

# 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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- **70% of California almonds are exported abroad**

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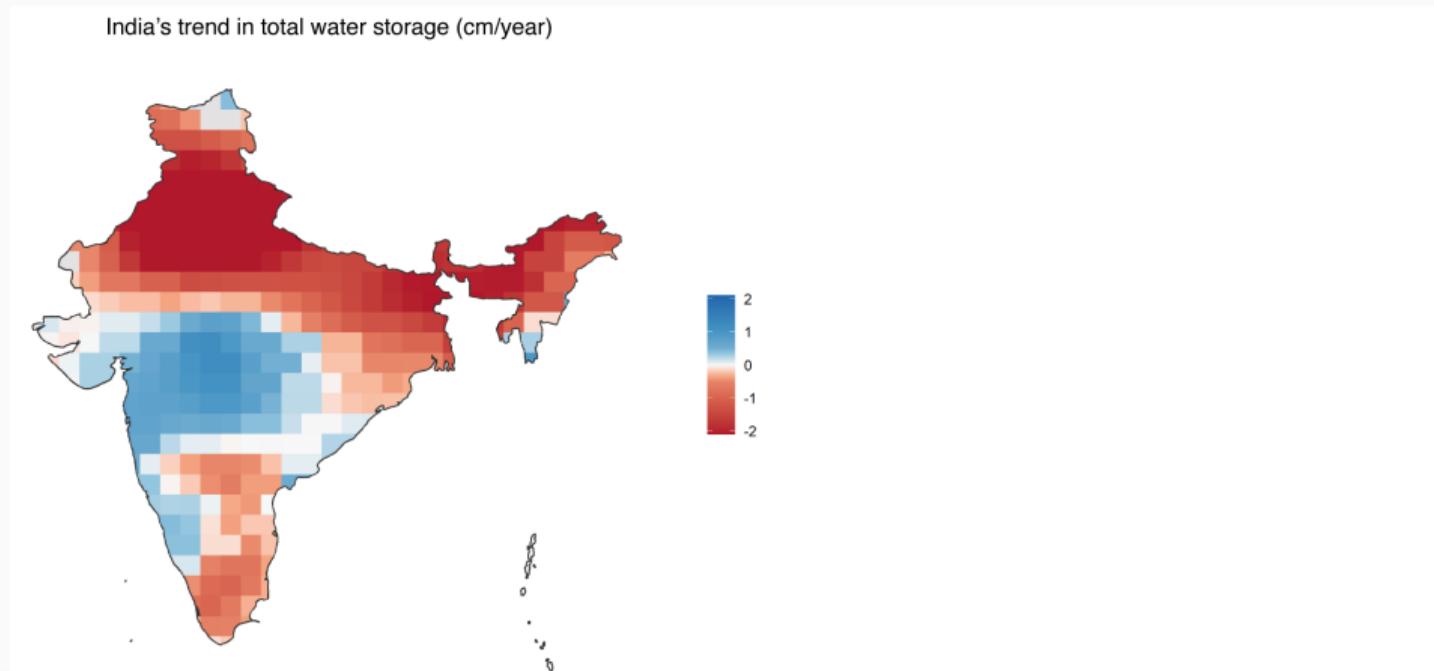
## Tough nut to crack: the almond boom and its drain on the Murray-Darling

Demand for the thirsty crop has created a gold rush but irrigators and growers fear there might not be enough water



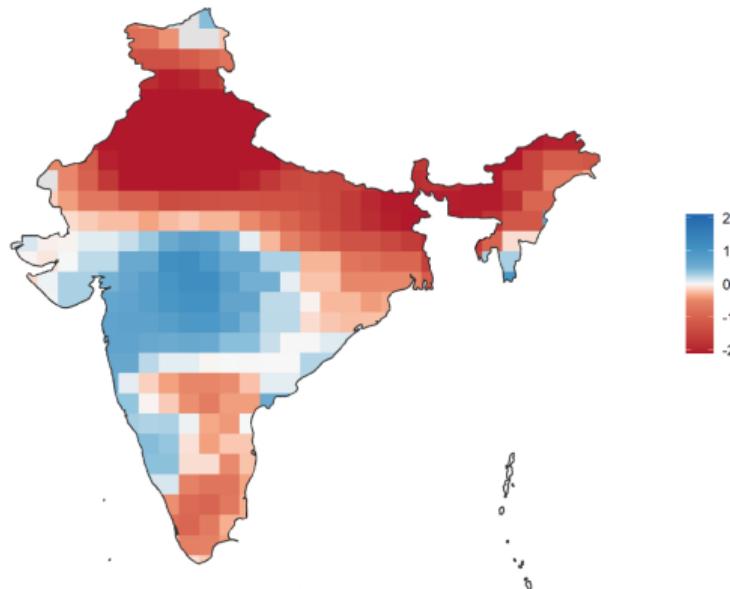
 Almond fields near Mildura. There are fears the Murray-Darling water management regime may not be able to handle the boom in the water-intensive crop. Photograph: Mike Bowers/The Guardian

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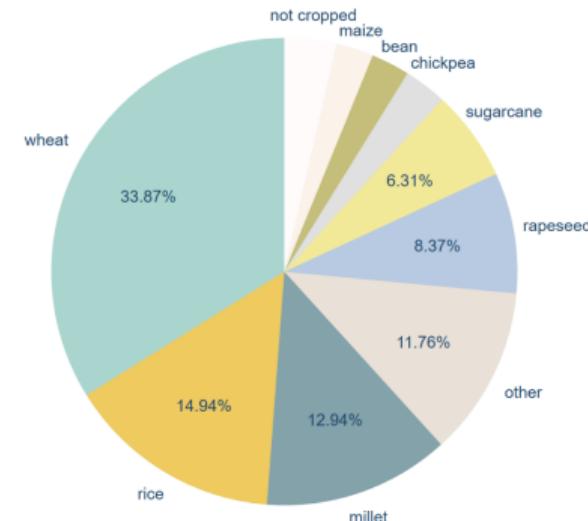


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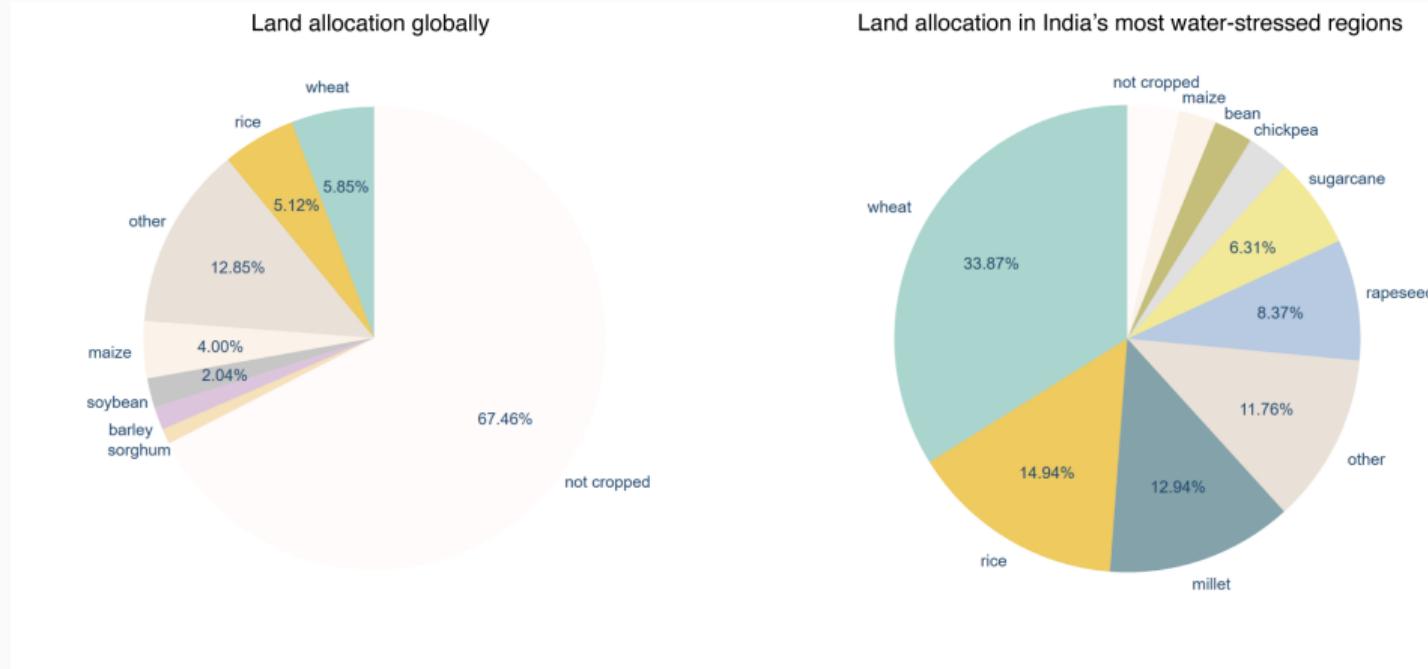
India's trend in total water storage (cm/year)



Land allocation in India's most water-stressed regions



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India is the world's leading exporter of rice

## Research questions

**Key Idea:** Water is effectively non-tradable, but it is embedded in agricultural trade

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We ask:

1. How **systematically** does water-intensive production occur in water-scarce regions throughout the world?
2. What are the current and future **welfare and policy** implications?

