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Tradeoff between groundwater exploitation and food production in the deep groundwater overexploited area of North China Plain

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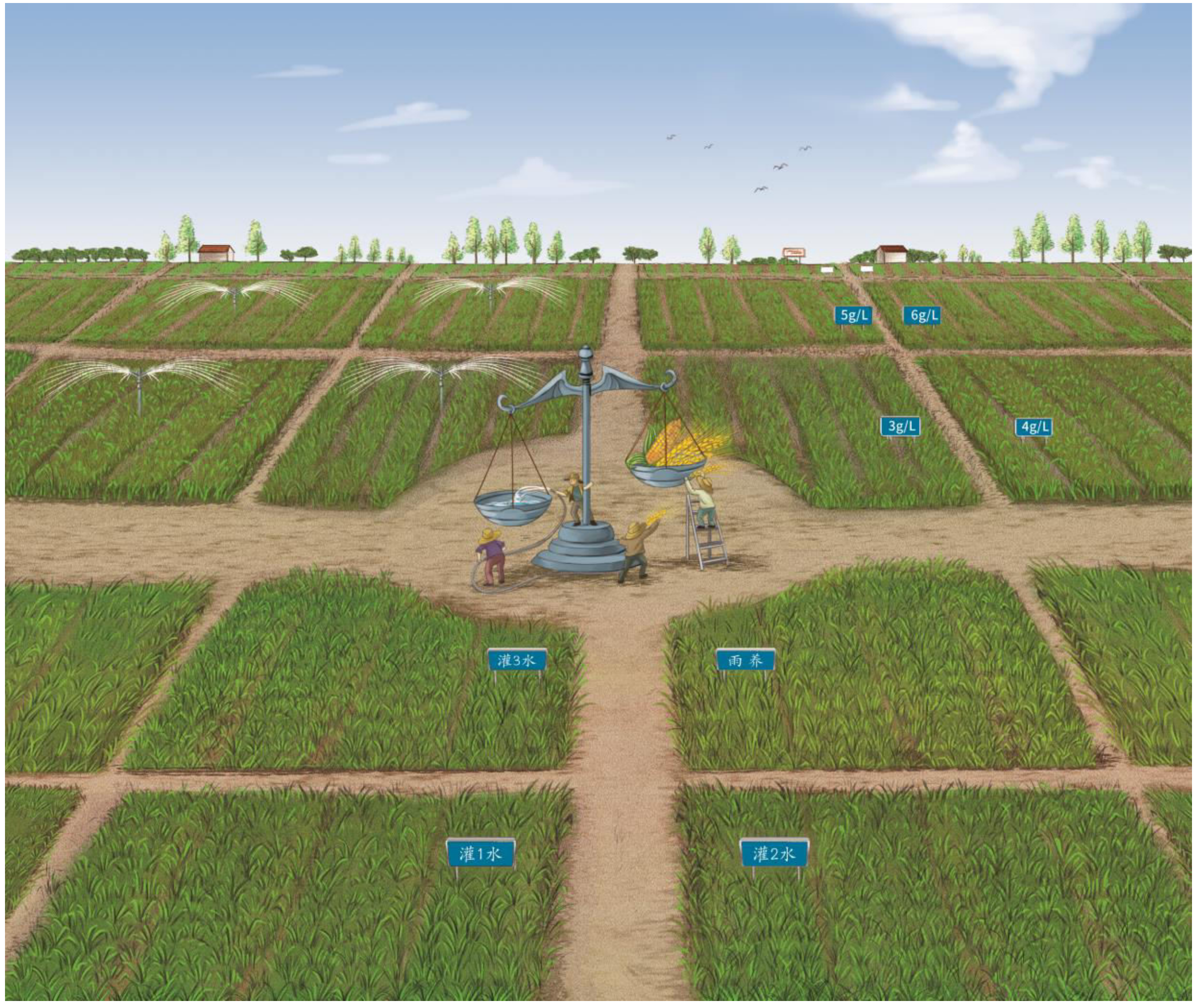
14, September, 2023, Beijing, China

