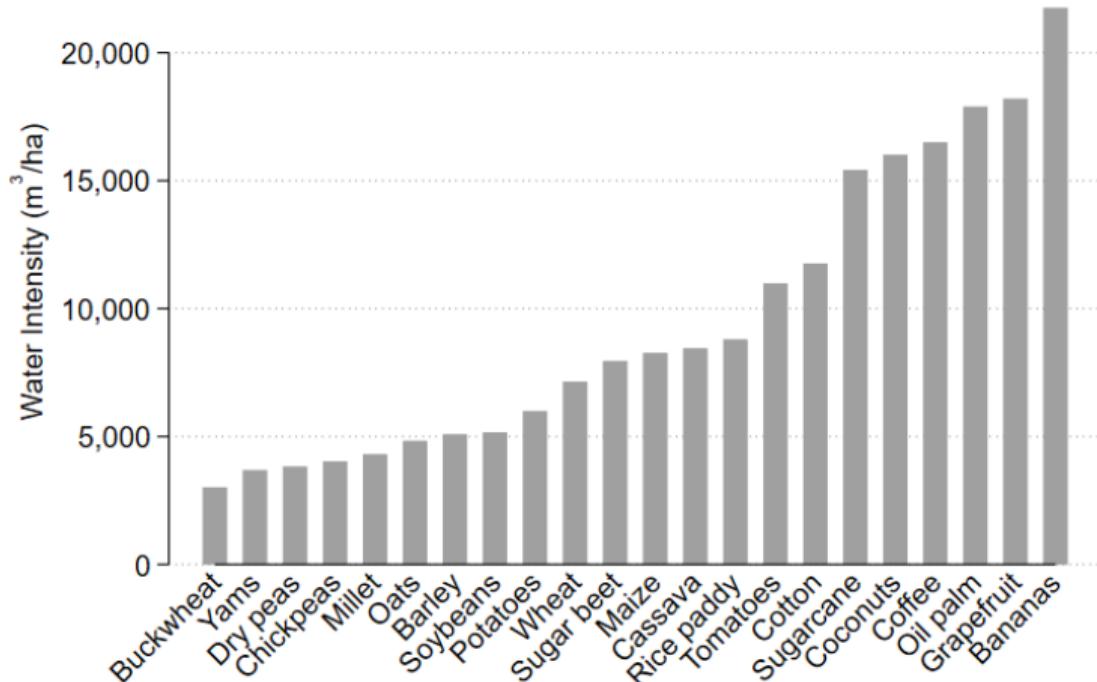
Sample selection: Crops

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

Water Intensities of Crops Included in Model



Sample selection: Aquifers

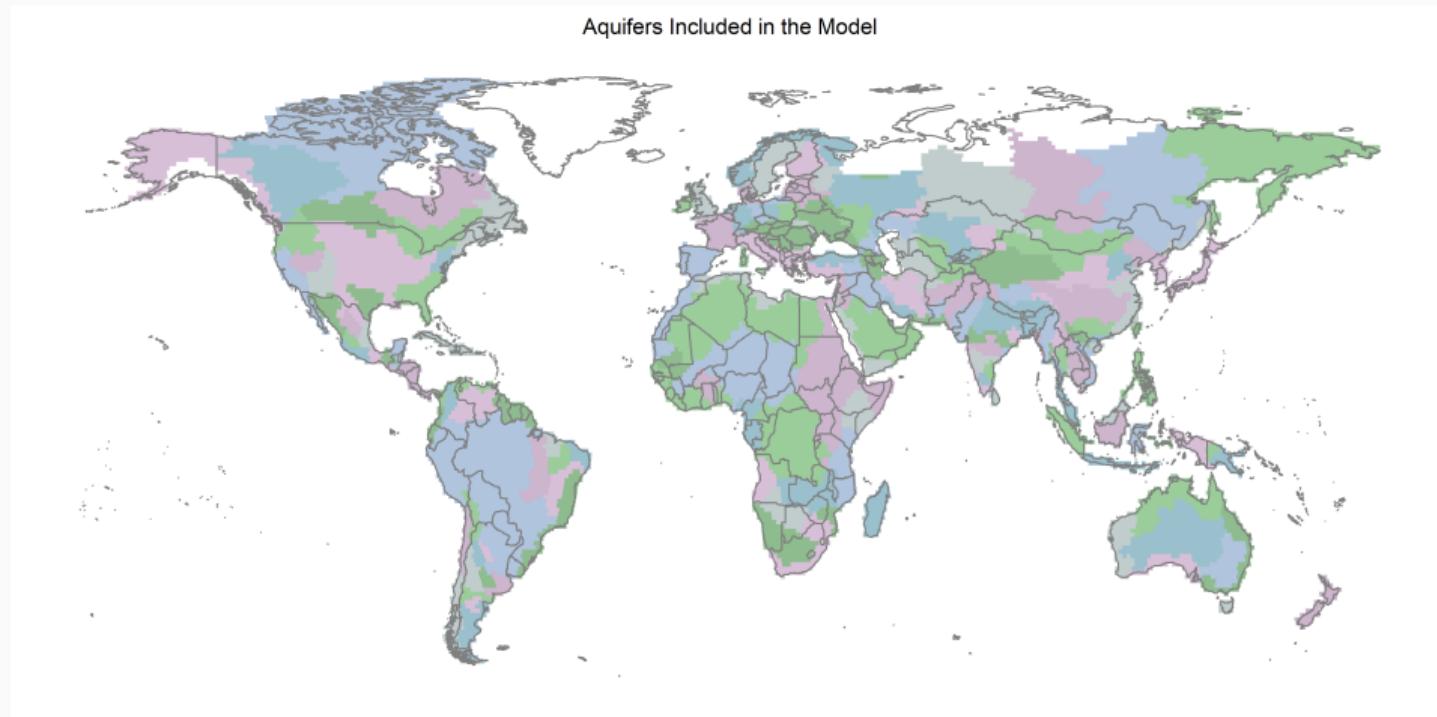


Include **37 aquifers** (WHYMAP), then cluster GRACE grid cells s.t. **180 water basins** (NASA)

Sample selection: Aquifers



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



Parameters to be calibrated/estimated

- 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 $A_q^w(D) = \Upsilon_q D^{-v}$
- v 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	v	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

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

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

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- $\{\delta_{ij}^k\}$ 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 $A_q^w(D) = \Upsilon_q D^{-v}$
- v elasticity of extraction productivity