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  - How would eliminating trade in agriculture affect regional water scarcity and global welfare?
  - How would eliminating *all* ag. market interventions affect welfare in a second-best setting?
  - Can *optimal* ag. market policies offset water input market distortions?

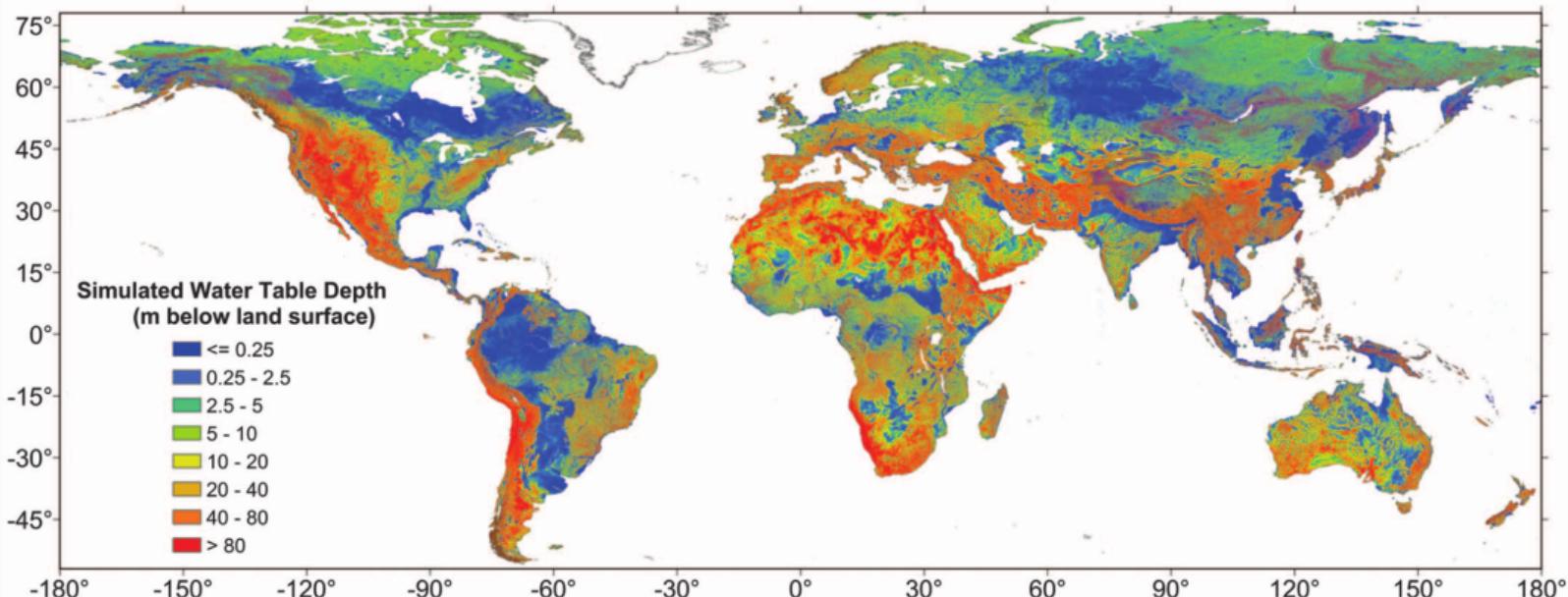
## Related literature

- Copeland, Shapiro, and Taylor (2022) review literature on the interplay between globalization and the environment, but little work on natural resources
- Anderson, Rausser, and Swinnen (2013) review literature on ag. policy distortions, but no investigation of their environmental effects [*Exception: Berrittella et al. (2008)*]
- Empirics of water & ag./trade policy: Debaere (2014), Carleton (2021), Sekhri (2022)
- Simpler 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 resources

## Data

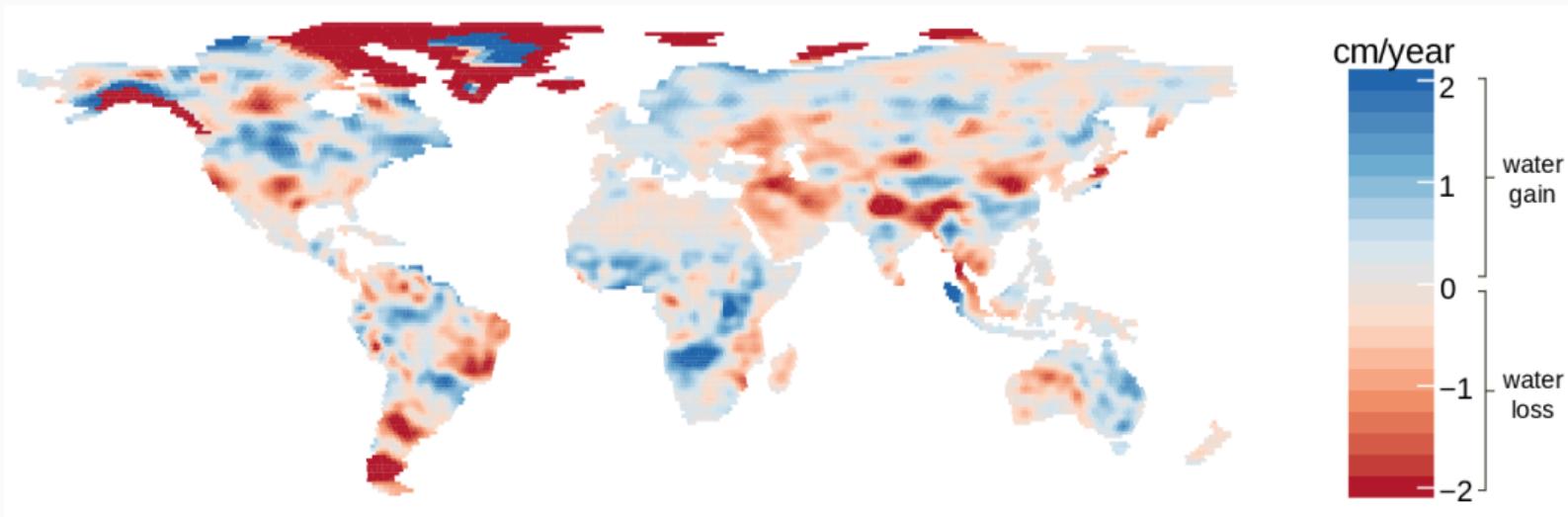
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## Water table depth: Fan, Li, and Miguez-Macho (2013)



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

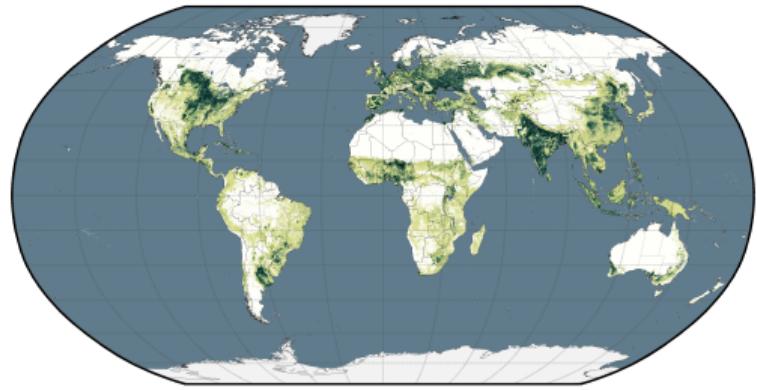
## Trends in total water storage: GRACE



- 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)

