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)

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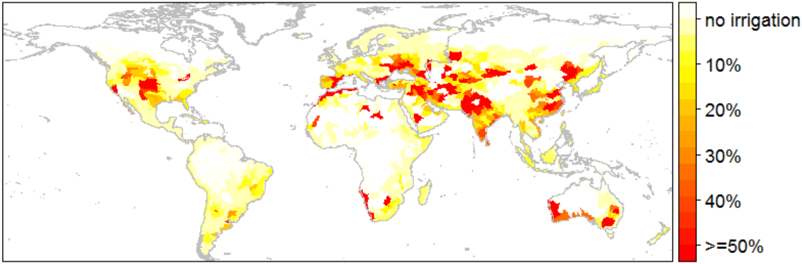
- Irrigation vulnerability index:

$$= \frac{Irrigation\ \ Withdrawal}{Water\ \ Available\ \ for\ \ Irrigation}$$

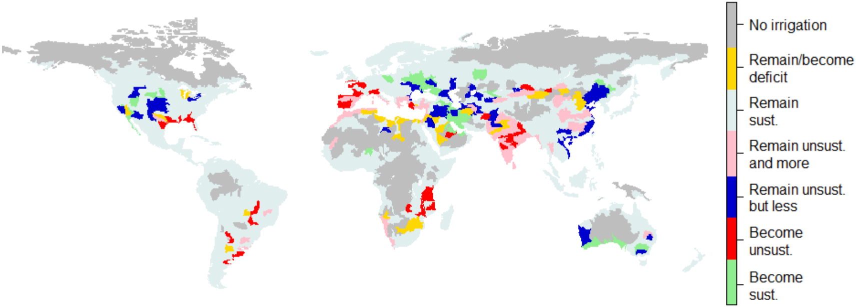
Vulnerable irrigation hotspots in 2006



Source: author's calculation based on 10-yr (2000-2010) average of simulated irrigation demand and irrigation availability.

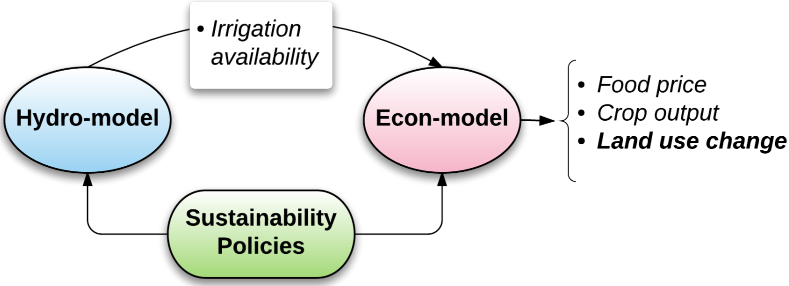
Where to target for sustainable irrigation in the future?

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 ‣ sub-basin1 ‣ sub-basin2
- Water is sourced from surface, reservoir, and soil-stored water
- Water available for irrigation is the residual after subtracting residential, industrial and livestock uses

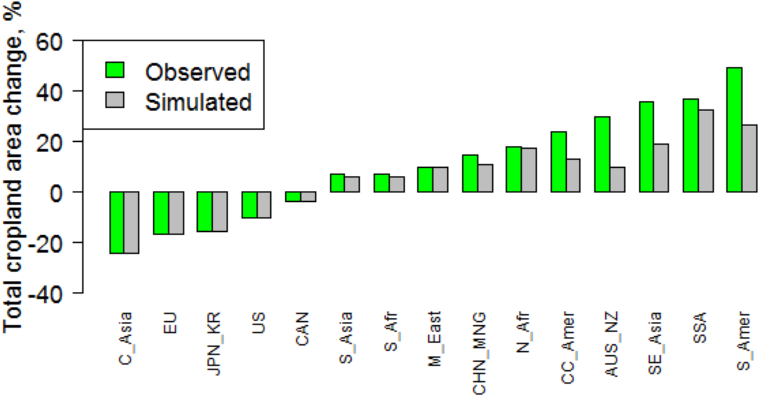
Global Econ-model (irrigation demand):

