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

Tamma Carleton (UCSB & NBER)
Levi Crews (UChicago)
Ishan Nath (Federal Reserve Bank of San Francisco)

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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

- $\sim$12 liters of water used to grow one almond
- California almond production has **doubled** in the last 20 years
- Expansion coincides with drought and land subsidence due to groundwater extraction
- **70% of California almonds are exported abroad**

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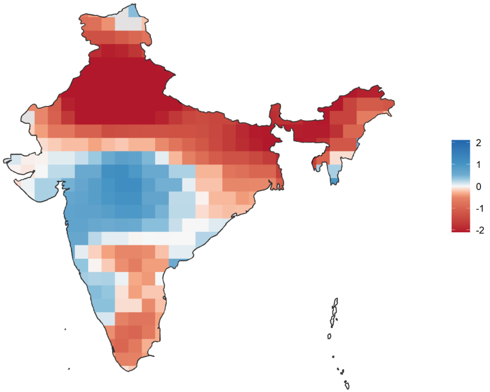
Tough nut to crack: the almond boom and its drain on the Murray-Darling

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

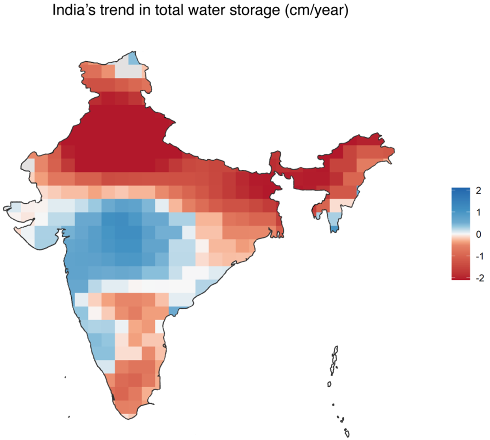
Almond fields near Mildura. There are fears the Murray-Darling water management regime may not be able to handle the boom in the water-intensive crop. Photograph: Mike Bowers/The Guardian

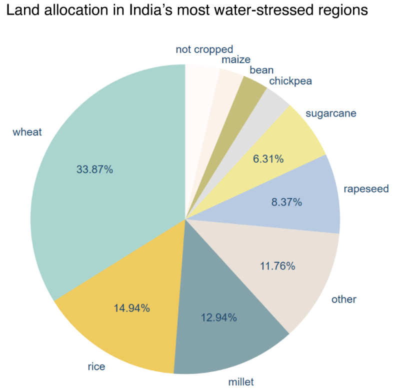
Water-intensive production in water-scarce regions

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

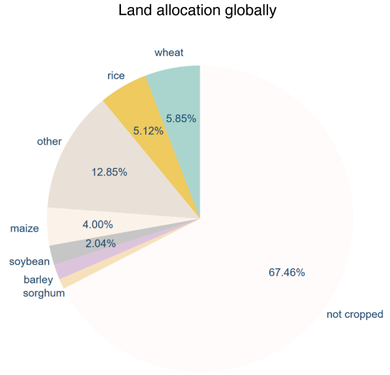


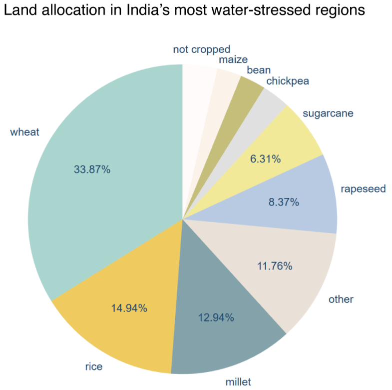
Water-intensive production in water-scarce regions





Water-intensive production in water-scarce regions





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

Ag./trade policy $\rightarrow$ ag./trade spatial allocation $\leftrightarrow$ long-run water availability

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?