# Agricultural land use: SAGE

Cropland Area in the Year 2000

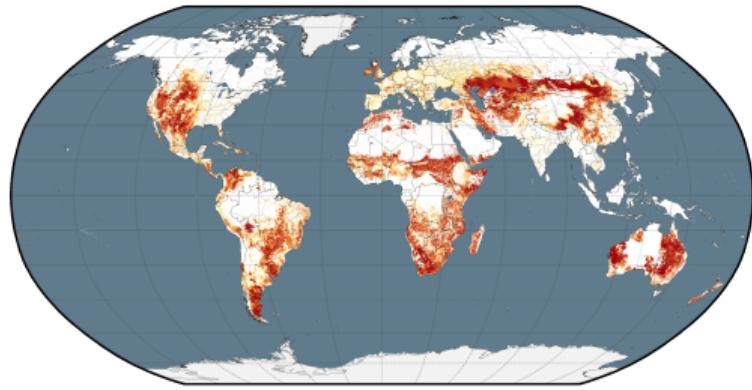


Cropland Area Fraction



Source: EarthStat.org. Citation: Ramankutty et al. 2008

Pasture Area in the Year 2000



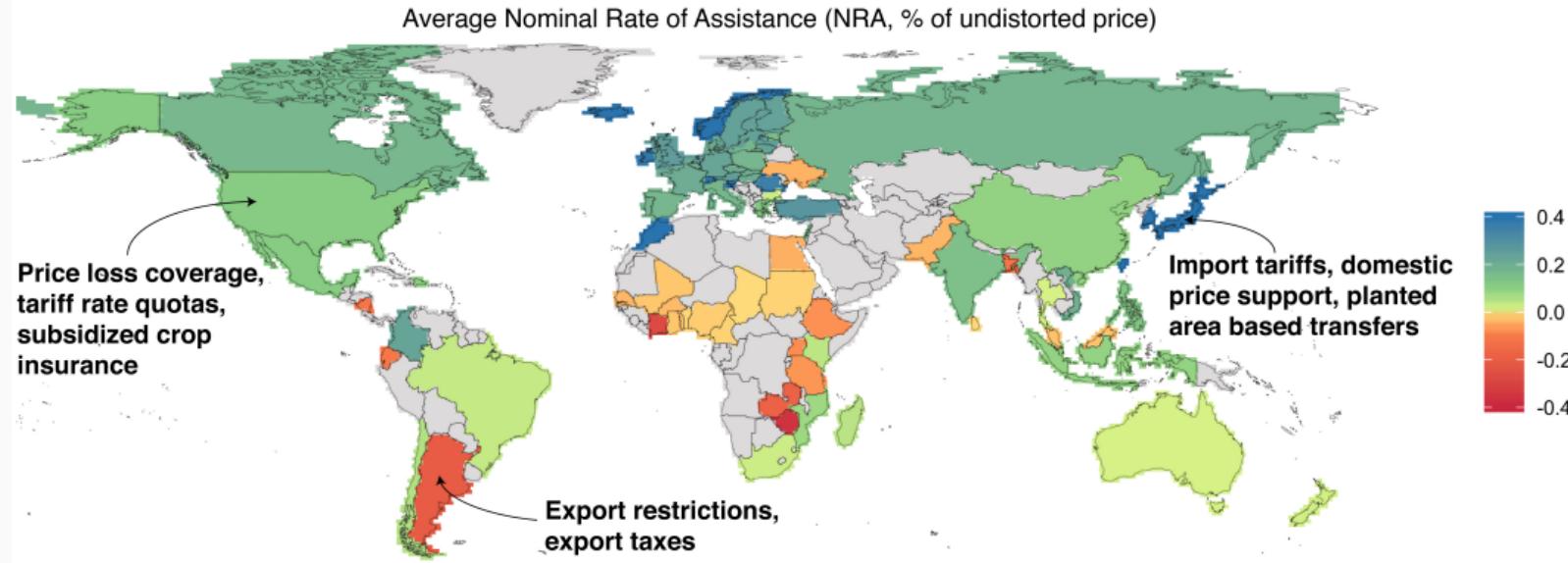
Pasture Area Fraction



Source: EarthStat.org. Citation: Ramankutty et al. 2008

- **Cropped area fraction** for 175 crops (& pasture) at  $\sim 10\text{km} \times 10\text{km}$  resolution c. 2000
- *How:* Combine census data with remotely-sensed maps of land cover ([Monfreda, Ramankutty, and Foley, 2008](#))

# Policy: World Bank Distortions to Agricultural Incentives (DAI)



- **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!*)

# Other datasets on agriculture and hydrology

## Potential Yields: **GAEZ**

- Crop-specific **potential yields** at 5 arc-minute resolution (~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 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

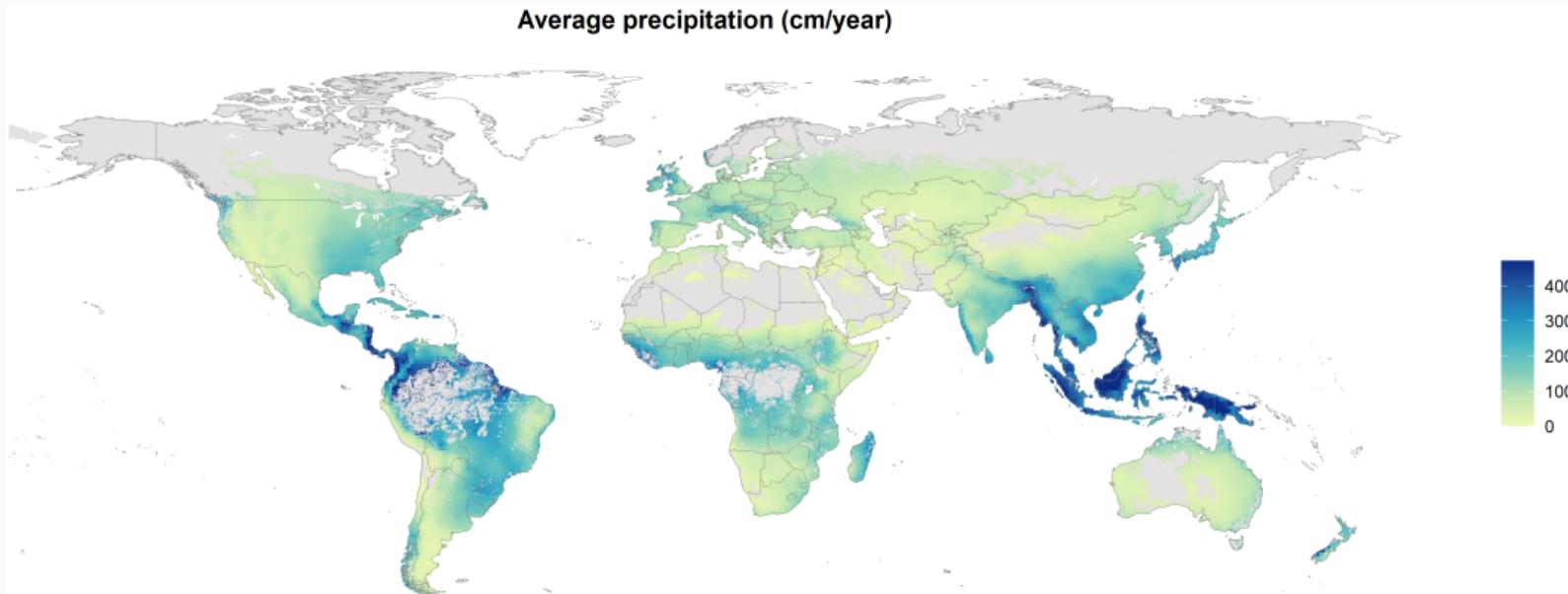
## Other Global Hydrological Spatial Data:

- Precipitation: **GMFD v.3**
- Aridity: [Trabucco and Zomer \(2019\)](#)
- Soil type: [Hengl et al. \(2017\)](#)
- Specific yield by soil type: [Loheide, Butler, and Gorelick \(2005\)](#)
- Surface water occurrence: [Pekel et al. \(2016\)](#)