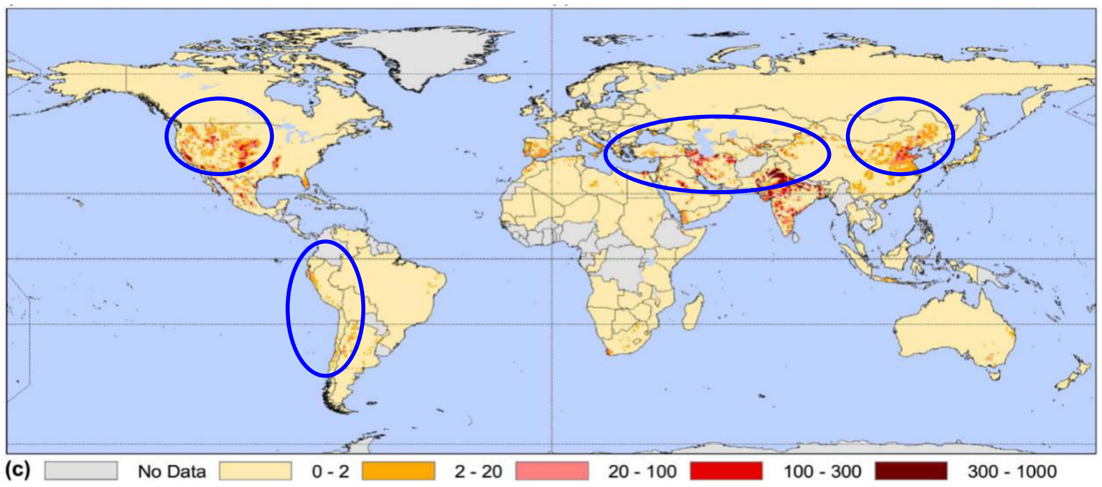
Contents

- **Background and Motivation**
  - -Groundwater overexploitation
  - -Contradiction between groundwater exploitation and food production
- **Materials and Methods**
  - -Distributed agro-hydrological model
  - -Scenario simulations and evaluations
- **Results and Discussion**
  - -Limited surface irrigation
  - -Saline water irrigation
  - -Sprinkler irrigation
- **Conclusions**
- **Acknowledgements**