This Paper

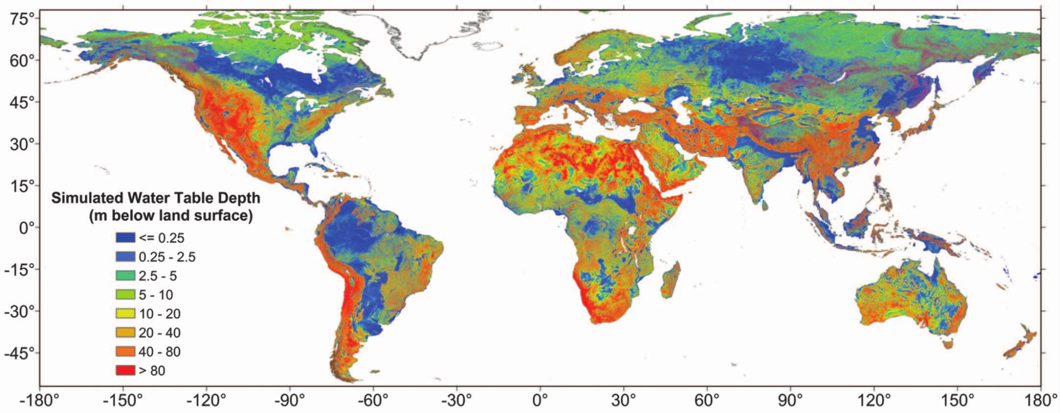
- Compile **globally comprehensive geospatial dataset** on water and agriculture
- Establish a **series of facts** about the allocation of water in global agricultural production:
  - Input market property right failures and agricultural market interventions are ubiquitous
  - Water-intensive crops concentrate *highly* in water-abundant locations, and also in a few locations losing water rapidly
- Calibrate a **quantitative dynamic spatial equilibrium model** for the world
  - Model captures aquifer drawdown and recharge, crop production and consumption, agricultural trade and policy
- Use **model simulations** to answer the following research questions: (*in progress*)
  - What are the potential welfare gains from reallocating global water use in agriculture?
  - 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 $\rightarrow$ 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

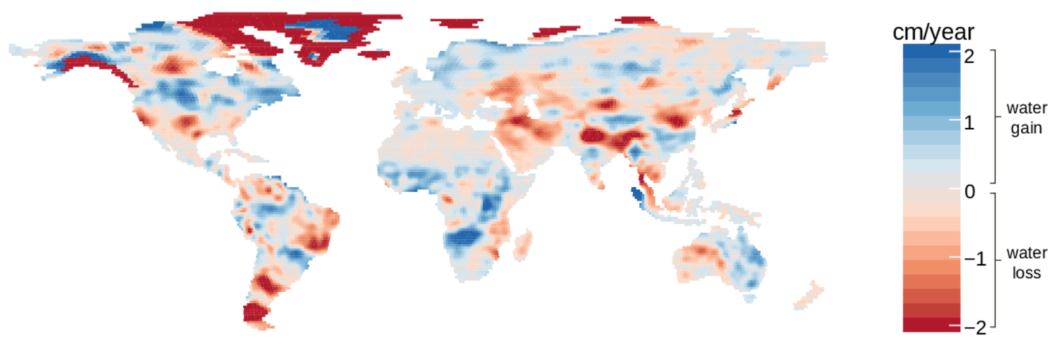
Data

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



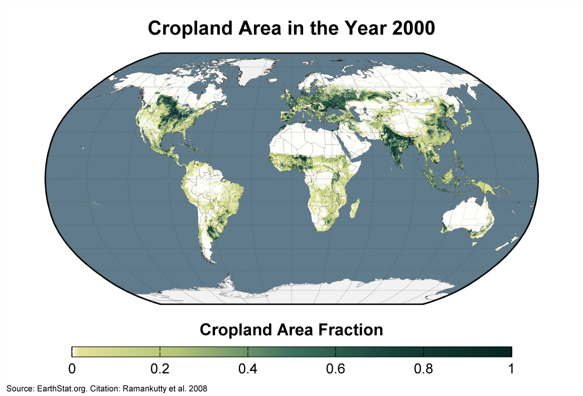
- Global snapshot at 30 arc-second ($\sim$1km) resolution
- *How*: Hydrological model interpolates over measurements from $>$1.6 million well sites