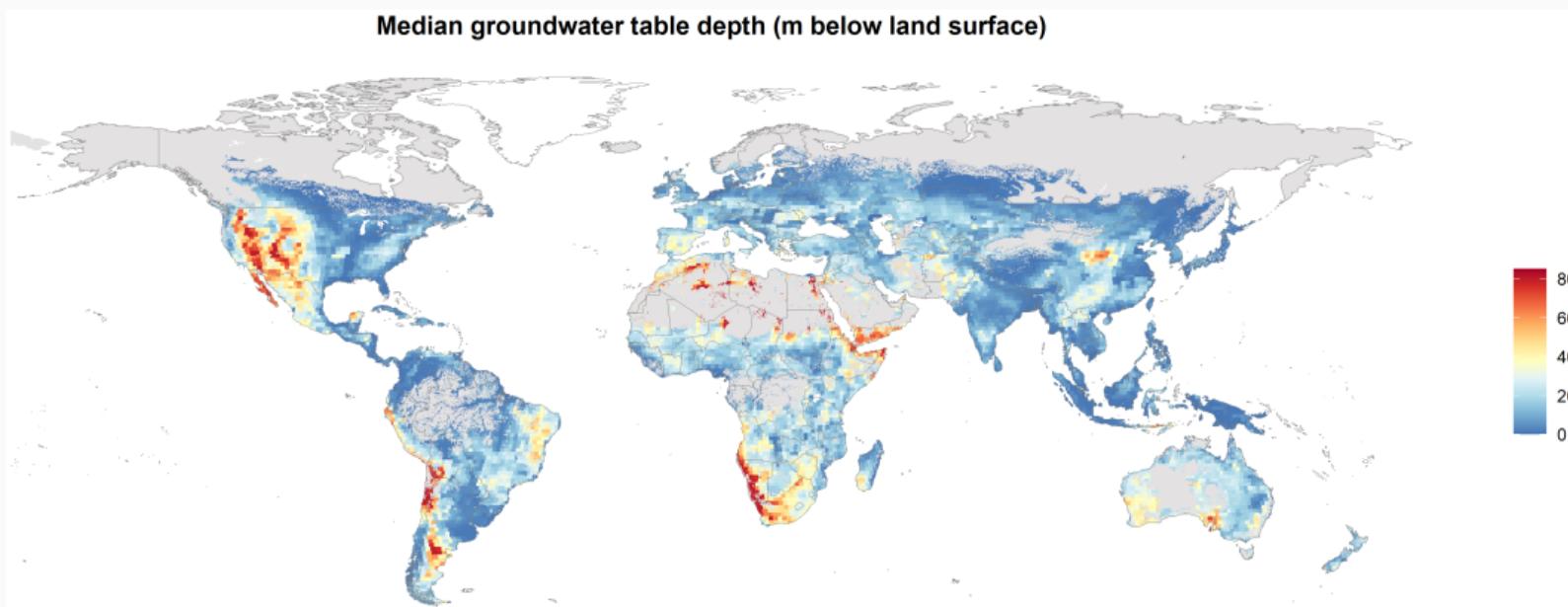
## Facts

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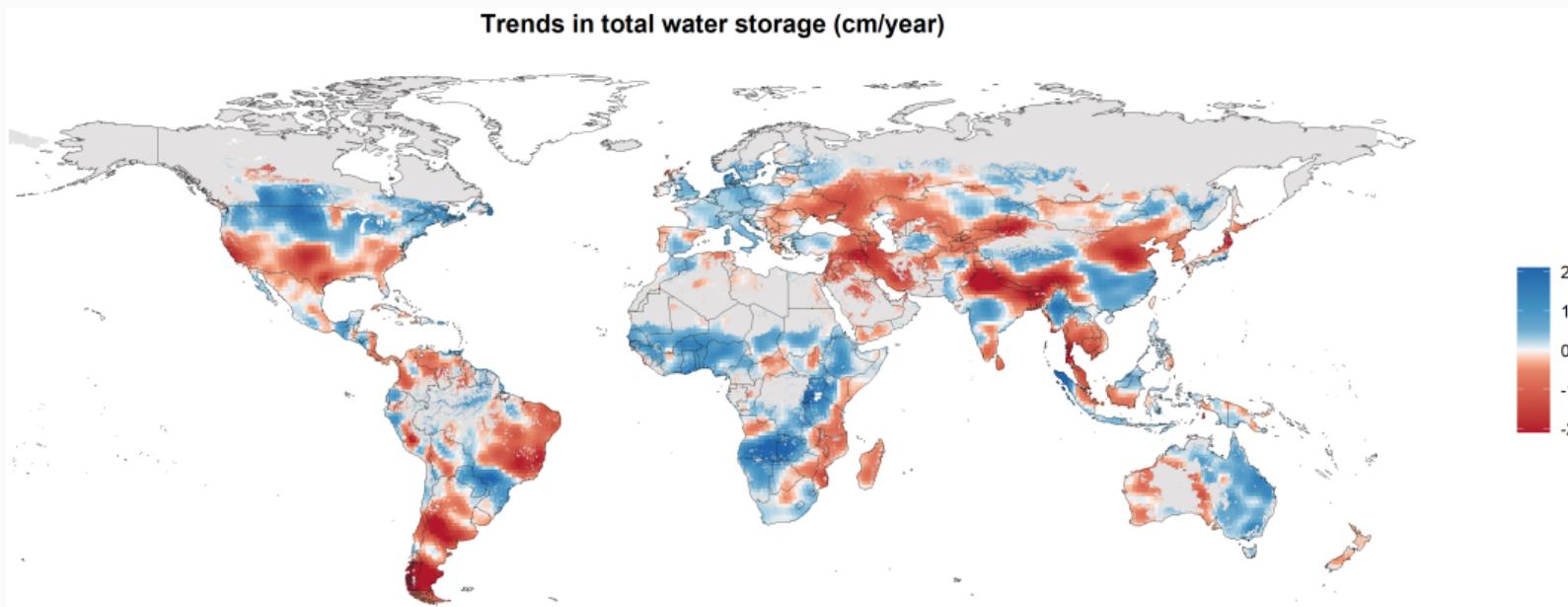
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## Fact 2: Agriculture dominates global water consumption

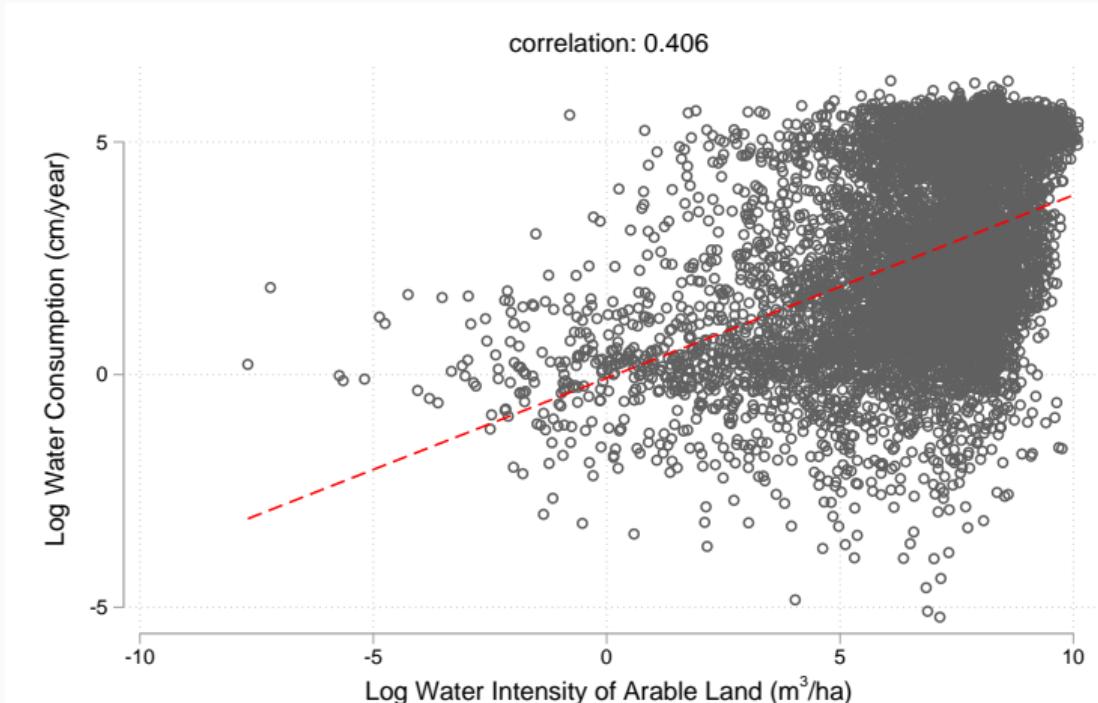
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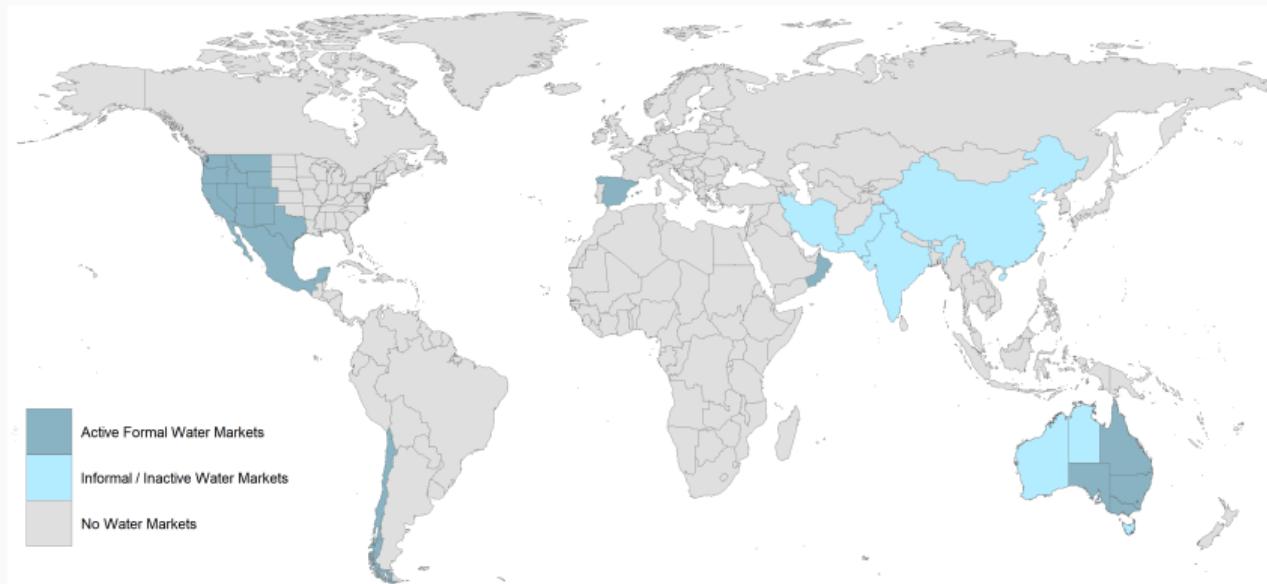
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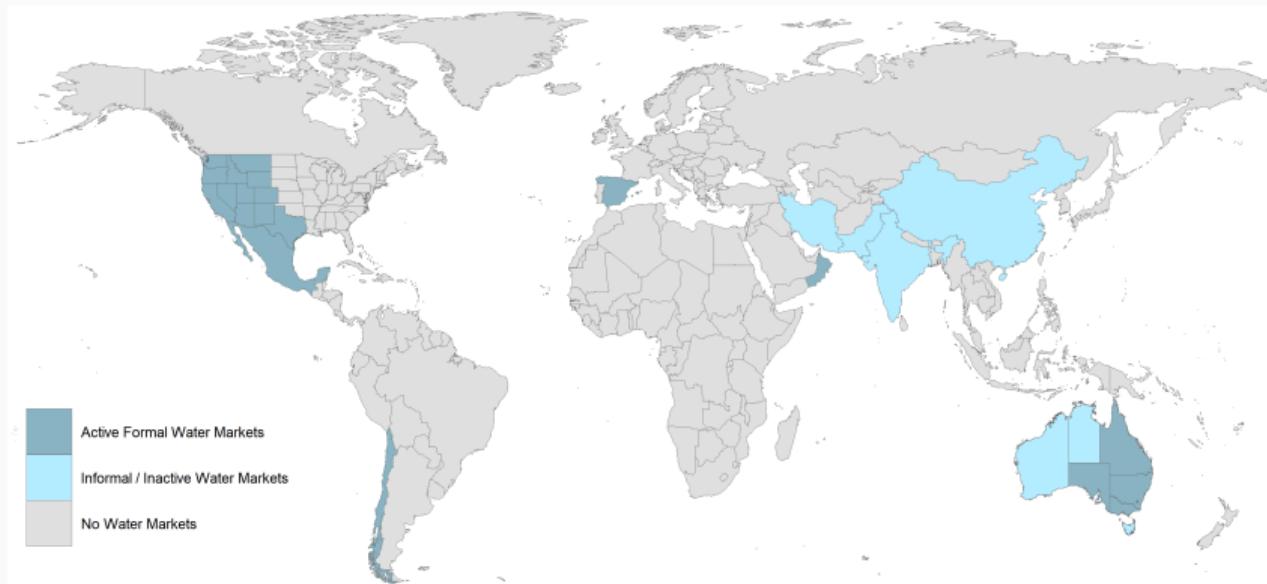
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## Fact 3: Local markets for water rarely exist



