


OPTIMIZING THE GROUNDWATER-FOOD-ENERGY NEXUS AND ITS IMPLICATION FOR CHINA'S WATER PRICING REFORM:

EVIDENCE FROM NORTHERN CHINA

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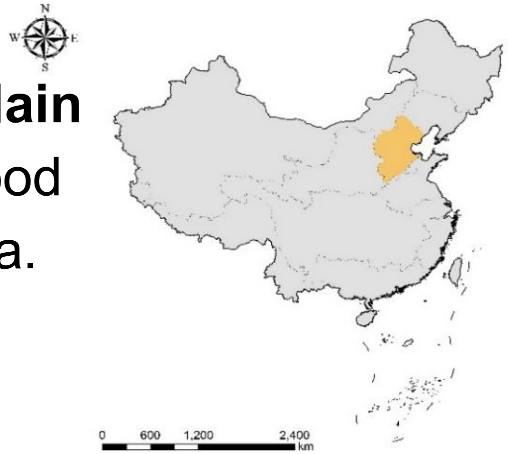
Motivation



- **North China Plain** (NCP) is the “food basket” of China.

Food

- **Agriculture** consumes over 70% of groundwater withdrawals; 70% of its irrigated land heavily reliant on groundwater (Wang et al., 2017).

Ground water

Energy

- **Groundwater table levels** in agricultural areas declined at a rate faster than 1 m/year by the late 1990s (Yang et al., 2021).
- **Energy use** for groundwater pumping has increased by 22% during the past two decades (Qiu et al., 2018).

Water policy development

Time	Policy	Content
2002	New Water Law	Ideas for a water pricing
2014	Water Supply Price Management	Definitions of full-cost pricing of agricultural water services
2015	Notification on Promoting Water Price Reform to Saving Water and Protect Water Resources	
2016	Opinions on Integrated Agricultural Water Pricing Reform	Metering methods, e.g. electricity to water
2019	‘Fee to Tax’ water resources	Stipulations on a water resources tax on industries and individuals who use surface- and groundwater
2020	Notification on Continuously Promoting the Comprehensive Reform of Agricultural Water Prices	Exchange of reform experiences

Dilemma in agricultural water price reform

- The agricultural water pricing reform is unsatisfactory (Yang et al., 2022), e.g. due to complex duties for fee collection between relevant departments (Tian et al., 2021), irregular financial management (Chen et al., 2021). The overall low water prices do not reflect the scarcity and true economic values of water (Huang et al., 2010; Dou, 2016).

- The water resources tax rate needs scientific calculations regarding social welfare maximization (Yang et al., 2022).

- The potential impacts of water price reforms on food security, energy utilization, and changes in water savings are not yet recognized (Xin et al., 2022).

Groundwater management in North China Plain

- Since 2014, China's seasonal fallowing policy has been piloted in areas of NCP. This policy requires a "one-season fallow, one-season rain-fed" farming practice.

- Farmers are compensated at a rate of 500 yuan/mu for reducing the planting area of winter wheat, and adjust their agricultural planting patterns, with the aim of achieving groundwater extraction reduction (Deng et al., 2021).

- The uniform fallow compensation standard implemented in the seasonal fallowing policy fails to adequately reflect region-specific incentive mechanisms, and it also increases the burden on public finances (Yu et al.， 2018； Liu et al.， 2019).

Contribution

- **Study I: Seasonal fallow compensation model**

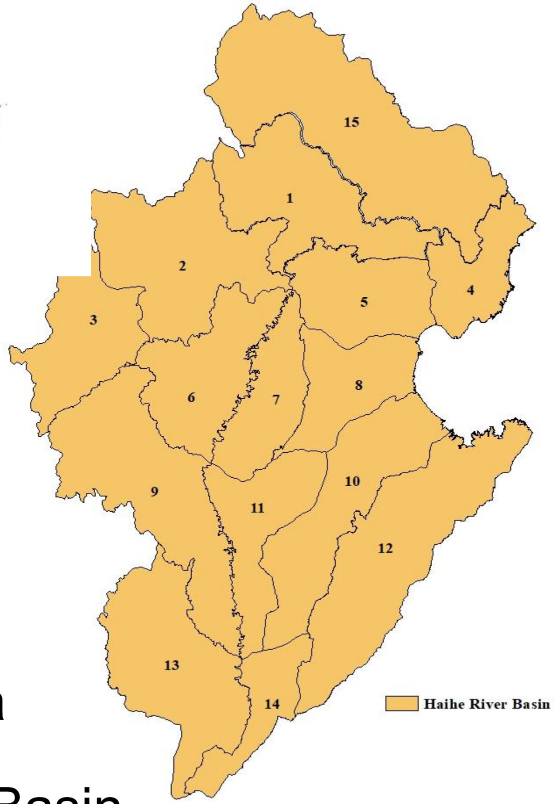
We proposed implementation of **regionally differentiated fallow compensation**, as a part of groundwater management in China**.**