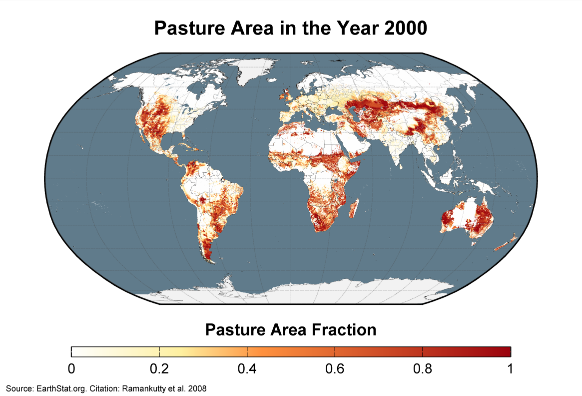
Trends in total water storage: GRACE



- 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)

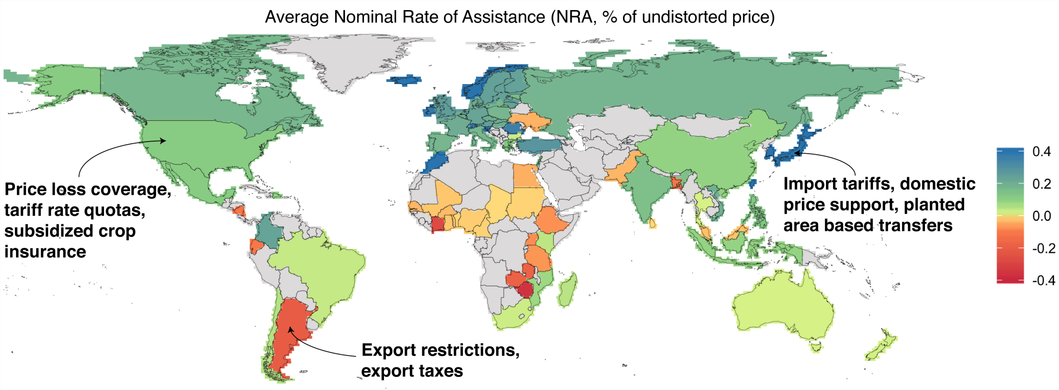
Agricultural land use: SAGE





- **Cropped area fraction** for 175 crops (& pasture) at ∼10km×10km 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 ($\sim$2.2 million grid cells on land)
- *How*: Agronomic model combining detailed land & crop characteristics with different input mix and climate scenarios, taking time series average over 1961–90

Agricultural Production & Trade: **FAOSTAT**

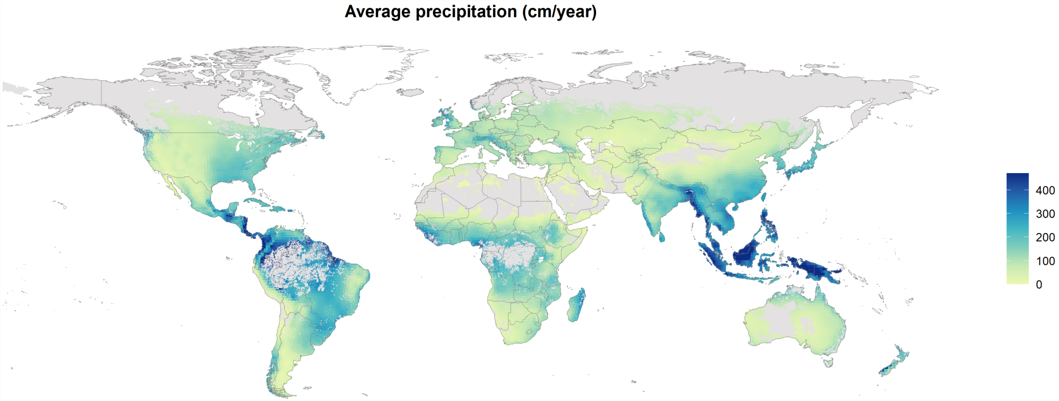
- Crop-specific quantities *and* farm-gate prices (USD/ton) for $>$200 countries back to 1961
- Bilateral trade flows in USD by crop, but we use **Comtrade** for better coverage