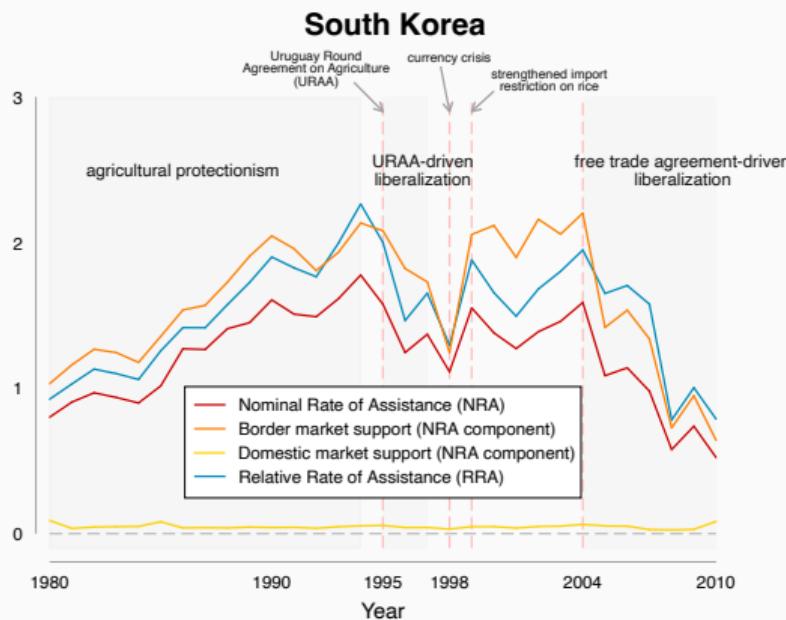
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- ~94% of global agricultural production is in regions with no formal water markets
- With markets, price may not reflect social cost because of dynamic/spatial externalities

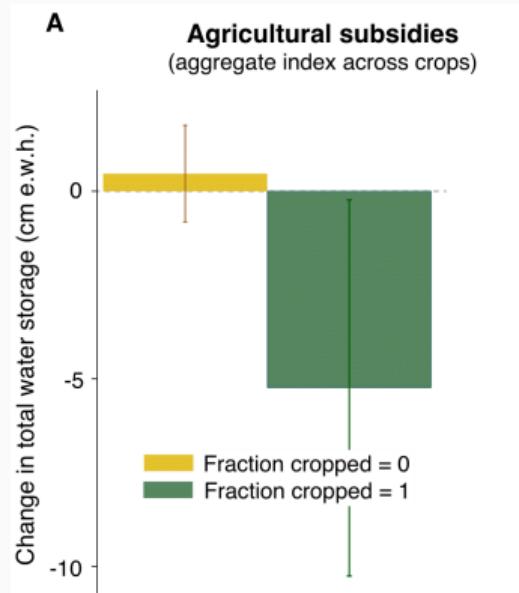
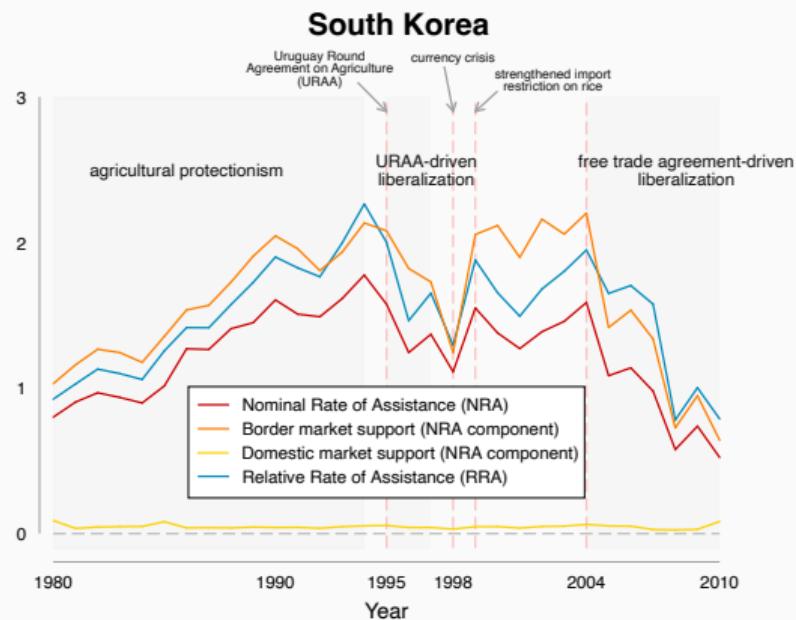
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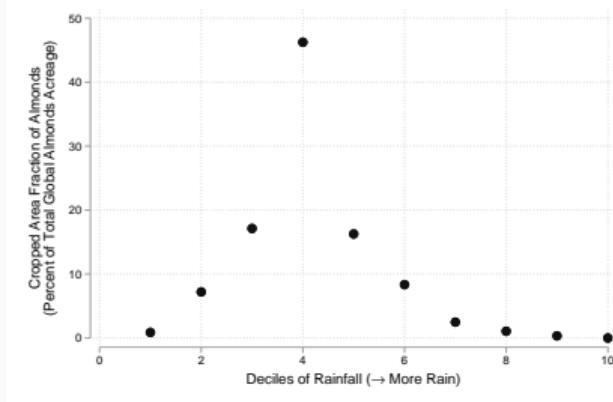
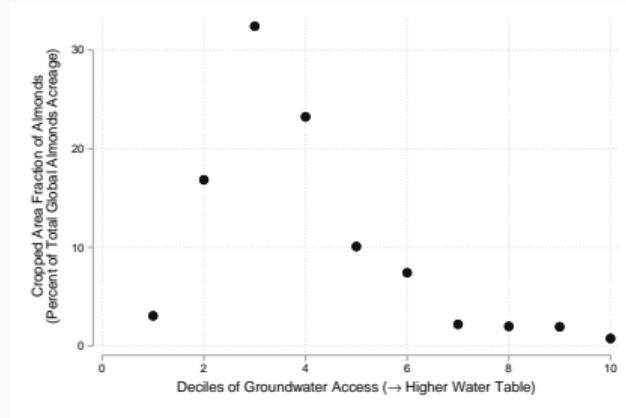