Estimating the supply side

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

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

where *observed* extraction is

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

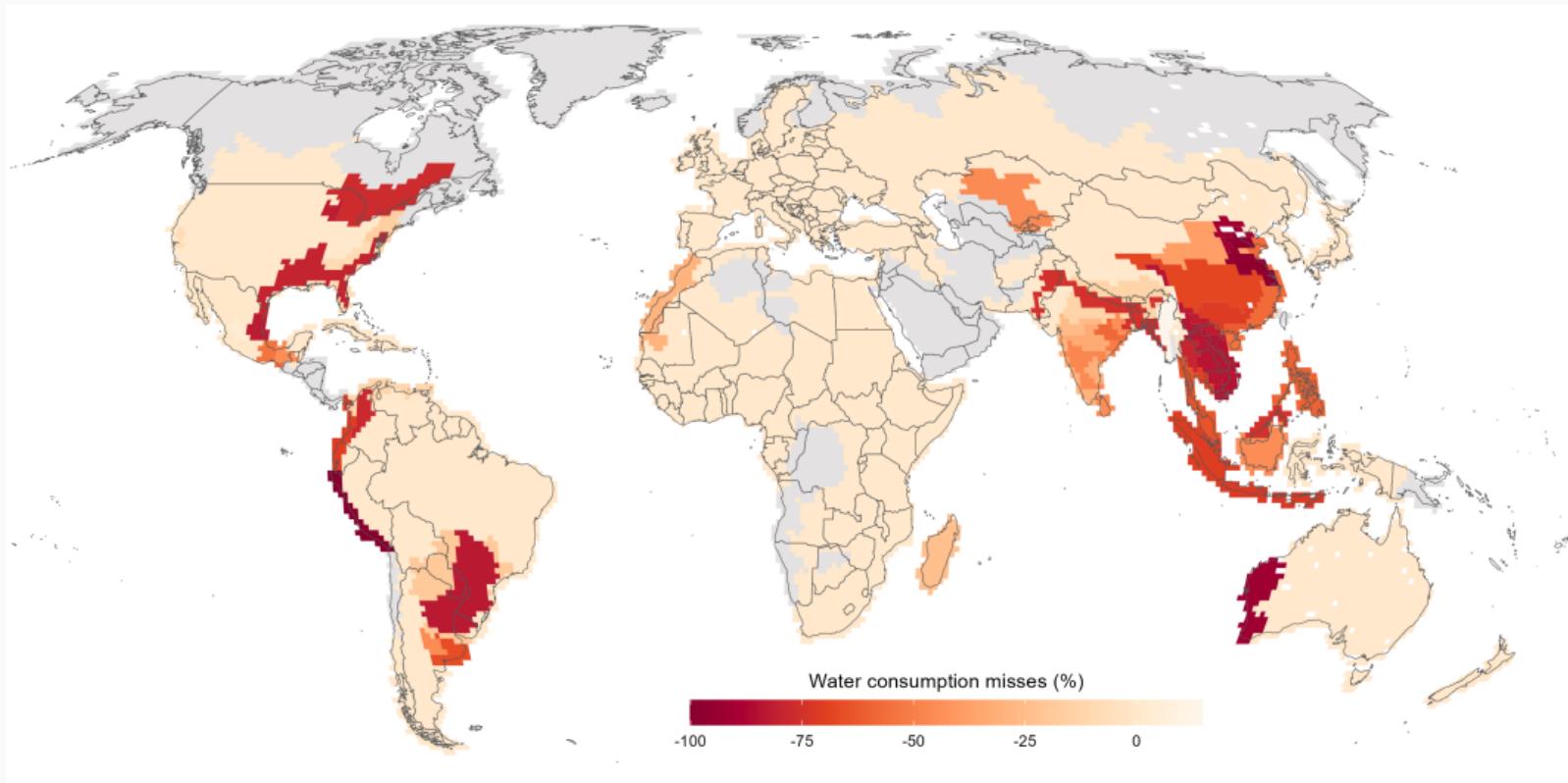
Intuition for identification

- 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