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

Fact 1: Vast spatial heterogeneity in water resources



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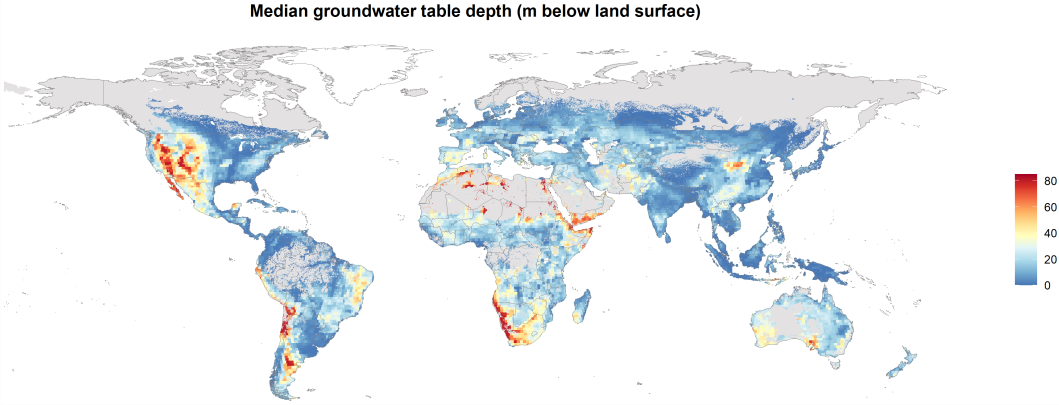

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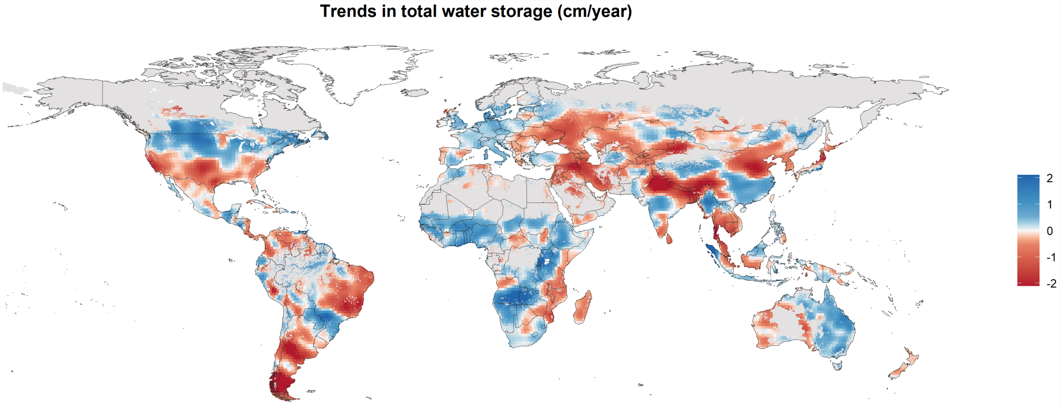
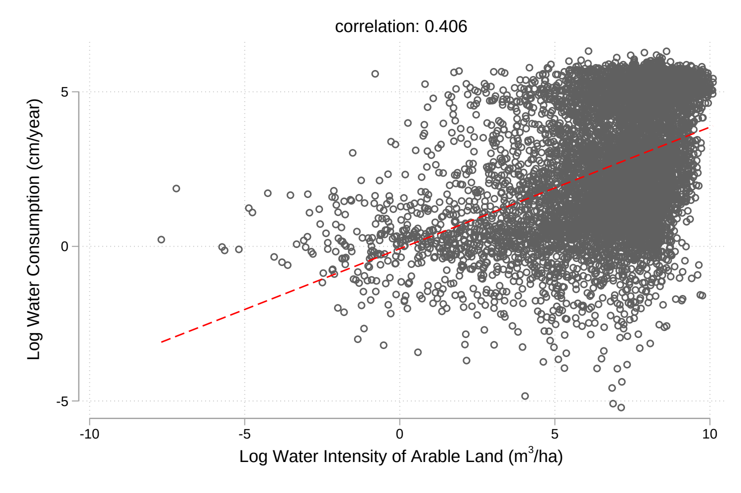