## Fact 5: Water-intensive crops locate primarily in water-abundant regions

**Almonds**

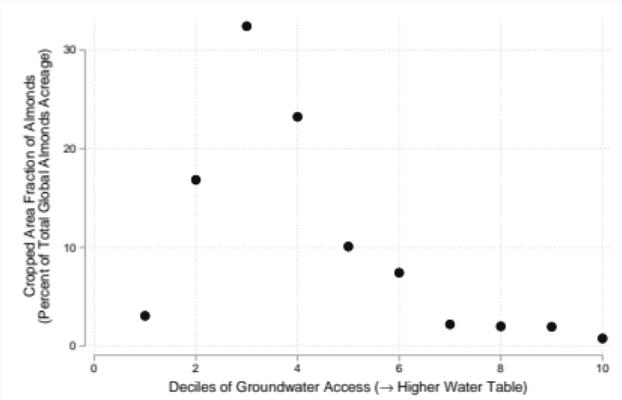
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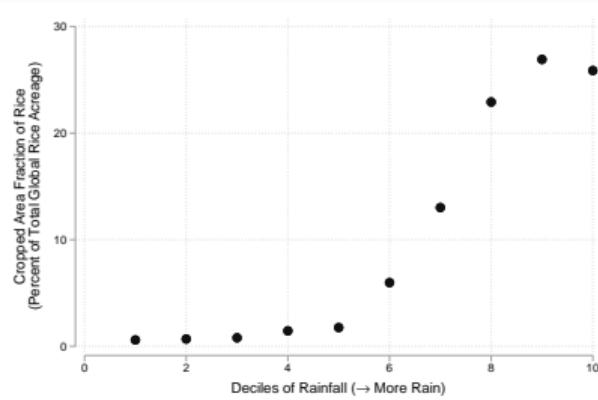
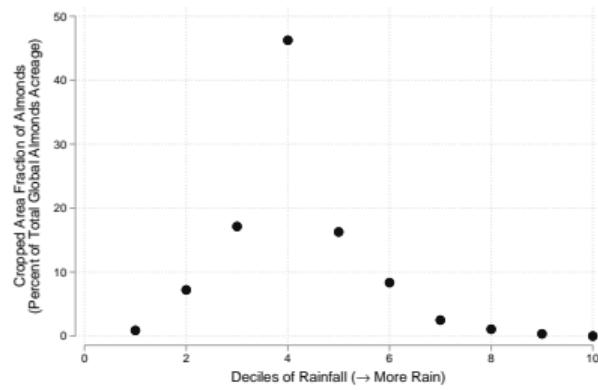
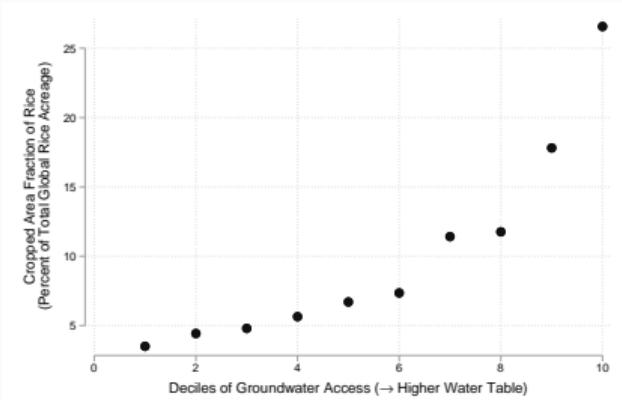


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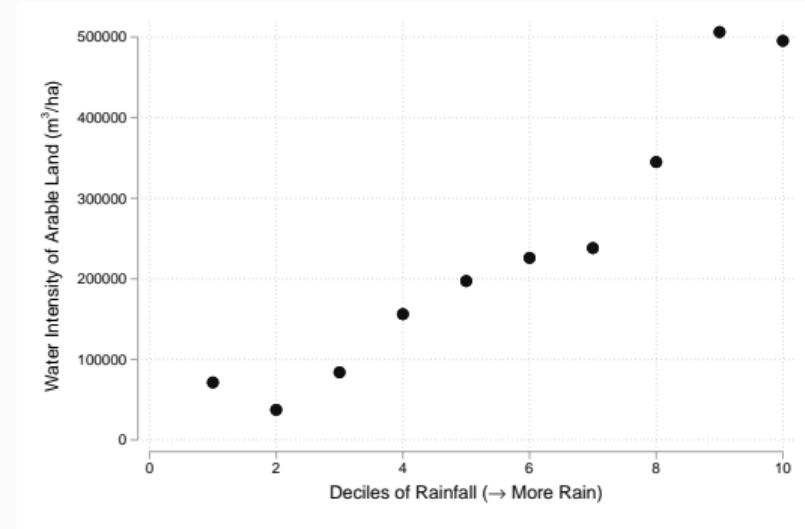
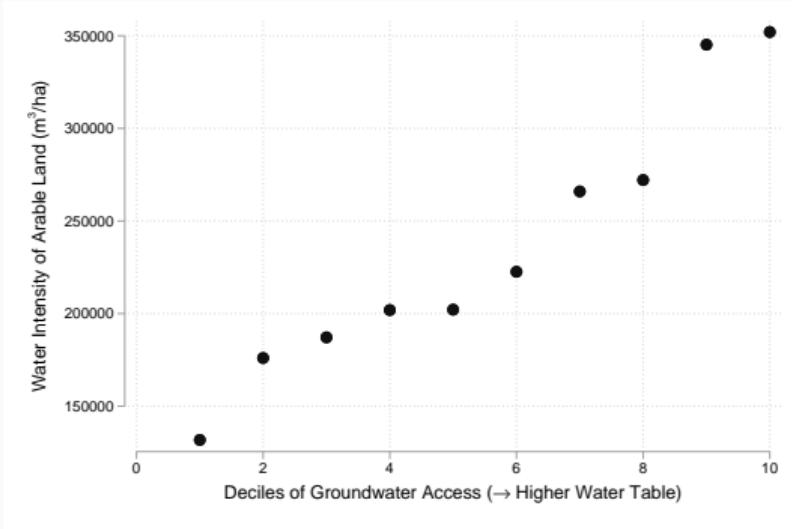
Almonds



Rice



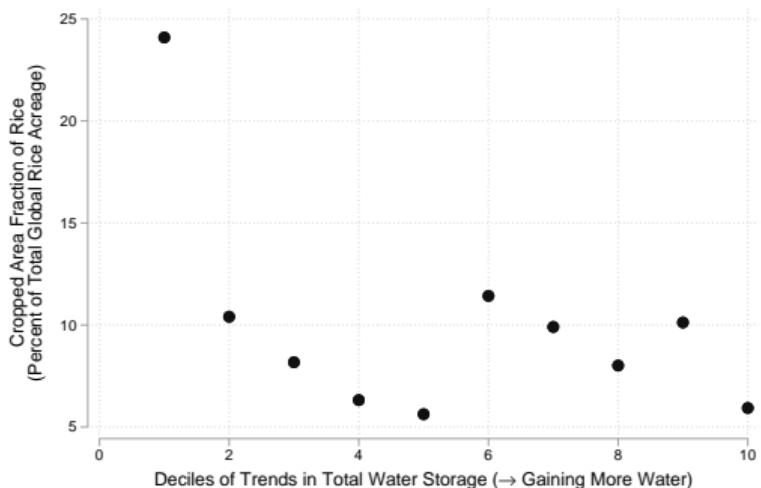
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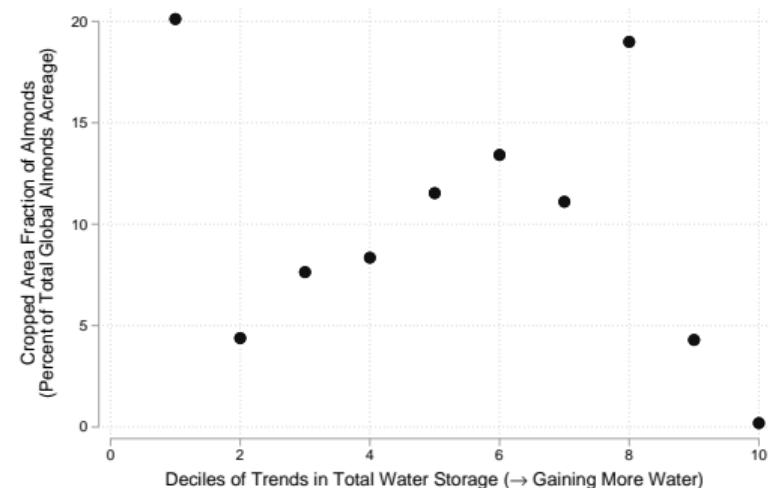
$$\text{Water Intensity of Arable Land} = \frac{\sum_{k \in K} \text{Acres}^k \times \left( \frac{\text{Water } (m^3)}{\text{Acre}} \right)^k}{\sum_{k \in K} \text{Acres}^k + \text{Pasture Land}} = \frac{\text{Water } (m^3)}{\text{Acre}}$$