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

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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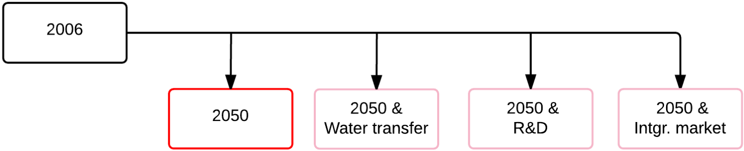

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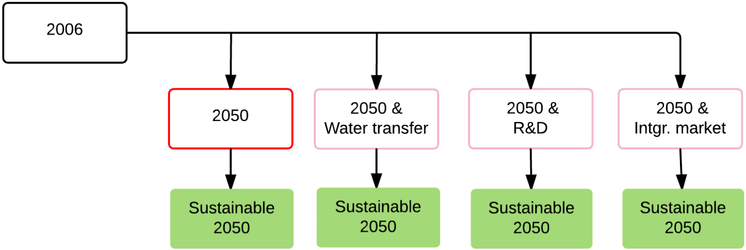

2006

2050

2050 & Water transfer

2050 & R&D

2050 & Intgr. market

Sustainable 2050

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Result 1: Cropland area change (Mha, no adaptation), 2050 relative to 2006

▸ Experiment

Region	Sustainable			Unsustainable		
	Irrigated	Rainfed	Total	Irrigated	Rainfed	Total
S_Asia			-18			31
CHN_MNG			-20			3
US			9			12
S_Amer			29			29
SSA			121			120
Rest of world			35			45
Total			156			240

- Sustainability constraint suppresses global cropland expansion in 2050.

Result 1: Cropland area change (Mha, no adaptation), 2050 relative to 2006

Region	Sustainable			Unsustainable		
	Irrigated	Rainfed	Total	Irrigated	Rainfed	Total
S_Asia	-40	22	-18	14	17	31
CHN_MNG	-23	3	-20	2	1	3
US	-3	12	9	2	10	12
S_Amer	2	28	29	2	27	29
SSA	3	118	121	3	117	120
Rest of world	-4	39	35	9	36	45
Total	-67	223	156	32	208	240

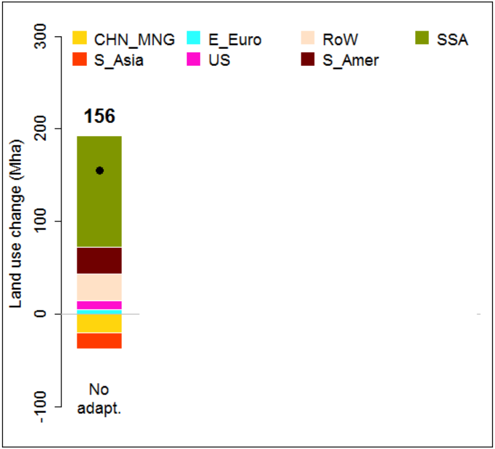
- Sustainability constraint suppresses global cropland expansion in 2050. However, it encourages more expansion into the carbon-rich rainfed area.

- Global cultivated cropland area in 2006: 1486 Mha
$\approx$ 1.5 US

- Without sustainability constraint, global cropland area in 2050
$\approx$ 1.5 US + Alaska + Texas

- With sustainability constraint, global cropland area in 2050
$\approx$ 1.5 US + Alaska

Result 2: Compare across adaptations



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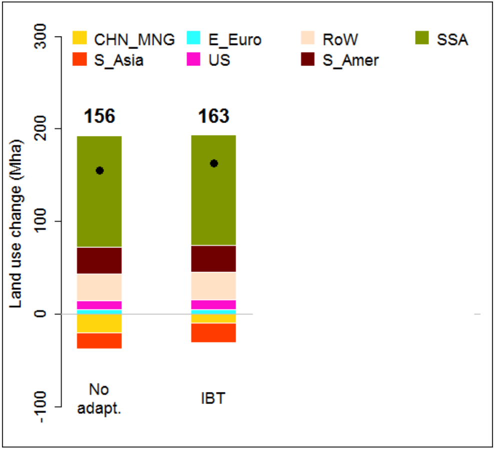

- IBT will keep China from losing 10 Mha cropland.