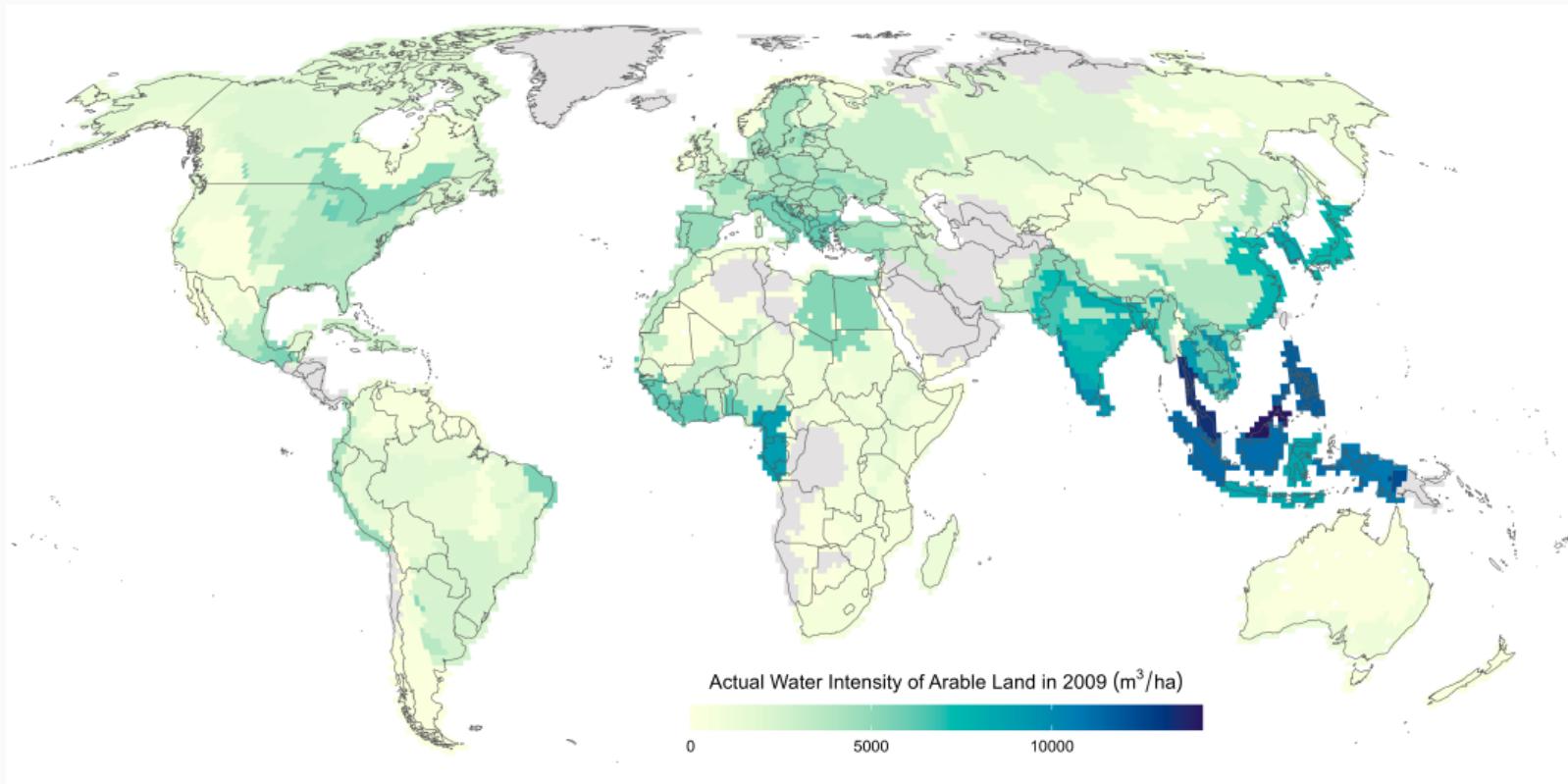
Parameters to be calibrated/estimated

- 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)
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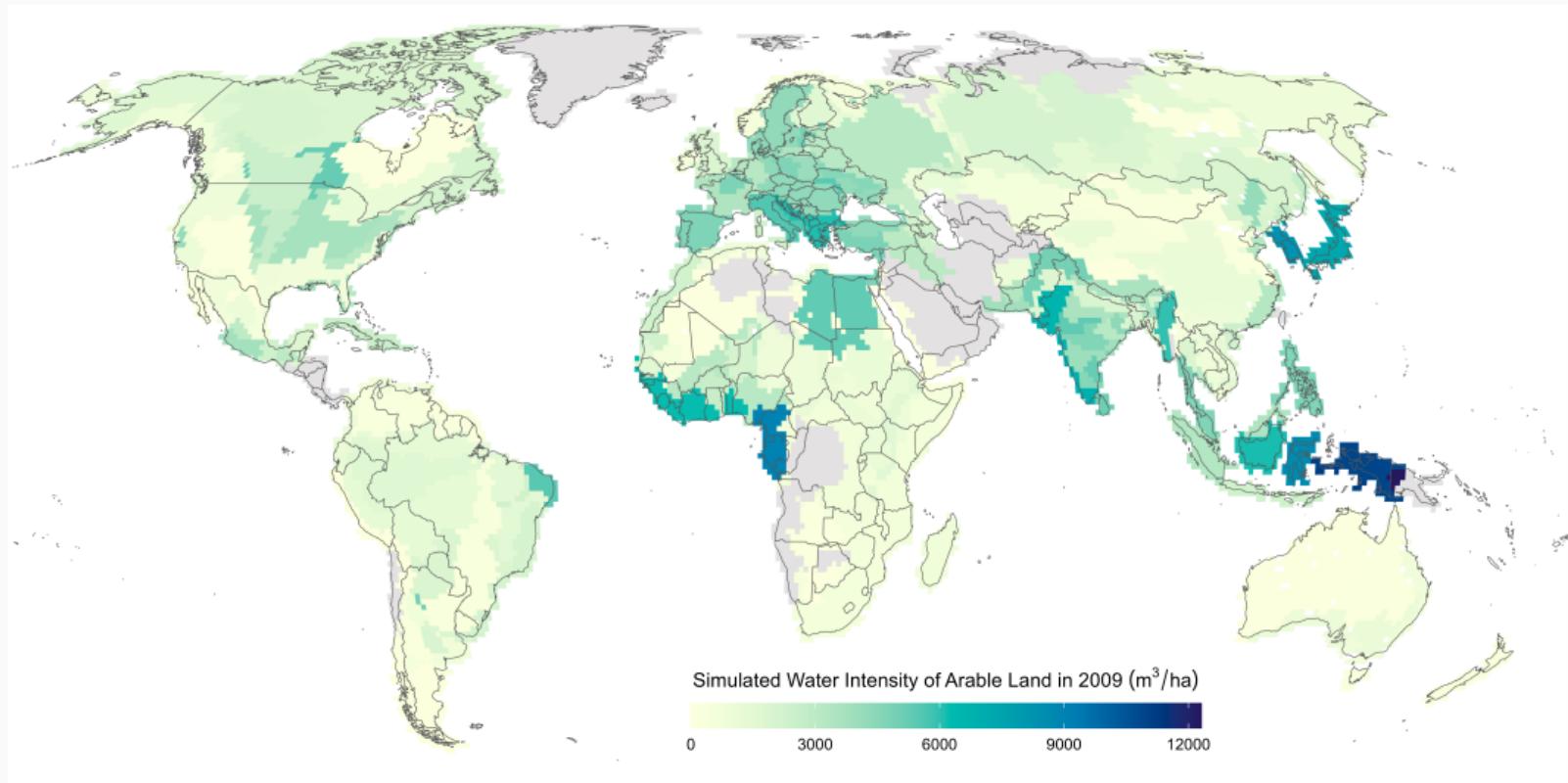
Model fit: Agricultural water extraction



Model fit: Agricultural water extraction (target)