Trade offs between groundwater exploitation and food production

Background and Motivation

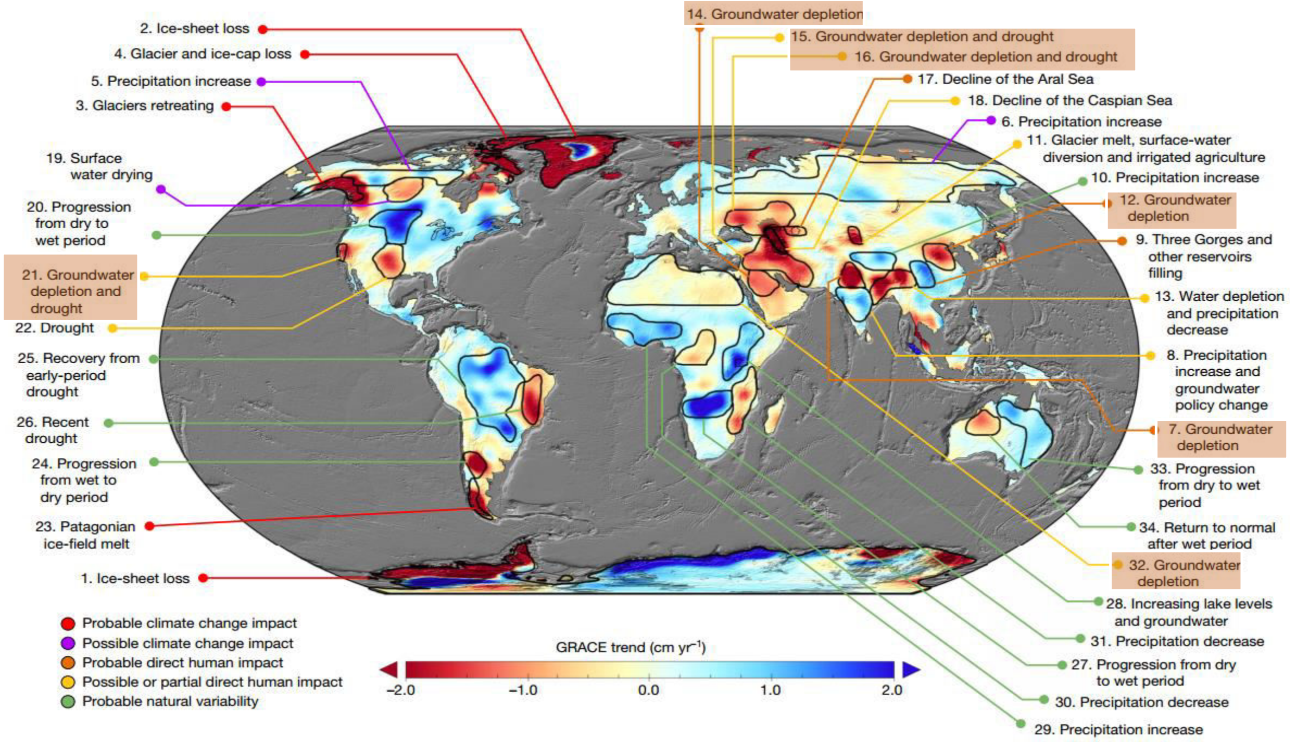


Groundwater abstraction for irrigation for the year 2000 (10^6 m^3 yr^{-1})

Source: Wada et al. (2012)

Groundwater provides around 25% of all water withdrawn for irrigation, serving 38% of the world's irrigated land (United Nations, 2022).

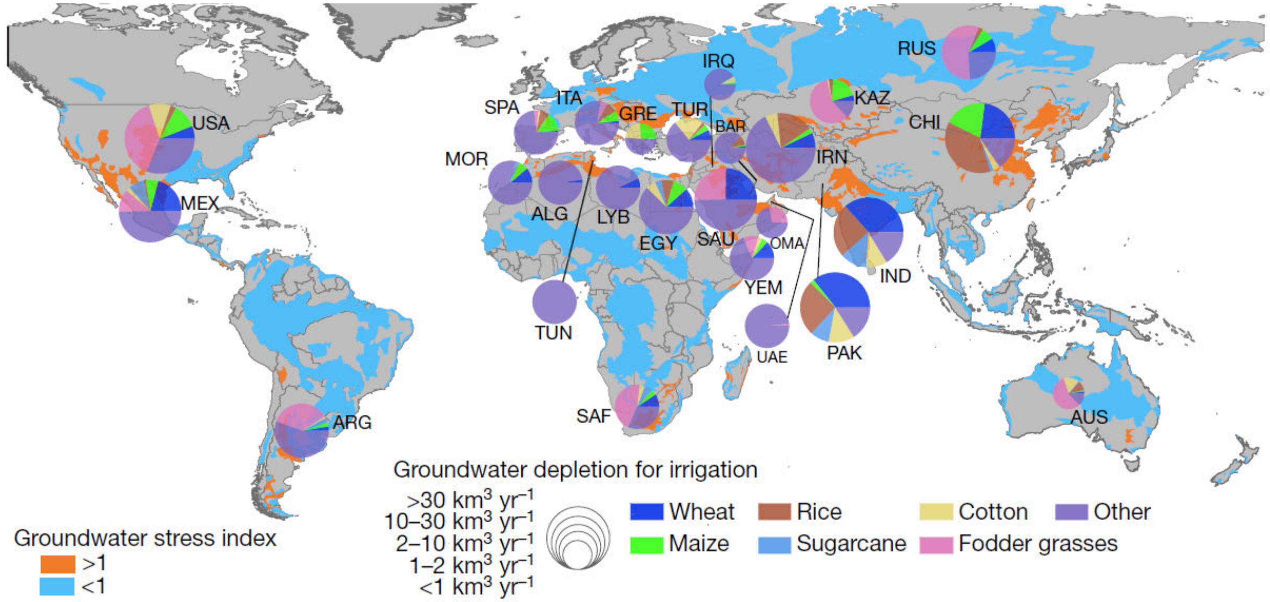
About 70% of the pumped groundwater worldwide is used to sustain irrigation and is important for food security (de Graaf et al., 2019).