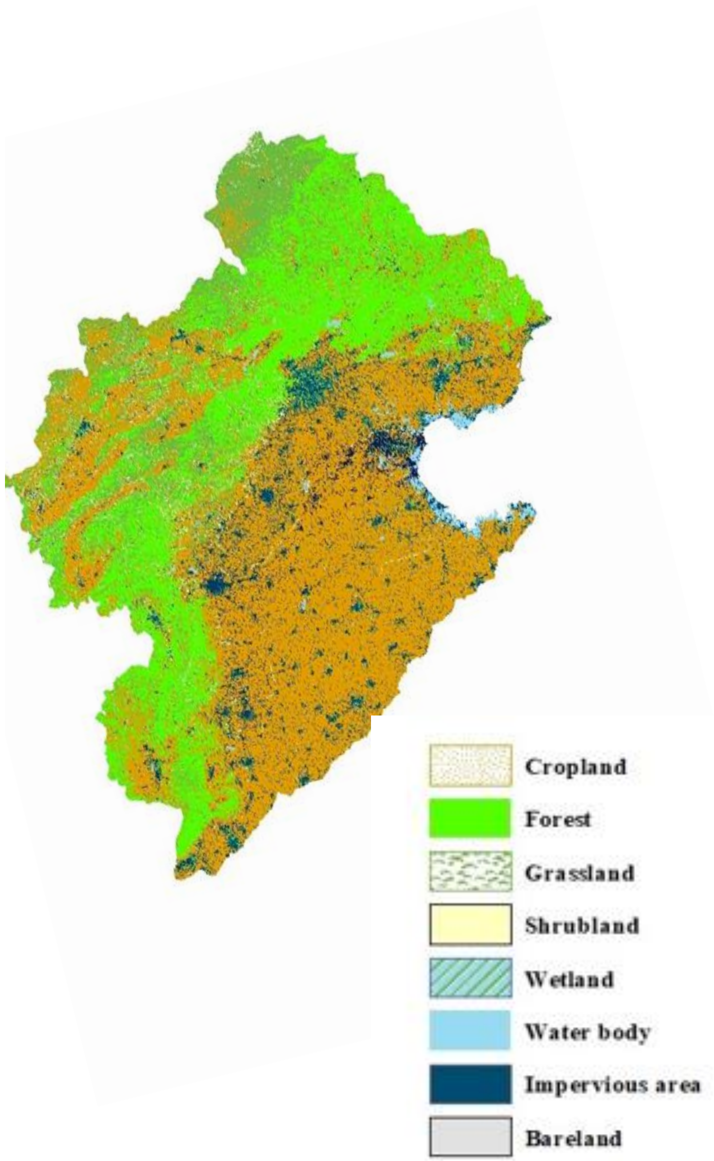
- **Study II: Optimum water-pricing model**

We developed **a market-based instrument of water pricing** that considers both the net value of water and the cost of water supply to balance the synergies across the WFE sectors.

Data

- **Ecological data：**
  - ☐ Sub-basins are calculation units.
  - ☐ Global Land Cover (2019).
  - ☐ Hydrological data from 2011 to 2015.





- **Statistic data：**
  - ☐ The National Bureau of Statistics in China
  - ☐ Water Resources Bulletin of Haihe River Basin
  - ☐ Local Statistical Yearbooks

Data

➢ **Socio-economic data：**

- 2019 Haihe River Basin Household Survey.
- The survey data includes information on crop irrigation water usage, farmers' production input costs (including seeds, pesticides, fertilizers, and labor), agricultural product prices, irrigation water prices, the severity of groundwater overextraction, and the proportion of irrigated area using different water sources.
- 15 sub-basins, 588 households.
- 84% only use groundwater, 15% only use surface water.