Model fit: Agricultural water extraction (simulated)



Model validation: Water extraction productivity

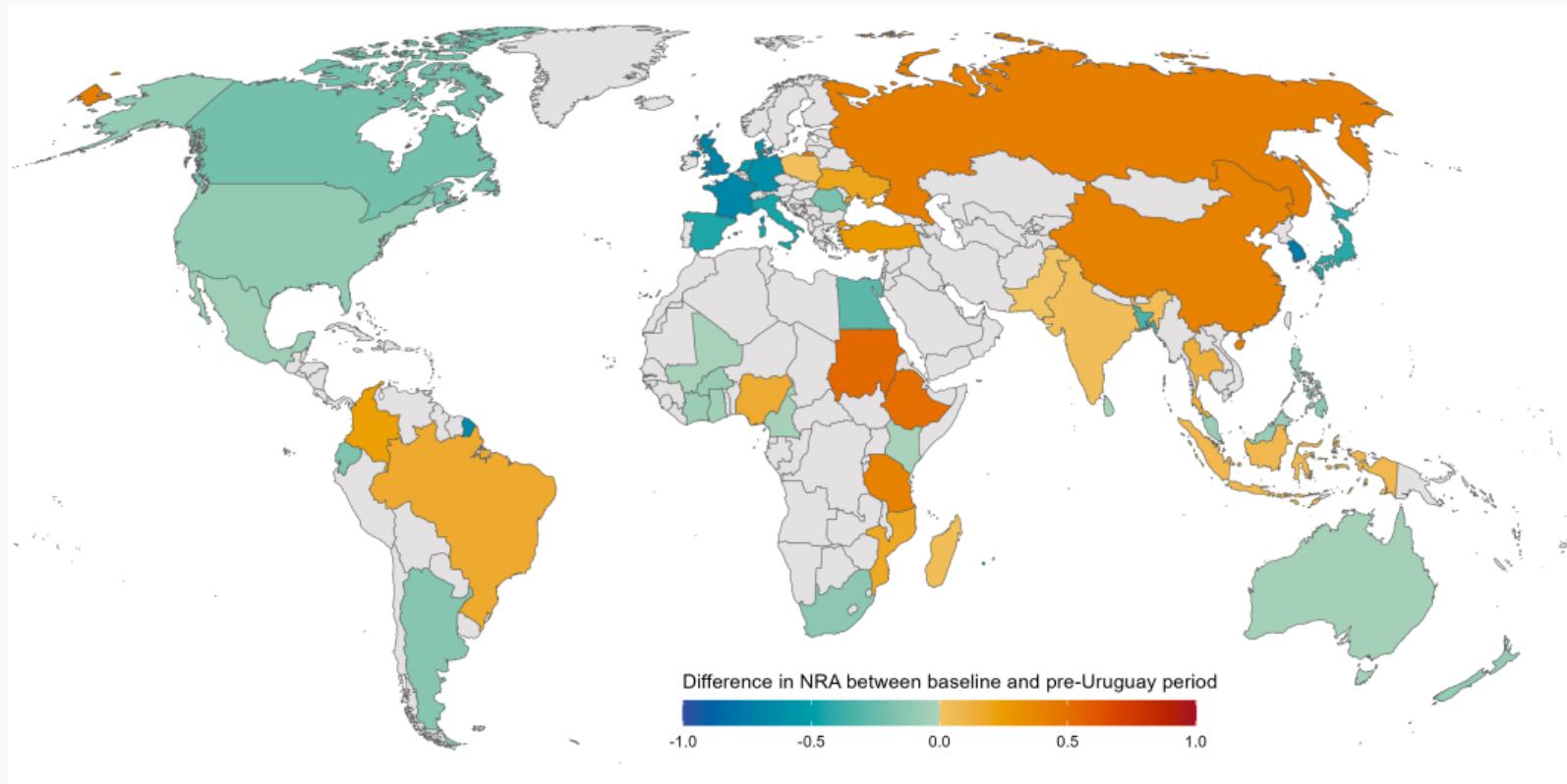
Table 1: Partial Correlations of Aquifer-Level Covariates, Impact of Depth on Extraction Productivity (Υ_q), and Extraction Productivity ($A_q^w(D_{qt})$)