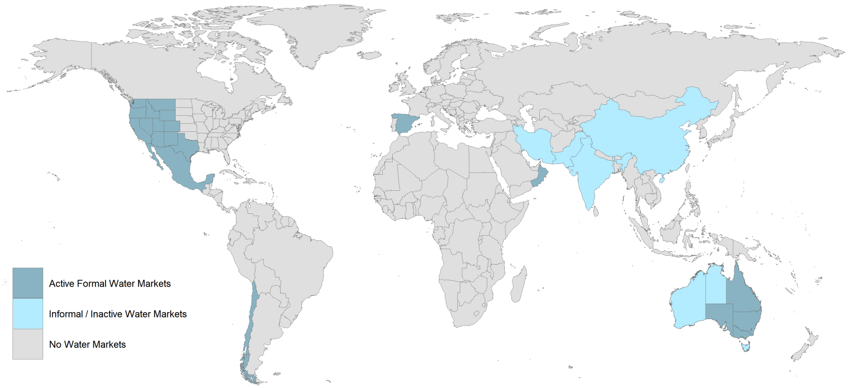
Fact 2: Agriculture dominates global water consumption

Hoekstra and Mekonnen (2012): Agriculture accounts for **92%** of global water consumption

22% of water consumption embedded in international agricultural trade



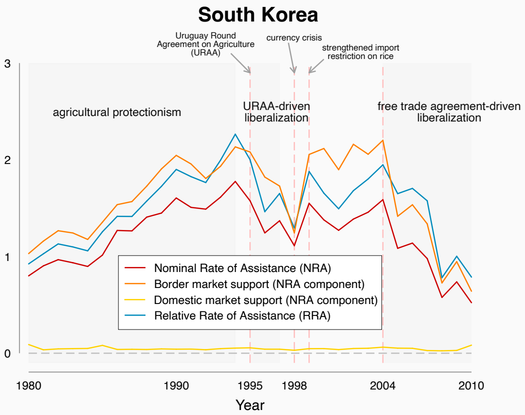
Fact 3: Local markets for water rarely exist



- ∼**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

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

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



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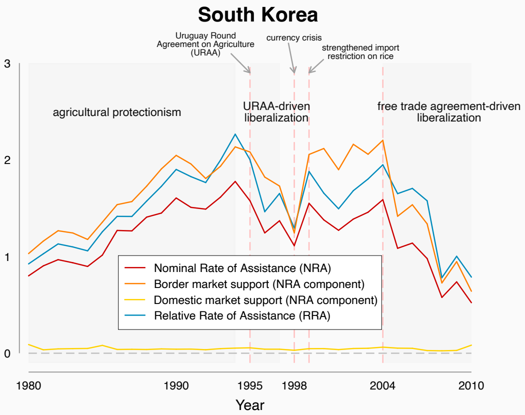
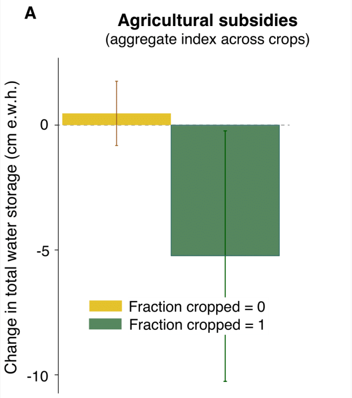
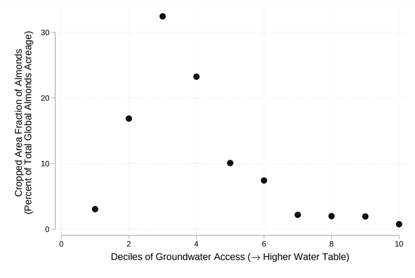
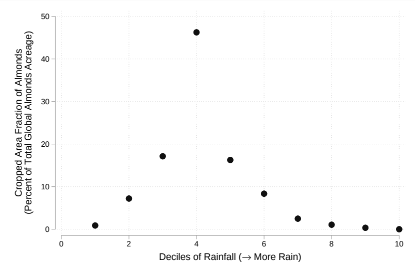




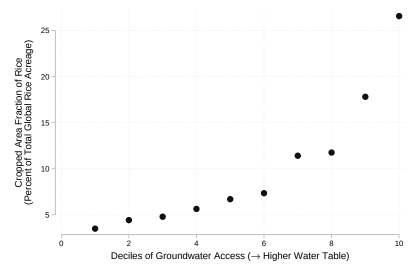
Fact 5: Water-intensive crops locate primarily in water-abundant regions