Study 1: Fallow compensation optimization

Baseline Model		Fallow compensation Model
• Net income from agricultural production • Groundwater withdrawals • Irrigation water demand • Cultivated land area • Irrigated land area	**Objective:** **Max net profits of agricultural production**	• Spatial differentiated ecological compensation • Strong limits on groundwater savings • Other constraints on land and groundwater usage

Study II: Water pricing optimization

Baseline Model

- Net income from agricultural production
- Groundwater withdrawals
- Irrigation water demand
- Cultivated land area
- Irrigated land area

Multi-Objective:

Max net profits of agricultural production

Max benefits from water savings

Max revenue from electricity utilization

Optimum water-pricing Model

- Shadow price of water
- Electricity price
- Strong limits on food security
- Groundwater table control
- Energy saving target: reduce energy use per unit of GDP by 13.5% by 2025.

Results: (1) Baseline model

- The total cultivated area of the four major crops was 12.98 million hectares in the Haihe River Basin.
- The average proportions of summer maize, winter wheat, cash crops, and vegetables were 46%, 24%, 5%, and 10%, respectively.
- The total fallow area was 134,007 hectares, 0.5% higher than the actual area.

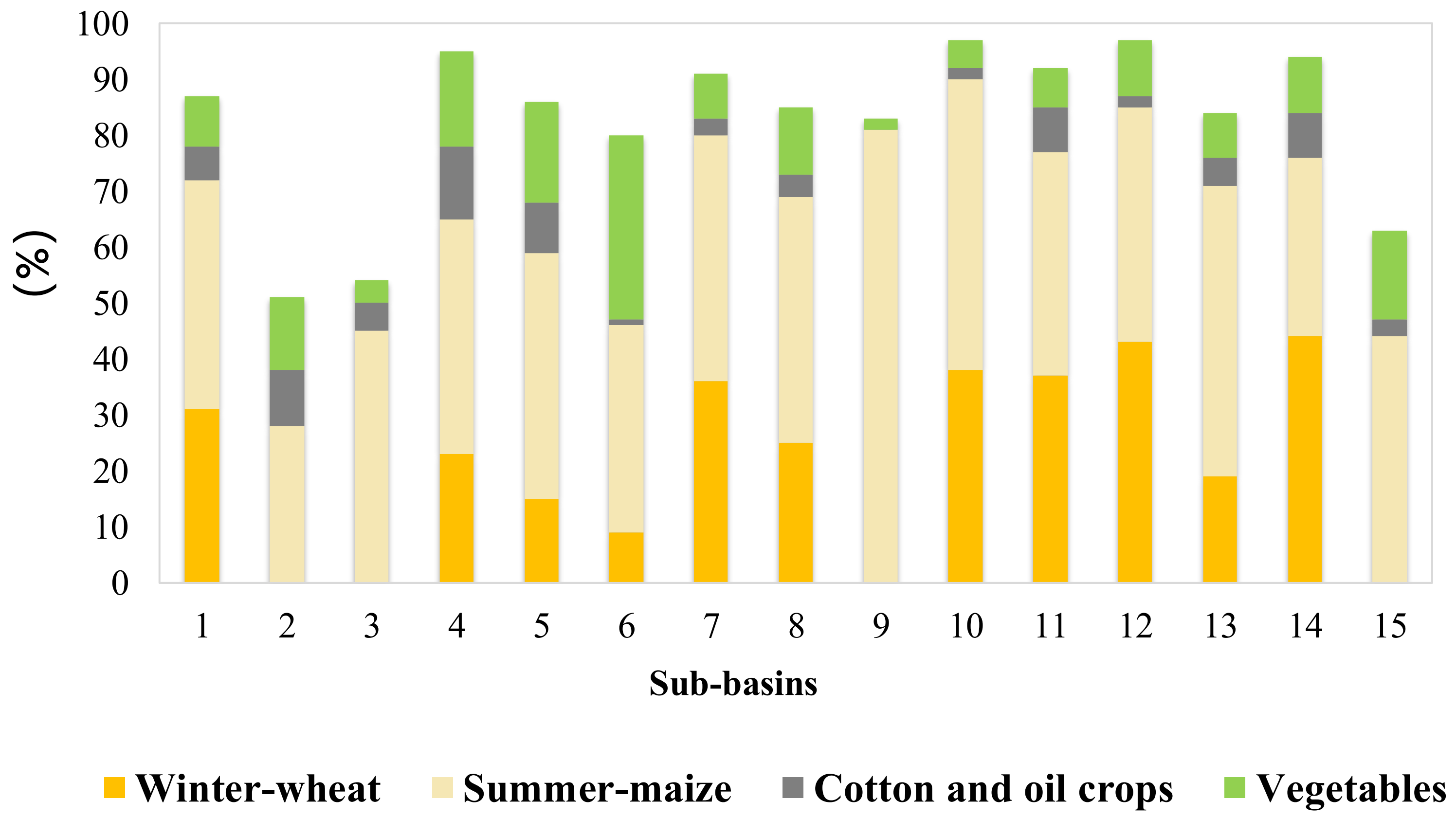


Figure 1. Current cropping structure

Study I: Fallow compensation model

TABLE 2. Comparison between spatial optimization model and the baseline

Sub-basin ID	Changes in the optimization results compared to the baseline (%)					
	Wheat cultivated area	Maize cultivated area	Cotton and oil crops cultivated area	Vegetable cultivated area	Irrigation water use	Seasonal fallow area
1	-33.37	-44.94	446.38	-79.25	-11.60	369.38
2	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00
4	-24.13	-14.10	7.48	15.75	-0.90	10.70
5	-17.30	-3.20	41.35	-13.32	-4.33	142.81
6	-8.12	-15.35	152.62	6.64	-6.00	318.97
7	-11.73	-22.65	457.26	-62.86	-4.63	266.54
8	-21.06	-13.11	48.48	33.81	-3.86	355.18
9	0.00	0.00	0.00	0.00	0.00	0.00
10	-25.00	-34.08	557.99	82.44	-5.77	735.97