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

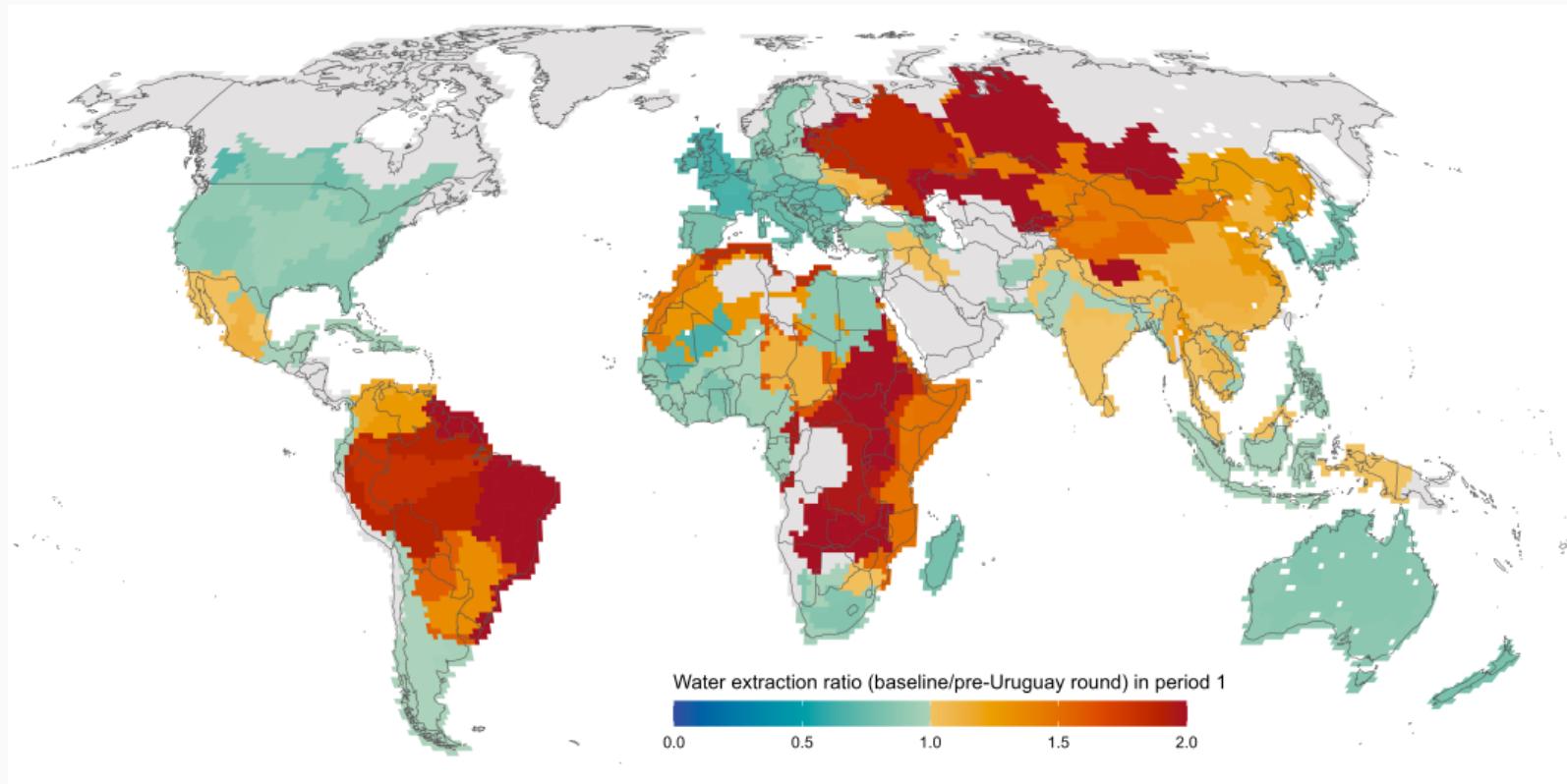
Alternative policy counterfactuals

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 $\tau_i^k = 1 + \text{avg. from Uruguay Round (1986-1994)}$
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