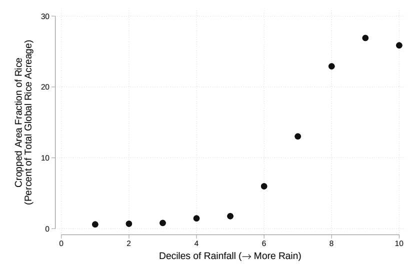
Almonds





Rice





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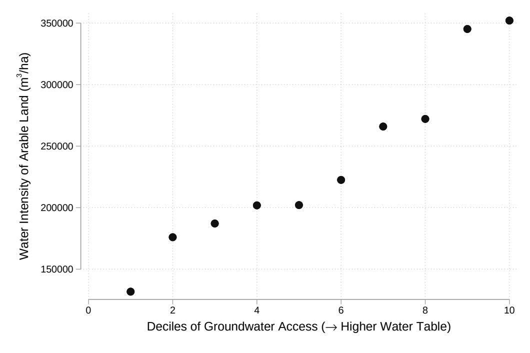
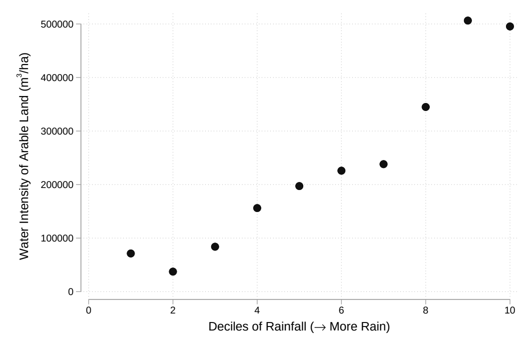
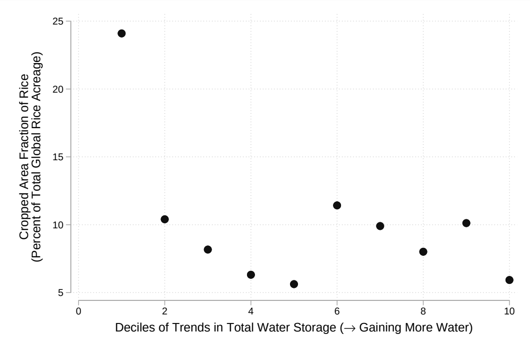




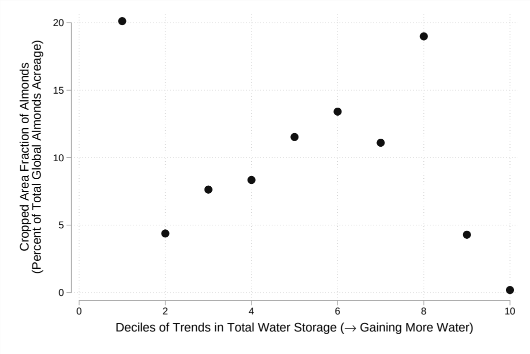
$$\text{Water Intensity of Arable Land} = \frac{\sum_{k \in K} \text{Acres}^k \times \left(\frac{\text{Water (m}^3)}{\text{Acre}}\right)^k}{\sum_{k \in K} \text{Acres}^k + \text{Pasture Land}} = \frac{\text{Water (m}^3)}{\text{Acre}}$$

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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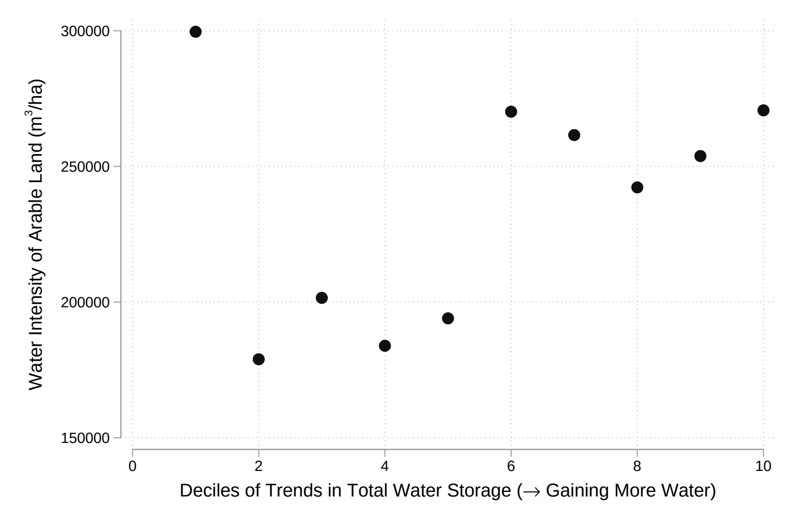