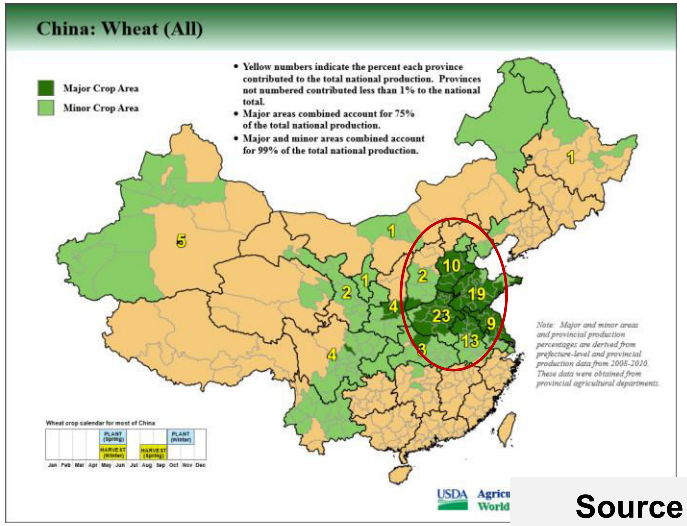
Trends in terrestrial water storage (TWS) obtained on the basis of Gravity Recovery and Climate Experiment (GRACE) satellite observations from April 2002 to March 2016 and the cause of the trend in each outlined study regions

Source: Rodell et al. (2018)

Background and Motivation



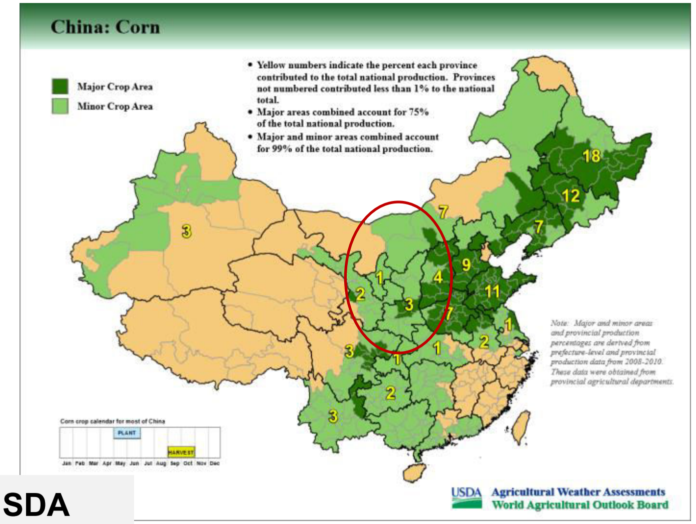
Source: Dalin et al. (2017)



China: Wheat (All)

- Yellow numbers indicate the percent each province contributed to the total national production. Provinces not numbered contributed less than 1% to the national total.
- Major areas combined account for 75% of the total national production.
- Major and minor areas combined account for 99% of the total national production.

Note: Major and minor areas and provincial production percentages are derived from prefecture-level and provincial production data from 2008-2010. These data were obtained from provincial agricultural departments.