11	-25.00	-23.96	45.87	78.23	-6.85	718.47
12	-25.00	-25.00	837.60	-76.30	-12.72	853.22
13	-36.12	19.23	-80.00	-80.00	-16.74	515.19
14	-10.74	-10.74	23.60	29.97	-3.10	311.65
15	0.00	0.00	0.00	0.00	0.00	0.00
Average	**-22.69**	**-14.02**	**145.93**	**-8.62**	**-6.63**	**538.18**

TABLE 3 Regionally differentiated fallow ecological compensation scheme

Sub-basin ID	Optimal compensation standard (CNY/mu)	Optimal model				Baseline model		
		Optimal fallow area (million mu)	Newly added water savings (m3/mu)	Optimal compensation (100 million CNY)	Previous compensation (100 million CNY)	Current fallow area (million mu)	Optimal compensation (100 million CNY)	Previous compensation (100 million CNY)
1	276	58.85	93.52	2.41	2.94	11.54	0.47	0.58
4	510	6.70	86.19	0.34	0.34	0.00	0.31	0.30
5	406	43.44	129.58	1.76	2.17	0.00	0.73	0.89
6	689	32.90	101.46	2.82	1.65	6.05	0.67	0.39
7	532	56.51	94.40	3.01	2.83	17.89	0.82	0.77
8	618	66.57	58.72	4.11	3.33	7.85	0.90	0.73
10	589	271.14	53.83	15.97	13.56	15.42	1.91	1.62
11	673	163.07	65.45	10.97	8.15	14.63	1.34	1.00
12	291	428.96	111.63	19.63	21.45	0.00	2.06	2.25
13	218	103.20	178.24	5.19	5.16	32.43	0.84	0.84
14	291	51.42	66.65	1.50	2.57	19.92	0.36	0.62
Total		**1,282.03**	**101.34**	**56.29**	**64.14**	**200.00**	**8.91**	**10.00**

Policy implication I

- **The seasonal fallow ecological compensation standard exhibits spatial heterogeneity.**
- **For regions with severe groundwater over-extraction**, increasing the fallow compensation standard as an incentive mechanism can guide farmers to reduce winter wheat planting while expanding the planting of cash crops and vegetables, ensuring farmers' production income. **In areas with moderate groundwater over-extraction**, the fallow compensation standard can be moderately lowered to ease the task of groundwater extraction reduction, allowing for the production of grain crops.
- This study recommends that policymakers consider spatial heterogeneity when formulating seasonal fallow ecological compensation schemes to improve the effectiveness and sustainability of seasonal fallow policies.