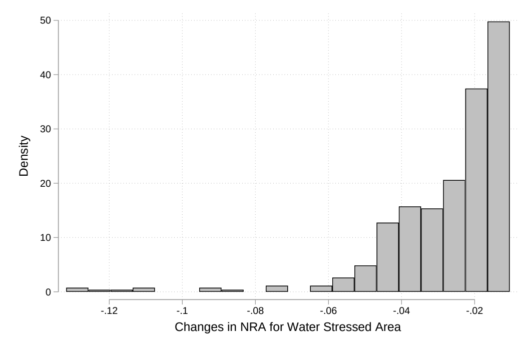
Additional results

Fact summary

1. Vast spatial heterogeneity in water resources → **comparative advantage + dynamics**
2. Agriculture dominates global water consumption → **focus on agriculture & trade**
3. Local markets for water rarely exist → **spatial & temporal externalities**
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:

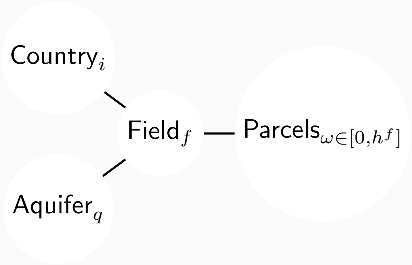


But PE counterfactuals miss: **Welfare**, **GE effects**, **Policy interactions**

Model

Basic environment

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



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

Preferences of each country's representative consumer

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

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

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

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 $A^w_q(D) = \Upsilon_q D^{-\upsilon}$.
- **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:

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

- **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/...
- **Groundwater evolution**: The depth D_{qt} follows the law of motion

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

where

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

No dynamic choices, but the evolution of depths matters!

Equilibrium I: Utility maximization

Utility maximization by the representative household in each country requires that

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

where

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

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

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

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

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

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

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

Equilibrium III: Definition of competitive equilibrium

Given NRAs, $\{\tau_{it}^k\}$, and initial groundwater depths, $\{D_{q0}\}$, a competitive equilibrium is a **path** of consumption, $\{C_{jit}^k\}$, output, $\{Q_{it}^k\}$, prices, $\{p_{it}^k\}$, shares, $\{\pi_t^{fk}\}$, groundwater depths, $\{D_{qt}\}$, and groundwater extractions, $\{X_{qt}\}$, such that

- representative consumers maximize their utility;
- laborers select activities to maximize their returns;
- markets clear:

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

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

- depths obey their law of motion.

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

Quantification

Data

- 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 τ_{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)**
  - ΔTWS $\equiv R_q - (1-\psi)X_{qt}$
  - initial depths $D_{q,0}$

Parameters to be calibrated/estimated

☐	σ, κ	demand elasticities
☐	$\{\zeta_j, \zeta_j^k, \zeta_{ij}^k\}$	demand shifters
☐	$\{\delta_{ij}^k\}$	bilateral crop-specific trade costs
☐	α	labor share in crop production
☐	$\{\phi^k\}$	crop-specific water intensity
☐	θ	technological heterogeneity (Fréchet shape parameter)
☐	$\{A_i^o\}$	mean labor productivity in outside sector
☐	ψ	return flow rate
☐	$\{\rho_q\}$	specific yield
☐	$\{R_q\}$	natural recharge
☐	$\{\Upsilon_q\}$	scale of extraction productivity $A_q^w(D) = \Upsilon_q D^{-\upsilon}$
☐	υ	elasticity of extraction productivity

Calibrating technological and hydrological parameters

Parameter		Value	Source
labor share	α	0.75	Boppart et al. (2019)
return flow rate	ψ	0.25	Dewandel et al. (2008)
extraction elasticity	υ	1.0	Burlig, Preonas, and Woerman (2021)
water intensity	$\{\phi^k\}$		convert from Mekonnen and Hoekstra (2011)
specific yield	$\{\rho_q\}$		s.y. by soil type (Loheide, Butler, and Gorelick, 2005)
			soil type (Hengl et al., 2017)
natural recharge	$\{R_q\}$		function of rainfall & aridity (Berghuijs et al., 2021)
			rainfall (GMFD v.3)
			aridity (Trabucco and Zomer, 2019)

