Achieving Sustainable Irrigation Water Withdrawals: Global Impacts on Land Use

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Increasing reliance on unsustainable water withdrawal

- Non-renewable groundwater abstraction tripled over the period 1960-2000 (Wada et al., 2012)

- **Sustainable irrigation**: withdrawal less than 20% of available (Alcamo et al., 2000)
Increasing reliance on unsustainable water withdrawal

- Non-renewable groundwater abstraction \textit{tripled} over the period 1960-2000 (Wada et al., 2012)
- \textbf{Sustainable irrigation}: withdrawal less than 20\% of available (Alcamo et al., 2000)
- Irrigation vulnerability index:

\[
= \frac{\text{Irrigation Withdrawal}}{\text{Water Available for Irrigation}}
\]
Vulnerable irrigation hotspots in 2006

Source: author’s calculation based on 10-yr (2000-2010) average of simulated irrigation demand and irrigation availability.
Where to target for sustainable irrigation in the future?

Evolving irrigation vulnerability index, 2050 relative to 2006

Source: author’s calculation.
Method: Integrated hydro-economic modeling

- **Hydro-model**
  - **Irrigation availability**

- **Econ-model**
  - **Food price**
  - **Crop output**
  - **Land use change**

- **Sustainability Policies**

$model structure$
Method: Integrated hydro-economic modeling (cont.)

Global Hydro-model (irrigation supply):

- 30 arc-min, aggregated to 958 sub-basins
- Water is sourced from surface, reservoir, and soil-stored water
- Water available for irrigation is the residual after subtracting residential, industrial and livestock uses

Global Econ-model (irrigation demand):

- Partial equilibrium model with sub-national detail on water and land
- Irrigated and rainfed crop production at the 30 arc-min level
Model calibration

- Look back in time: calibrate the model to capture the stylized facts about historical cropland area change 1961-2006

- Modest overall growth, +12%, but much faster growth of irrigated area, +112% (FAOSTAT, Siebert et al., 2015)
Experiments:
Reduce sub-basin irrigation vulnerability index to 0.2 in 2050

- No adaptation
- With adaptation
  - inter-basin water transfer
  - faster TFP growth
  - integrated market
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Result 1: Cropland area change (Mha, no adaptation), 2050 relative to 2006

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<thead>
<tr>
<th>Region</th>
<th>Sustainable</th>
<th>Unsustainable</th>
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<td>Irrigated</td>
<td>Rainfed</td>
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<td>Rest of world</td>
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<tr>
<td>Total</td>
<td>156</td>
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- Sustainability constraint suppresses global cropland expansion in 2050.
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<tr>
<td>Total</td>
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<td>223</td>
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- Sustainability constraint suppresses global cropland expansion in 2050. However, it encourages more expansion into the carbon-rich rainfed area.
- Global cultivated cropland area in 2006: 1486 Mha
  \( \approx 1.5 \text{ US} \)

- Without sustainability constraint, global cropland area in 2050
  \( \approx 1.5 \text{ US} + \text{Alaska} + \text{Texas} \)

- With sustainability constraint, global cropland area in 2050
  \( \approx 1.5 \text{ US} + \text{Alaska} \)
Result 2: Compare across adaptations
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- IBT will keep China from losing 10 Mha cropland.
Result 2: Compare across adaptations

- Faster TFP growth will reduce global cropland expansion by 1/3, from 156 to 98 Mha.
Result 2: Compare across adaptations

- Trade has a similar overall effect on suppressing global cropland expansion, but the spatial distribution is remarkably different.
Result 3: Grid-level irrigated cropland change ($10^3$ ha/grid)

Global sum = -67 Mha
Summary

- Pursuing sustainable irrigation may undermine other environment and development goals.

- Adaptations affect food supply in a similar manner, but have different implications for land use change.