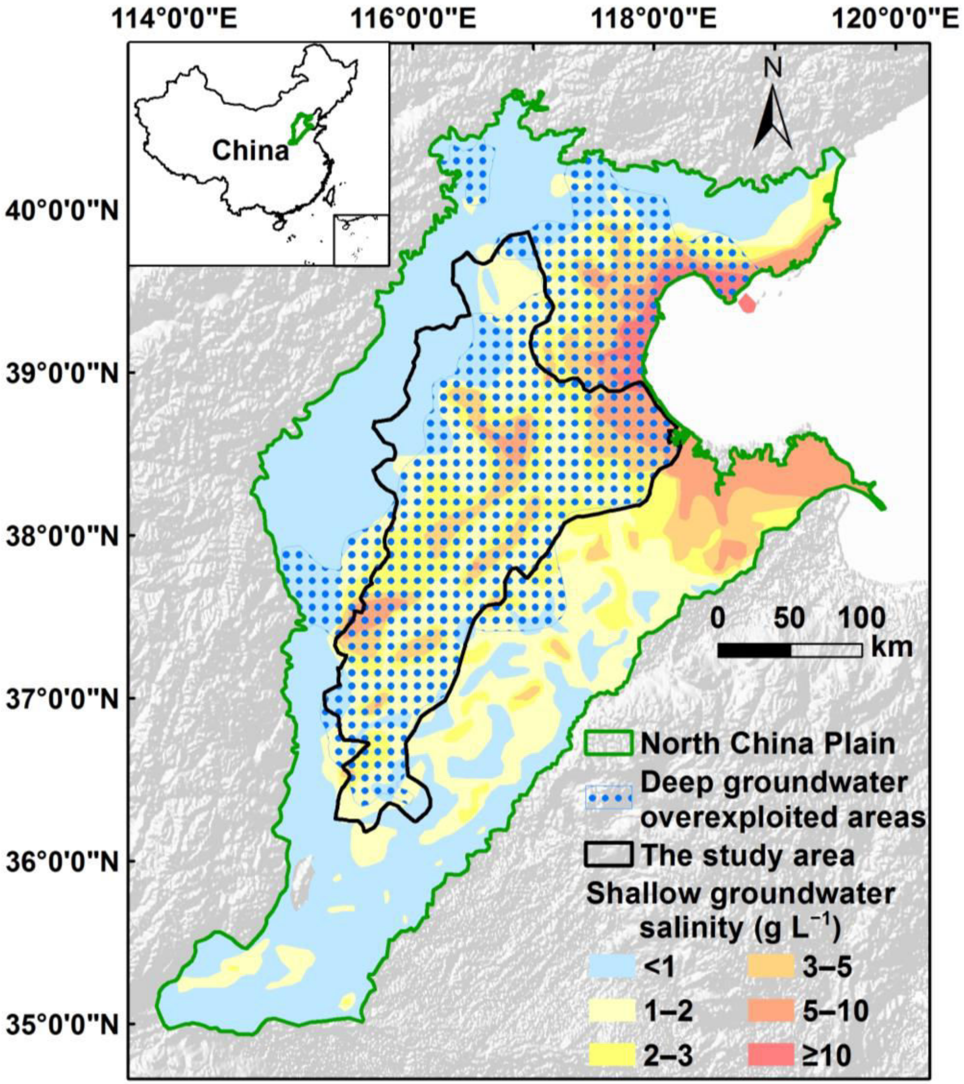


China: Corn

- Yellow numbers indicate the percent each province contributed to the total national production. Provinces not numbered contributed less than 1% to the national total.
- Major areas combined account for 75% of the total national production.
- Major and minor areas combined account for 99% of the total national production.

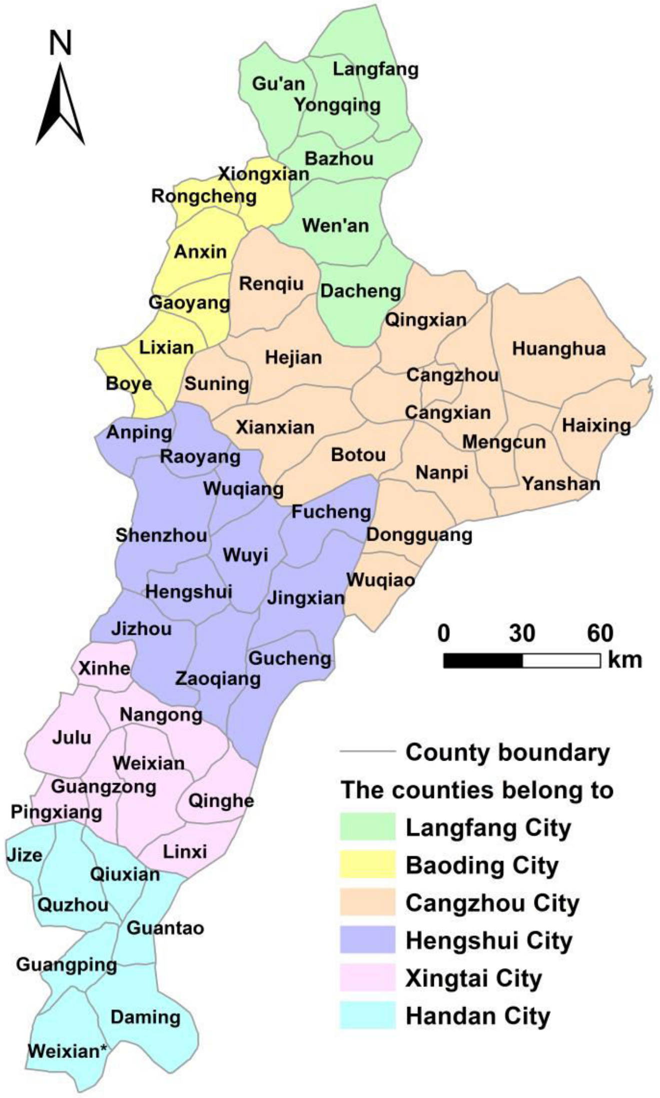
Note: Major and minor areas and provincial production percentages are derived from prefecture-level and provincial production data from 2008-2010. These data were obtained from provincial agricultural departments.