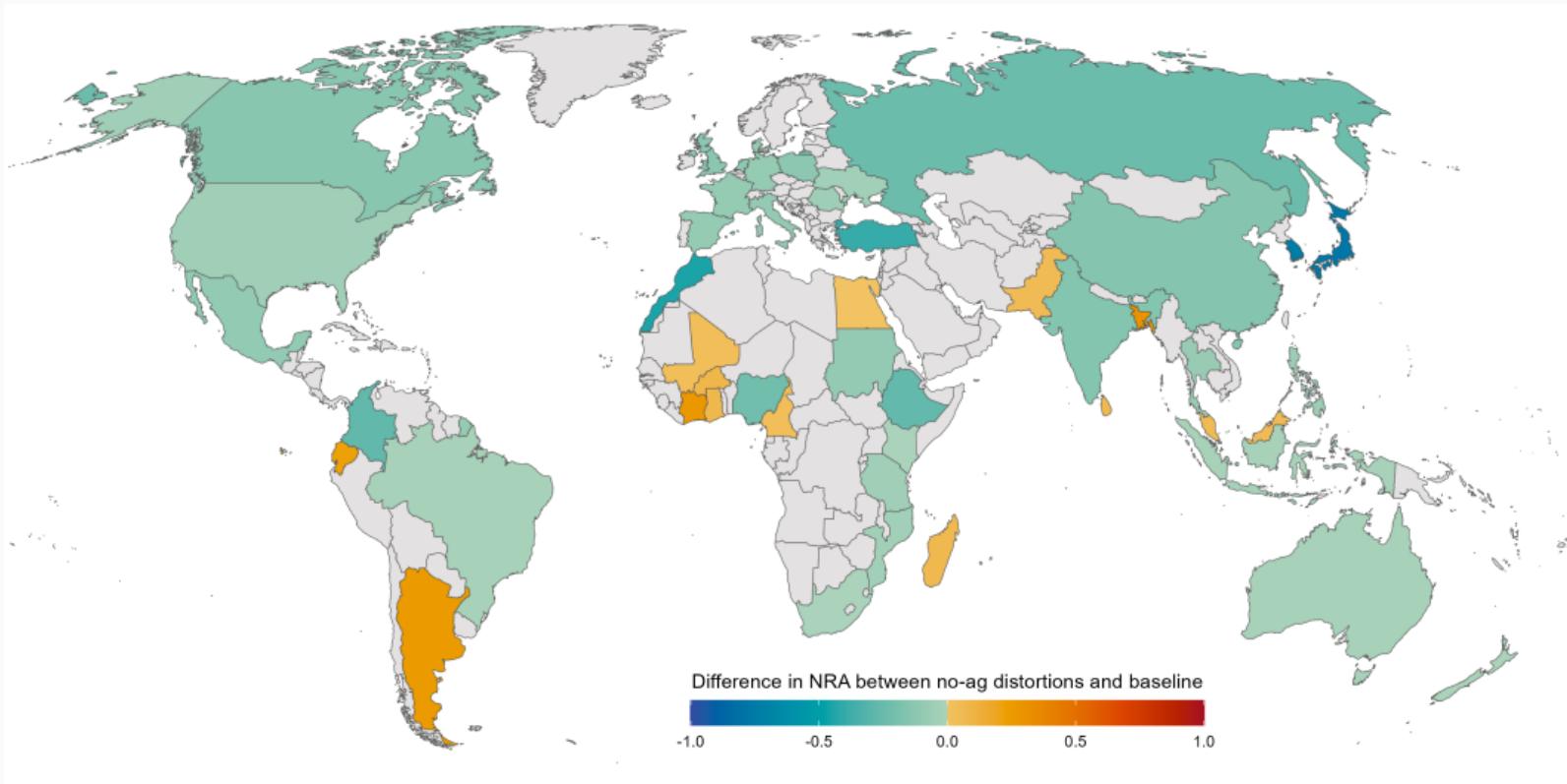
Uruguay Round lowered subsidies in the north, raised them in the south