- The global-local-global approach has the potential to identify sub-national variations and assist decision-making at the local level.
Next step

- **Irrigation availability**
  - Yields affected by climate

- **Irrigated area change**

- **Inter-basin transfer**
  - Dams & reservoirs
  - Groundwater regulation
  - Non-ag water use efficiency

- **R&D investment**
  - Market integration
  - Irrigation efficiency
  - Reduction of food waste & post-harvest loss

- **Food price**
  - Crop output
  - Land use change
  - Malnutrition
  - Carbon emissions
  - Geographical mismatch of production & consumption

**Sustainability Policies**
SUPPLEMENTARY SLIDES
Current model features:

- 16 regions, 2 sectors, 4 commodities
- globally 58447 grids (30 arc-min)
- constant elasticity of substitution production function
- split irrigated and rainfed cropland area and crop output, grid-specific irrigation intensity ($m^3/ha$)
- Armington substitution between domestic and imported commodities
Equilibrium of land (irrigated & rainfed) and water inputs

**Demand**

\[
q_{g}^{iLand} = q_{o,g,irr} - a_{o} - \sigma_{g,irr}(p_{g}^{iLand} - p_{o}) \tag{1}
\]

\[
q_{g}^{rLand} = q_{o,g,rfd} - a_{o} - \sigma_{g,rfd}(p_{g}^{rLand} - p_{o}) \tag{2}
\]

\[
q_{B}^{Water} = \sum_{g \in B} \gamma_{g} q_{g}^{iLand} \tag{3}
\]

**Supply**

\[
q_{g}^{iLand} = \nu_{g}^{iLand}(p_{g}^{iLand} - \lambda_{g}^{iLand}) \tag{4}
\]

\[
q_{g}^{rLand} = \nu_{g}^{rLand} p_{g}^{rLand} \tag{5}
\]
(1) \( p_o + a_o = \delta_{g}^{\text{Land}} p_{g}^{\text{Land}} + (1 - \delta_{g}^{\text{Land}}) p_{n}^{\text{Land}} \) : zero profits for irrigated crop sector in grid \( g \)

(2) \( p_o + a_o = \delta_{g}^{\text{Land}} p_{g}^{\text{Land}} + (1 - \delta_{g}^{\text{Land}}) p_{n}^{\text{Land}} \) : zero profits for rainfed crop sector in grid \( g \)

(3) \( q_{g}^{n_{\text{Land}}} = \sum_{j} \beta_{g,j}^{n_{\text{Land}}} \left[ q_{o,g,j} - a_o - \sigma_{g,j} (p_{g,j}^{n_{\text{Land}}} - p_o) \right], j = \text{irr, rfd} \) : grid-level demand for non-land inputs by crops

(4) \( q_{g}^{n_{\text{Land}}} = \sum_{g} \beta_{g}^{n_{\text{Land}}} q_{g}^{n_{\text{Land}}} \) : regional demand for non-land inputs by crops

(5) \( q_{g}^{n_{\text{Land}}} = v_{g}^{n_{\text{Land}}} p_{g}^{n_{\text{Land}}} \) : regional supply of non-land inputs to crop sectors

(6) \( q_{g}^{\text{Land}} = q_{o,g,\text{irr}} - a_o - \sigma_{g,\text{irr}} (p_{g}^{\text{Land}} - p_o) \) : grid-level demand for land inputs by irrigated crop

(7) \( q_{g}^{\text{Land}} = v_{g}^{\text{Land}} (p_{g}^{\text{Land}} - \lambda_{g}^{\text{Land}}) \) : grid-level supply of irrigated land input to irrigated crop sector

(8) \( q_{g}^{\text{Land}} = q_{o,g,r\text{fd}} - a_o - \sigma_{g,r\text{fd}} (p_{g}^{\text{Land}} - p_o) \) : grid-level demand for land inputs by rainfed crop

(9) \( q_{g}^{\text{Land}} = v_{g}^{\text{Land}} p_{g}^{\text{Land}} \) : grid-level supply of rainfed land input to rainfed crop sector

(10) \( q_{g}^{\text{Water}} = \sum_{g} \gamma_{g} q_{g}^{\text{Land}} \) : sub-basin level demand for water by irrigated crop sector

(11) \( q_o = \sum_{g} \sum_{j} \alpha_{g,j} q_{o,g,j}, j = \text{irr, rfd} \) : regional crop output

(12) \( p_{g,j}^{n_{\text{Land}}} = (1 - \delta_{g,j}^{n_{\text{Land}}}) p_{g,j}^{n_{\text{Land}}} + \delta_{g,j}^{n_{\text{Land}}} l_{g,j}^{n_{\text{Land}}}, j = \text{irr, rfd} \) : land-type specific tax on non-land input usage
References