Study II: Optimum water-pricing model

Results: (1) Price elasticity of water demand

TABLE 1. Estimates of price elasticity of irrigation water demand

	Irrigation water demand (logarithmic value) (m^3/ha)					
	Maize			Wheat		
	Full sample	Surface water	Ground water	Full sample	Surface water	Ground water
Water prices (log value) (CNY/m^3)	-0.3479***	-0.5362***	-0.1240	-0.1822***	-0.3092***	-0.0811*
	(10.05)	(12.97)	(1.39)	(8.31)	(8.78)	(1.93)

- Summer-maize is more sensitive to water prices than winter-wheat.
- Hydrological data proves an additional 1100 m^3 of rainfall per ha for summer-maize during the growing season than winter-wheat in 2015; hence, maize is less dependent on irrigation water.

Results: (2) Optimum water prices

- The MVP is from 2.25 to 2.35 CNY/m^3 associated with reduction in water use.
- With an increase in water prices, more water is saved from the current withdrawals.

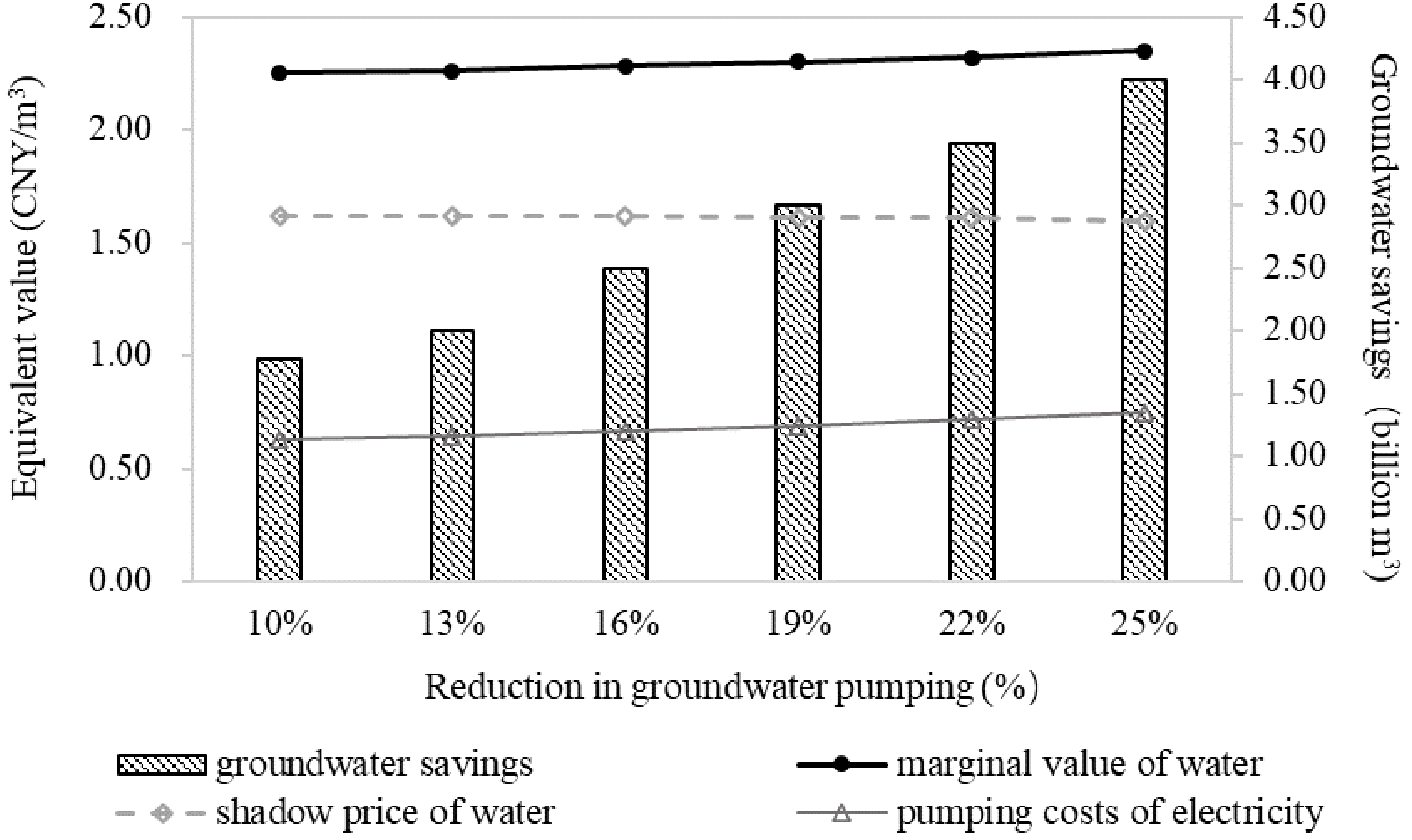


Figure 3. Pareto optimal front between water prices and reduction in groundwater pumping in the HRB.