## Fact 5: Water-intensive crops also locate in some regions rapidly losing water

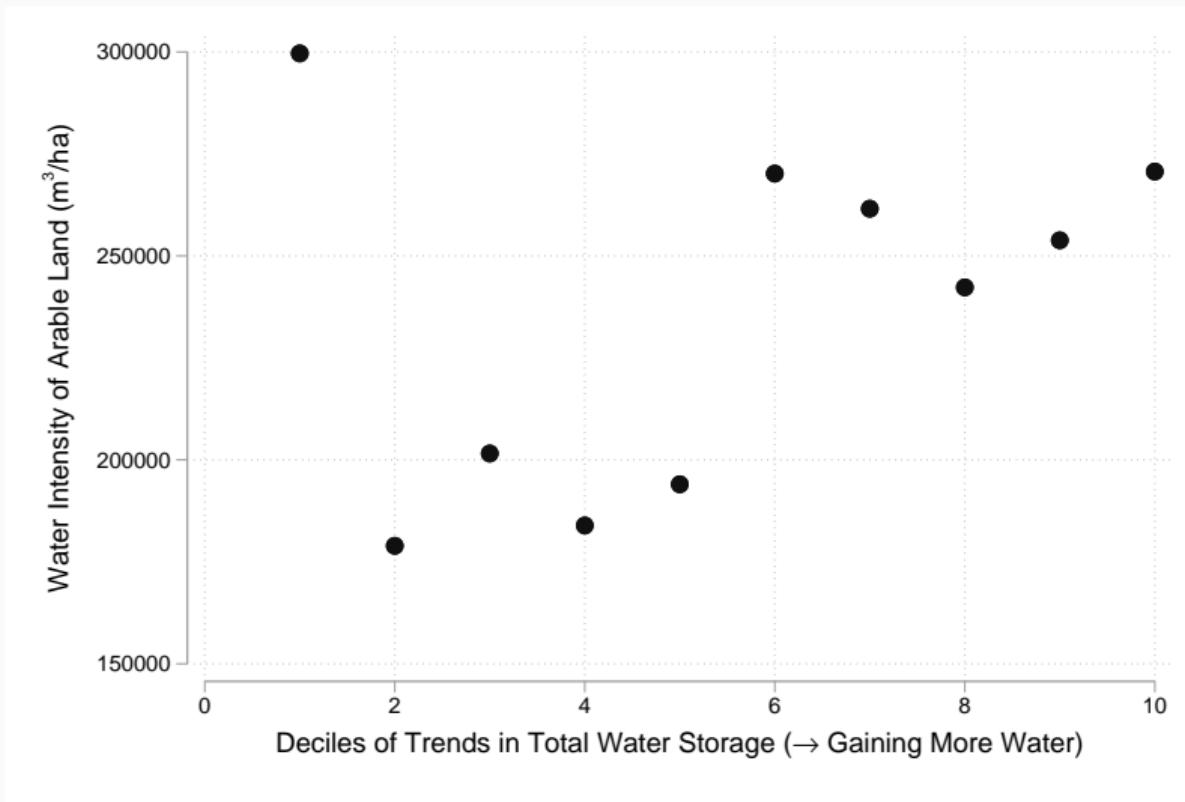
### Rice Acreage by Water Trends



### Almond Acreage by Water Trends



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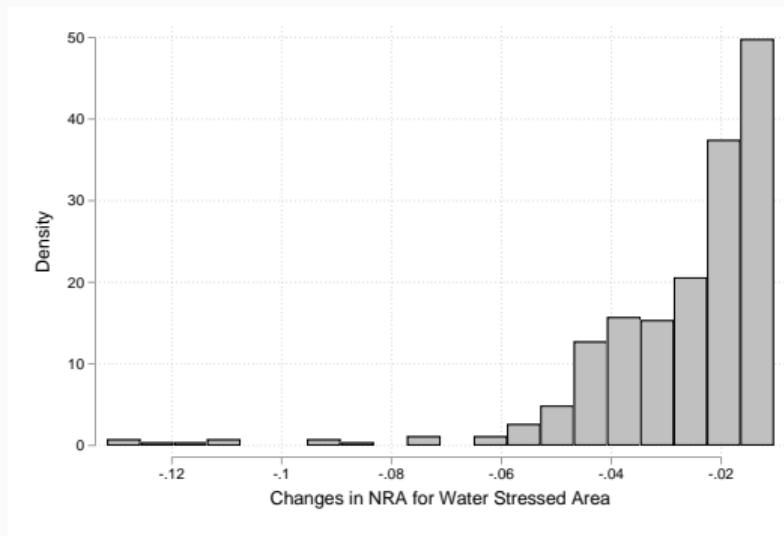
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4. Agricultural policy greatly affects water use → **maybe it hurts, but maybe it can help**
5. Water-intensive crops primarily locate in water-abundant regions, but also in some water-losing regions → **gains from existing trade, potential further reallocation**

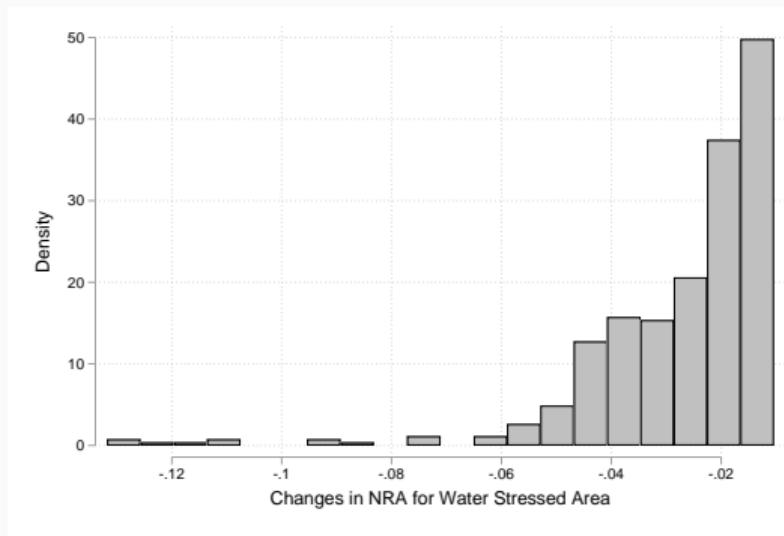
# Partial equilibrium counterfactual—Can ag. policy alleviate water stress?

Estimated change in NRA to bring “water stressed” regions to steady-state:



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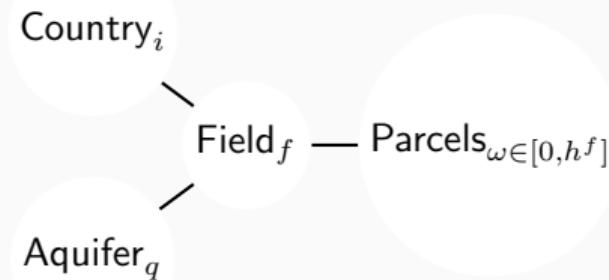
But PE counterfactuals miss: **Welfare, GE effects, Policy interactions**

# Model

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## Basic environment

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



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

## Preferences of each country's representative consumer

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

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

## Technology I: Agriculture

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

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

to produce

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

of crop  $k$ , where

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

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

## Technology II: Water extraction

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

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

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

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

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

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

## Technology III: Outside good

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

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

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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**  $\tau_{jt}^k$  summarizes effect of taxes/subsidies/tariffs/quotas/...