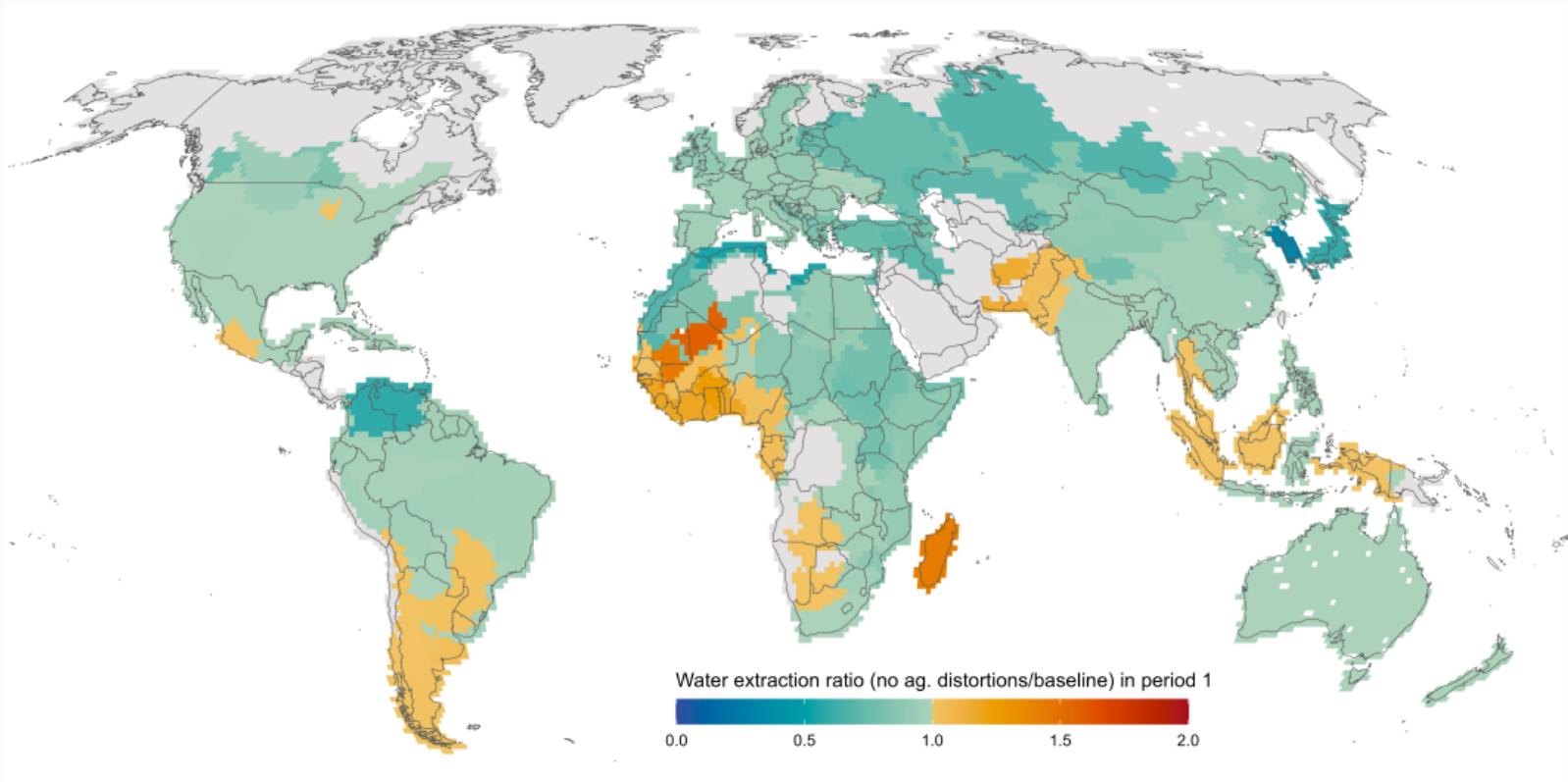
Uruguay Round increased water extraction in the south



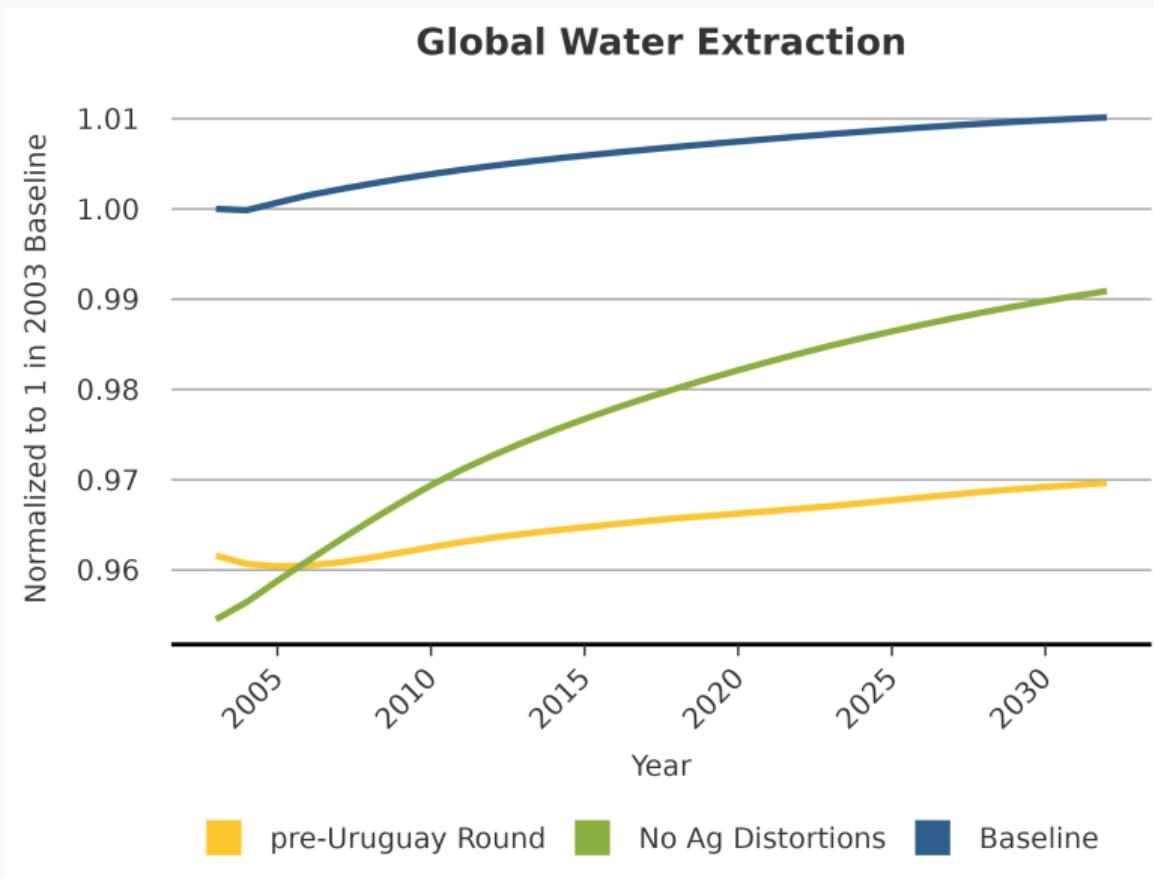
Removing current distortions lowers subsidies to ag. nearly everywhere