Results: (3) Electricity prices

TABLE 4. Numerical values of variables regarding energy sector derived from the model.

Variables	Baseline	Optimum
Electricity price (CNY/kWh)	0.5	1.23
Total groundwater withdrawals (billion m^3)	16	13.5
Total electricity consumption (billion kWh)	8.7	7.3
Total revenue of energy consumption (billion CNY)	4.4	8.9

- The electricity consumption will be reduced by 16% for OS under the optimum electricity price, while the total revenue of electricity use increases.

Results: (4) Optimized irrigation water application rate

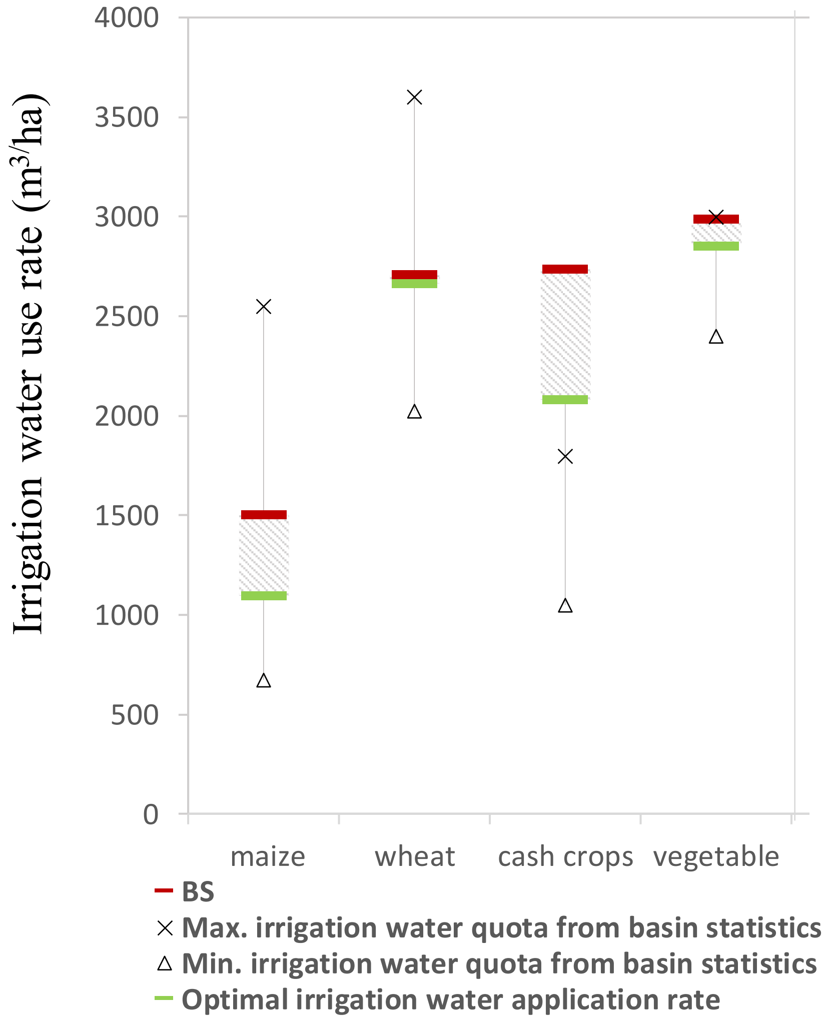


Figure 4. Referenced and simulated irrigation water application rates.

- Four crops reduce their water application rate by 27% for maize, 2% for wheat, 24% for cash crops, and 5% for vegetables.
- Cash crops show a great potential for water savings as they require less water than wheat and vegetables.
- Vegetables encounter challenges in reducing their irrigation water use while meeting the high water requirements for growth.