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

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

where

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

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

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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

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

where

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

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

## Equilibrium II: Profit maximization and labor choice

- Each laborer  $\omega$  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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- By i.i.d. Fréchet with common shape parameter,

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

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

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

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

- 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

- Field-level ( $f$ ): from **GAEZ** at 5-arc minute level
  - potential yields  $A^{fk}$  for each crop  $k$
  - area  $h^f$  (in hectares)
- Country-level ( $i$ ): from **FAOSTAT** and **World Bank**
  - crop-specific output  $Q_{it}^k$
  - crop-specific NRA  $\tau_{it}^k$  and farm-gate price  $\tau_{it}^k p_{it}^k$
  - total cultivated land  $L_{it}$
- Bilateral country-level ( $ij$ ): from **UN Comtrade**
  - bilateral trade flows  $Y_{ijt}^k \equiv \tau_{it}^k p_{it}^k \delta_{ij}^k C_{ijt}^k$
- Aquifer-level ( $q$ ): from **GRACE** and **Fan, Li, and Miguez-Macho (2013)**
  - $\Delta \text{TWS} \equiv R_q - (1 - \psi) X_{qt}$
  - initial depths  $D_{q,0}$

## 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
- $\alpha$  labor share in crop production
- $\{\phi^k\}$  crop-specific water intensity
- $\theta$  technological heterogeneity (Fréchet shape parameter)
- $\{A_i^o\}$  mean labor productivity in outside sector
- $\psi$  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	$\alpha$	0.75	Boppart et al. (2019)
return flow rate	$\psi$	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	$\{R_q\}$		function of rainfall & aridity (Berghuijs et al., 2021) rainfall (GMFD v.3) aridity (Trabucco and Zomer, 2019)

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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

$$\ln(Y_{ij}^k / Y_j^k) = FE_j^k + (1 - \sigma) \ln(\tau_i^k p_i^k) + \epsilon_{ij}^k$$

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

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

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## Estimating the supply side

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

$$\min_{\theta, \{A_i^o\}, \{\Upsilon_q\}} \sum_i \sum_k [\ln Q_i^k(\theta, \{A_i^o\}, \{\Upsilon_q\}) - \ln Q_i^k]^2 + \sum_q [\ln X_q(\theta, \{A_i^o\}, \{\Upsilon_q\}) - \ln X_q]^2$$

subject to

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

with a bootstrapped 95% confidence interval for  $\theta$ , where *observed* extraction is

$$X_q := \frac{R_q - \Delta \text{TWS}}{1 - \psi}$$

### 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 counterfactuals

1. **Eliminate trade in agriculture:** set  $\delta_{ji}^k = \infty$  for all  $k$  and  $i \neq j$ 
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  - Do *all* observed agricultural market interventions offset or exacerbate input market failures?

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## Model counterfactuals

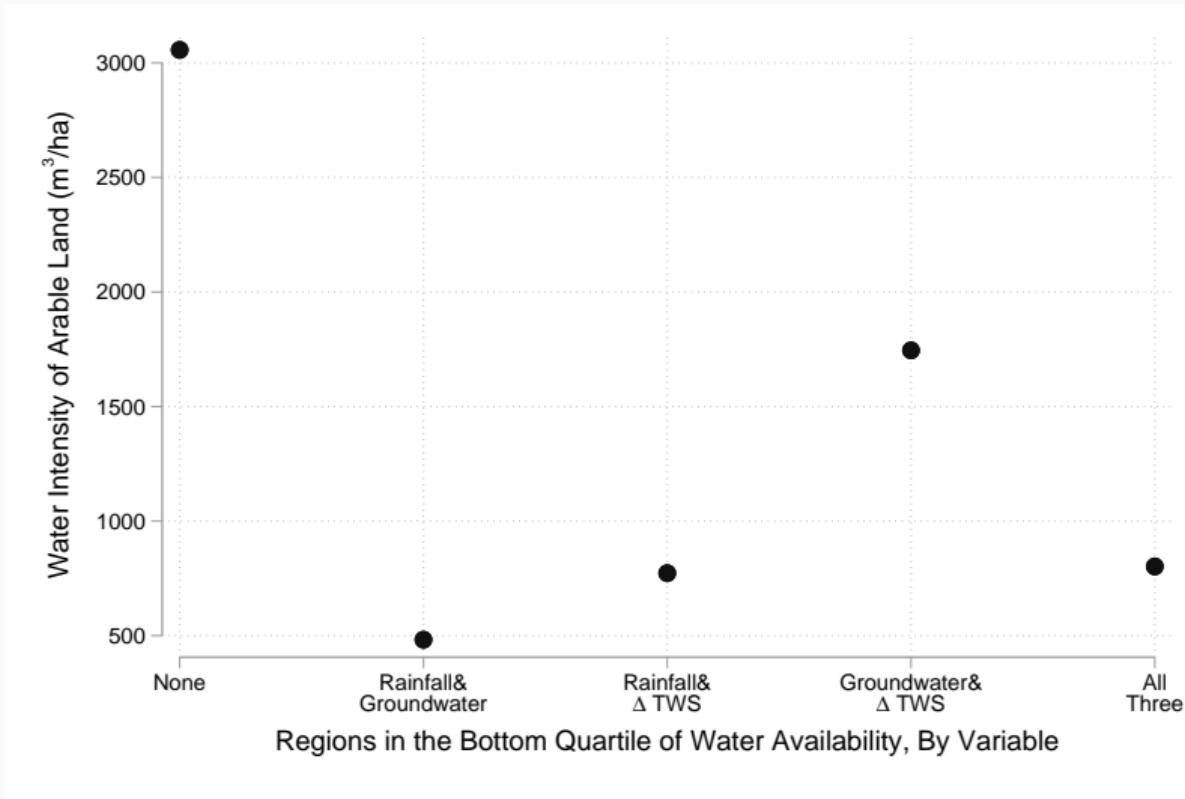
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  - Do *all* observed agricultural market interventions offset or exacerbate input market failures?
3. **Solve for optimal steady state:** planner internalizes dynamic cost of water extraction
4. **Solve for planner's constrained steady state:** find  $\{\tau_i^k\}$  that achieves closest to the unconstrained optimum
  - Can agricultural policies offset intractable water market distortions?

Stay tuned for the punch lines!

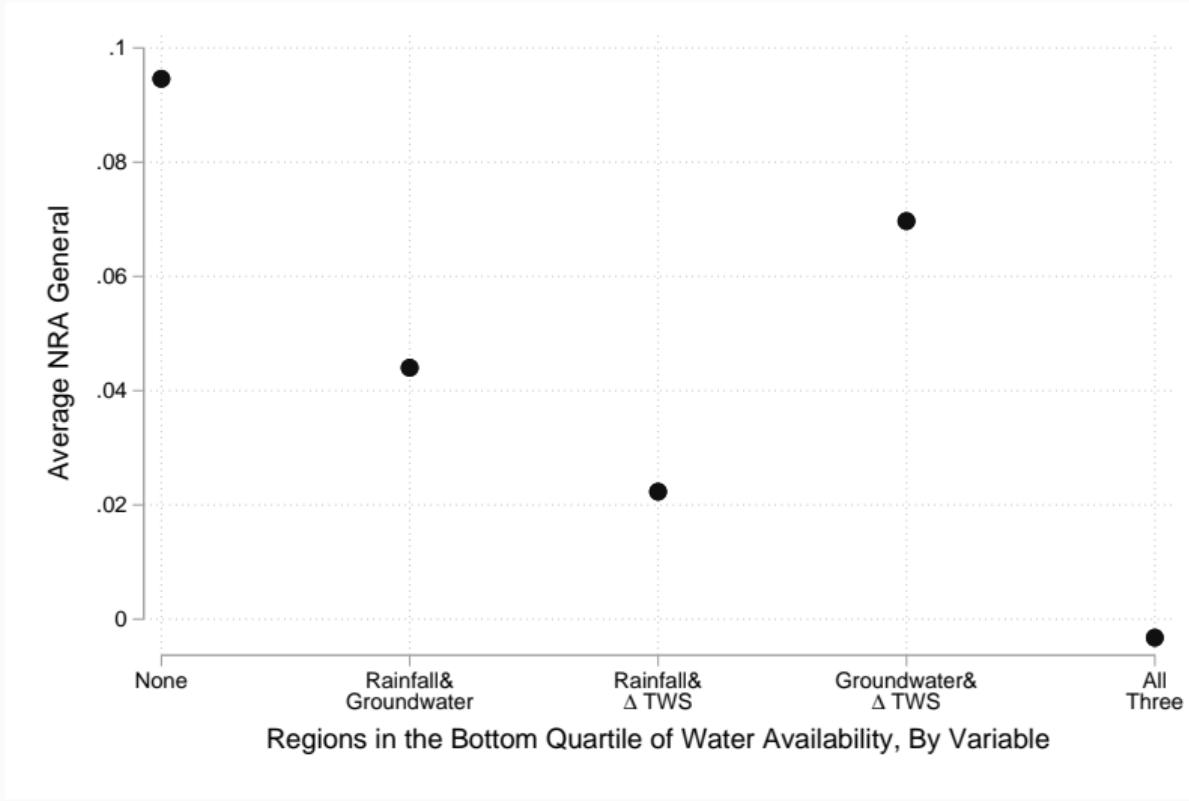
## Appendix

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## Fact 5: Water-intensive crops also locate in some regions rapidly losing water



# Similar patterns in water intensity and agricultural policy



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