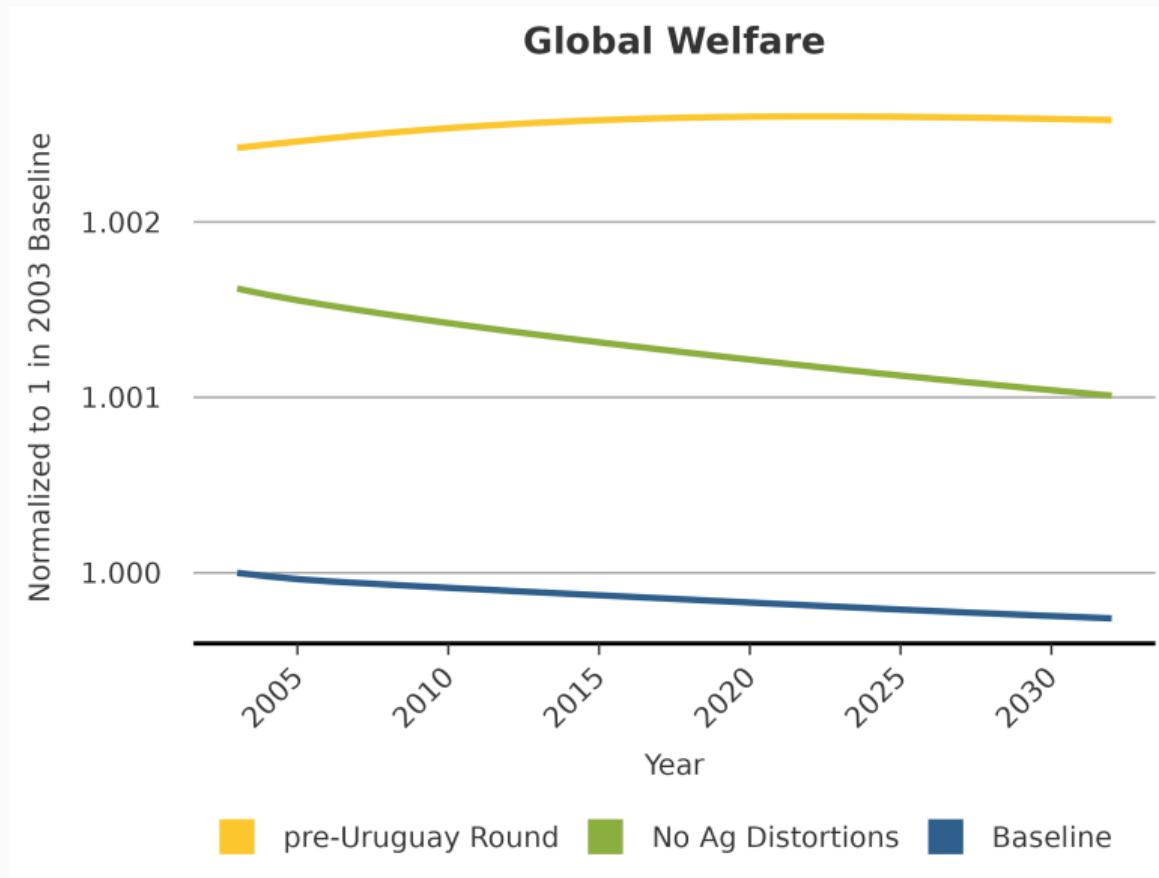
Removing current distortions lowers water extraction nearly everywhere



Global water extraction falls under both counterfactual policies



Global welfare rises under both counterfactual policies



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