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

$$\ln(Y_{ij}^{k}/Y_{j}^{k}) = FE_{j}^{k} + (1-\sigma)\ln\left(\tau_{i}^{k} p_{i}^{k}\right) + \epsilon_{ij}^{k}$$

   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 $\ln[\zeta_{ij}^{k}(\delta_{ij}^{k})^{1-\sigma}] \equiv \epsilon_{ij}^{k}$
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}
5. ζ_j is just the value of expenditure on agricultural goods by j

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

Parameters to be calibrated/estimated

☑	$\sigma,\ \kappa$	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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☑	υ	elasticity of extraction productivity

Estimating the supply side

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

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

subject to

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

with a bootstrapped 95% confidence interval for θ, where *observed* extraction is

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

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

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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☑	υ	elasticity of extraction productivity

Model counterfactuals

1. **Eliminate trade in agriculture**: set $\delta_{ji}^k = \infty$ for all k and $i \neq j$
   - Does existing trade in agriculture improve or worsen the allocation?

2. **Eliminate all output market distortions**: set $\tau_i^k = 1$ for all i, k
   - Do *all* observed agricultural market interventions offset or exacerbate input market failures?

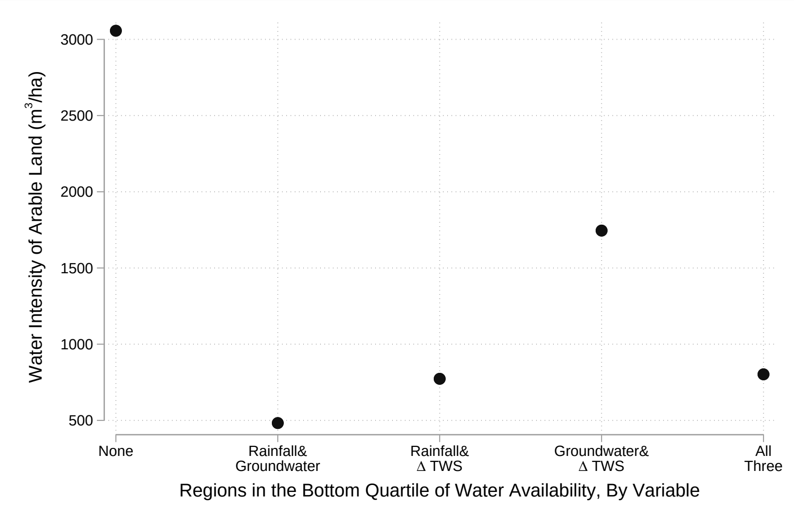
3. **Solve for optimal steady state**: planner internalizes dynamic cost of water extraction

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

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



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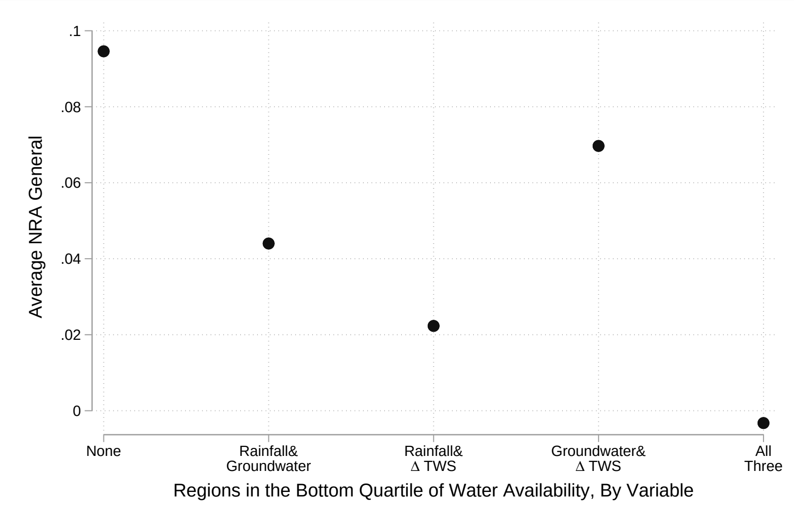
Similar patterns in water intensity and agricultural policy



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