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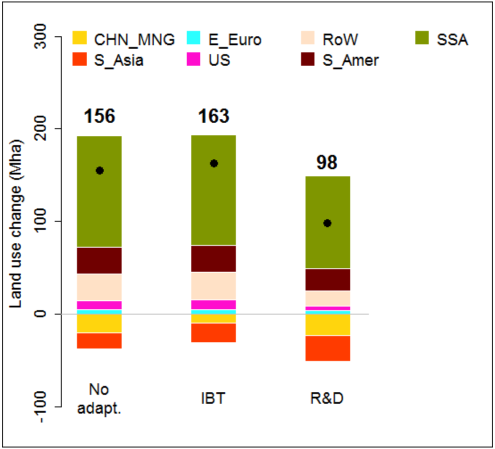
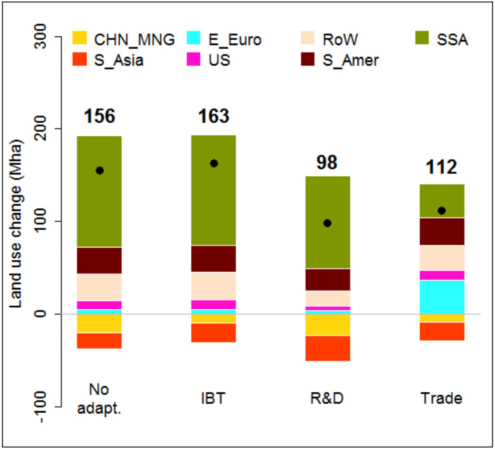


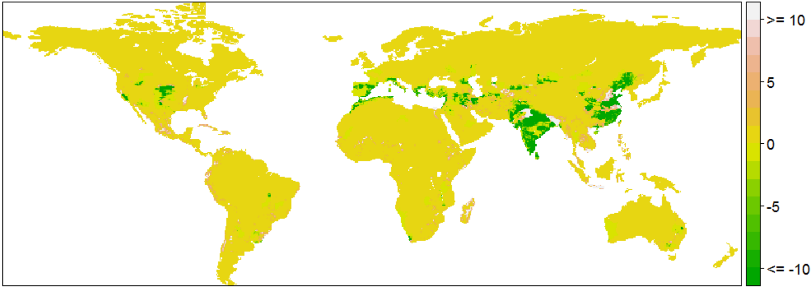
- Faster TFP growth will reduce global cropland expansion by 1/3, from 156 to 98 Mha.

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)