Results: (5) Tradeoffs within the nexus

- The net benefits of food production under the optimum water pricing will reduce by 20% to 27% as the water use decreases by 11% to 25% from the current withdrawals.
- Maize and vegetable will lose 60% and 20% of current net benefits, respectively.
- Wheat will lose 7% of the current net returns under the consideration for food security.
- The net benefits of cash crops will increase by 33%, on average, as the cultivation of cash will be promoted.

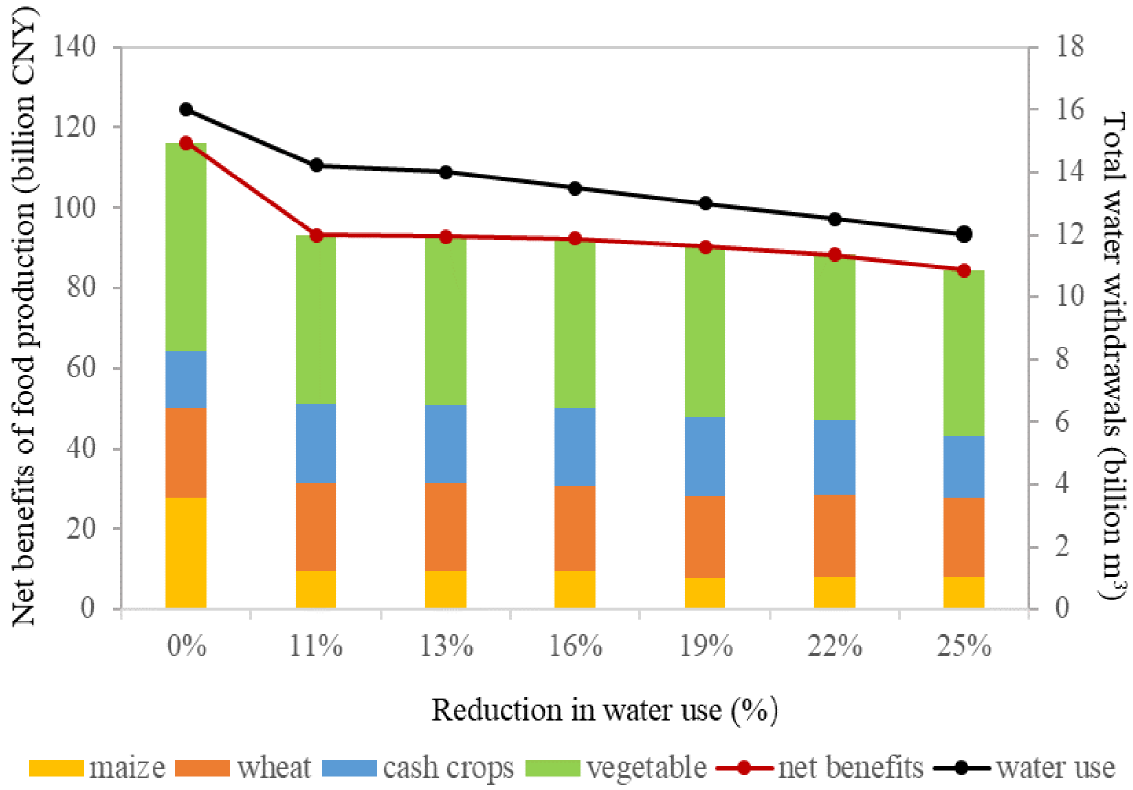


Figure 5. Trade-offs of the WFE Nexus.

Policy implication II

- **A water resources tax** in the agricultural sector can be set with reference to the shadow prices of water to reflect the scarcity costs, which could restrain irrigation behavior at the household level, thus saving the groundwater.
- **Increasing pumping costs** could reduce groundwater withdrawal and energy consumption, while increasing the revenue of power sector.
- **With the optimum water prices**, food production would be affected and may lose some benefits:
  - ✓ Irrigated area of vegetables will be reduced.
  - ✓ Cultivation of cash crops and rainfed maize will be encouraged.
  - ✓ Wheat production can be secured.
- **Subsidies should be considered in the water pricing reform** and especially used to compensate farmers for changing the cropping structure into less water-intensive crops.