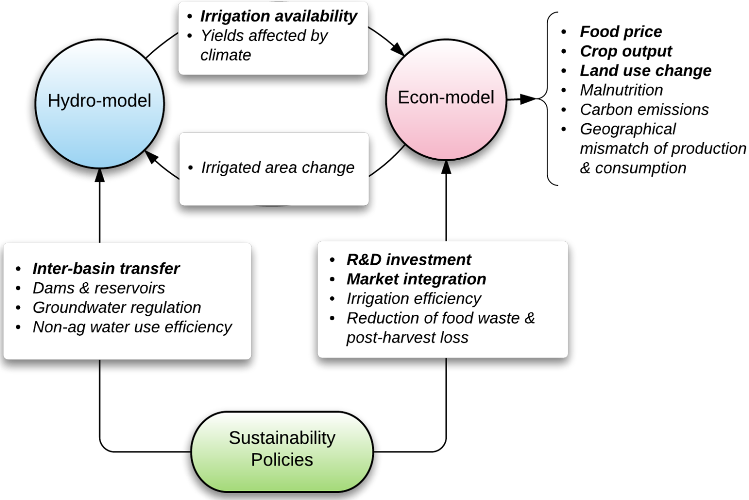


Global sum = -67 Mha

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



Hydro-model

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

Econ-model

- *Irrigated area change*

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

- ***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*

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

▸ return

Equilibrium of land (irrigated & rainfed) and water inputs

Demand

$$q_g^{iLand} = qo_{g,irr} - ao - \sigma_{g,irr}(p_g^{iLand} - po) \qquad (1)$$

$$q_g^{rLand} = qo_{g,rfd} - ao - \sigma_{g,rfd}(p_g^{rLand} - po) \qquad (2)$$

$$q_B^{Water} = \sum_{g \in B} \gamma_g q_g^{iLand} \qquad (3)$$

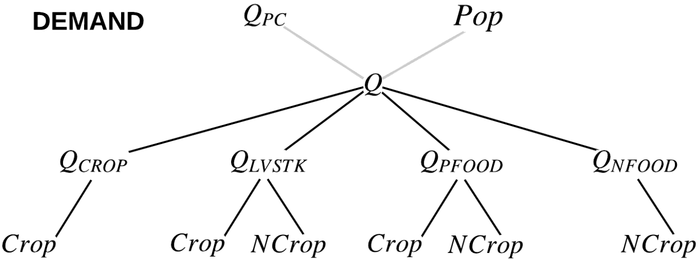
Supply

$$q_g^{iLand} = \nu_g^{iLand}(p_g^{iLand} - \lambda_g^{iLand}) \qquad (4)$$

$$q_g^{rLand} = \nu_g^{rLand} p_g^{rLand} \qquad (5)$$

▸ return

DEMAND



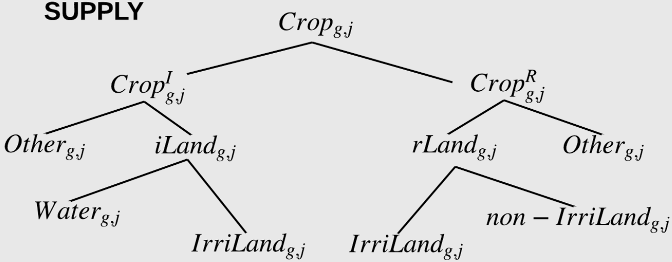
Q_{PC} Pop

Q

Q_{CROP} Q_{LVSTK} Q_{PFOOD} Q_{NFOOD}

$Crop$ $Crop$ $NCrop$ $Crop$ $NCrop$ $NCrop$

SUPPLY

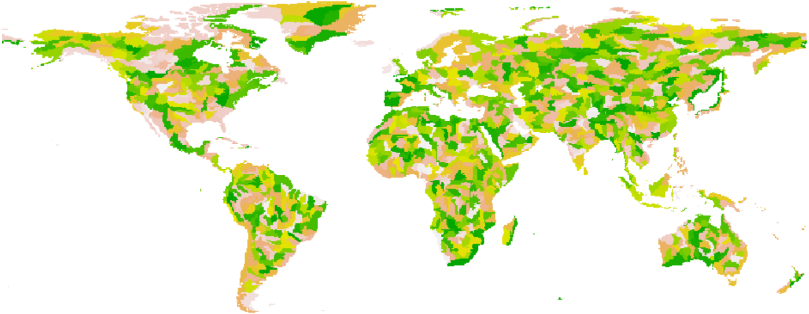


$Crop_{g,j}$

$Crop^{I}_{g,j}$ $Crop^{R}_{g,j}$

$Other_{g,j}$ $iLand_{g,j}$ $rLand_{g,j}$ $Other_{g,j}$

$Water_{g,j}$ $IrriLand_{g,j}$ $IrriLand_{g,j}$ $non-IrriLand_{g,j}$



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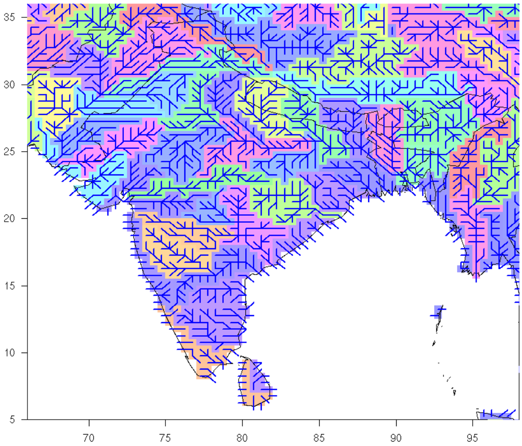
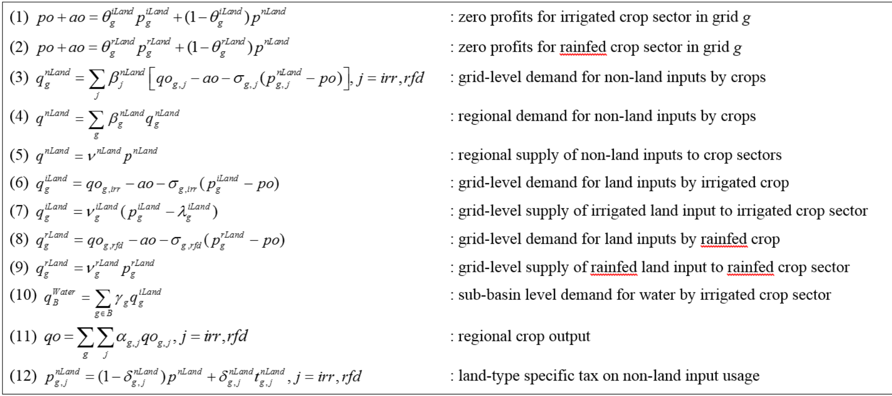


return



(1) $po + ao = \theta_g^{iLand} p_g^{iLand} + (1-\theta_g^{iLand}) p^{nLand}$	: zero profits for irrigated crop sector in grid g
(2) $po + ao = \theta_g^{rLand} p_g^{rLand} + (1-\theta_g^{rLand}) p^{nLand}$	: zero profits for rainfed crop sector in grid g
(3) $q_g^{nLand} = \sum_j \beta_j^{nLand}\left[qo_{g,j} - ao - \sigma_{g,j}(p_{g,j}^{nLand} - po)\right], j = irr, rfd$	: grid-level demand for non-land inputs by crops
(4) $q^{nLand} = \sum_g \beta_g^{nLand} q_g^{nLand}$	: regional demand for non-land inputs by crops
(5) $q^{nLand} = v^{nLand} p^{nLand}$	: regional supply of non-land inputs to crop sectors
(6) $q_g^{iLand} = qo_{g,irr} - ao - \sigma_{g,irr}(p_g^{iLand} - po)$	: grid-level demand for land inputs by irrigated crop
(7) $q_g^{iLand} = v_g^{iLand}(p_g^{iLand} - \lambda_g^{iLand})$	: grid-level supply of irrigated land input to irrigated crop sector
(8) $q_g^{rLand} = qo_{g,rfd} - ao - \sigma_{g,rfd}(p_g^{rLand} - po)$	: grid-level demand for land inputs by rainfed crop
(9) $q_g^{rLand} = v_g^{rLand} p_g^{rLand}$	: grid-level supply of rainfed land input to rainfed crop sector
(10) $q_B^{Water} = \sum_{g \in B} \gamma_g q_g^{iLand}$	: sub-basin level demand for water by irrigated crop sector
(11) $qo = \sum_g \sum_j \alpha_{g,j} qo_{g,j}, j = irr, rfd$	: regional crop output
(12) $p_{g,j}^{nLand} = (1-\delta_{g,j}^{nLand}) p^{nLand} + \delta_{g,j}^{nLand} t_{g,j}^{nLand}, j = irr, rfd$	: land-type specific tax on non-land input usage

▸ return

References

Alcamo, J., T. Henrichs, and T. Rosch (2000). World water in 2025: Global modeling and scenario analysis. *World water scenarios analyses*.