Source: USDA

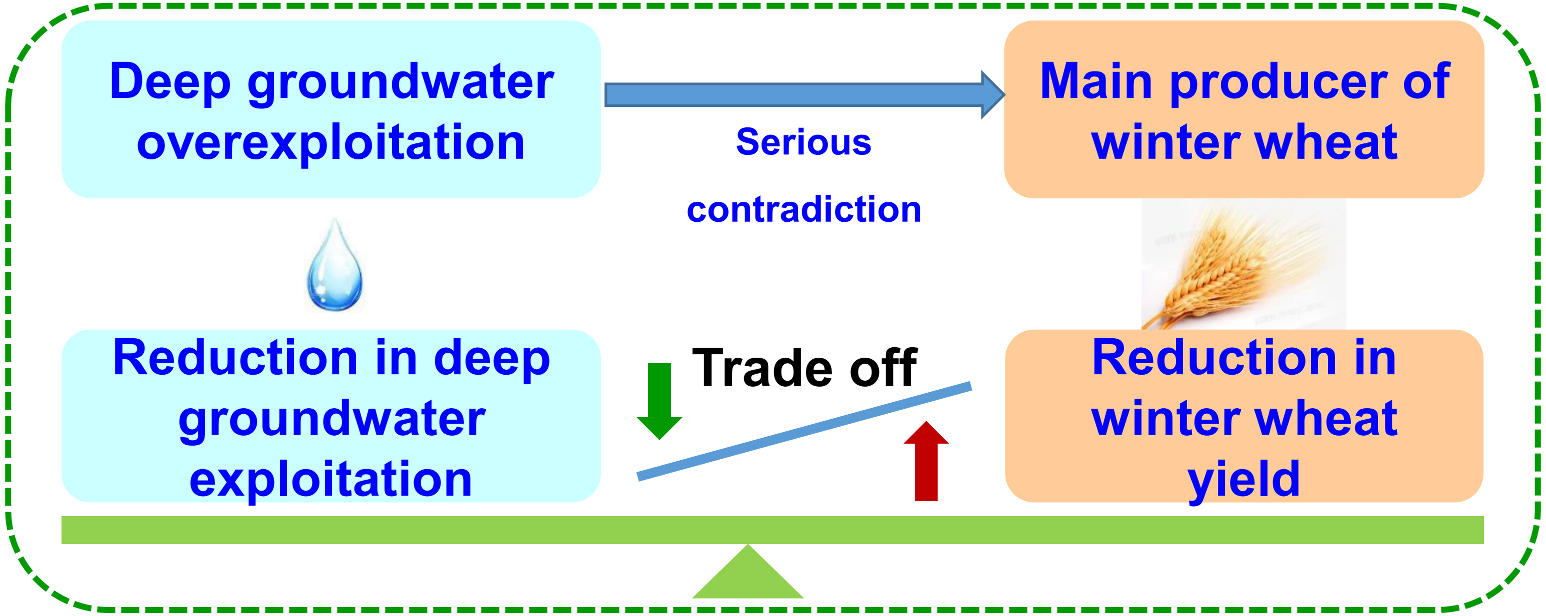


Source: Li and Ren (2021)

Background and Motivation



Source: Li and Ren (2019b)



Deep groundwater overexploitation

Serious contradiction

Main producer of winter wheat

Reduction in deep groundwater exploitation

Trade off

Reduction in winter wheat yield

Limited surface irrigation strategy

Saline water irrigation strategy

Sprinkler irrigation strategy

Background and Motivation

Experimental evaluation at the experimental station scale,

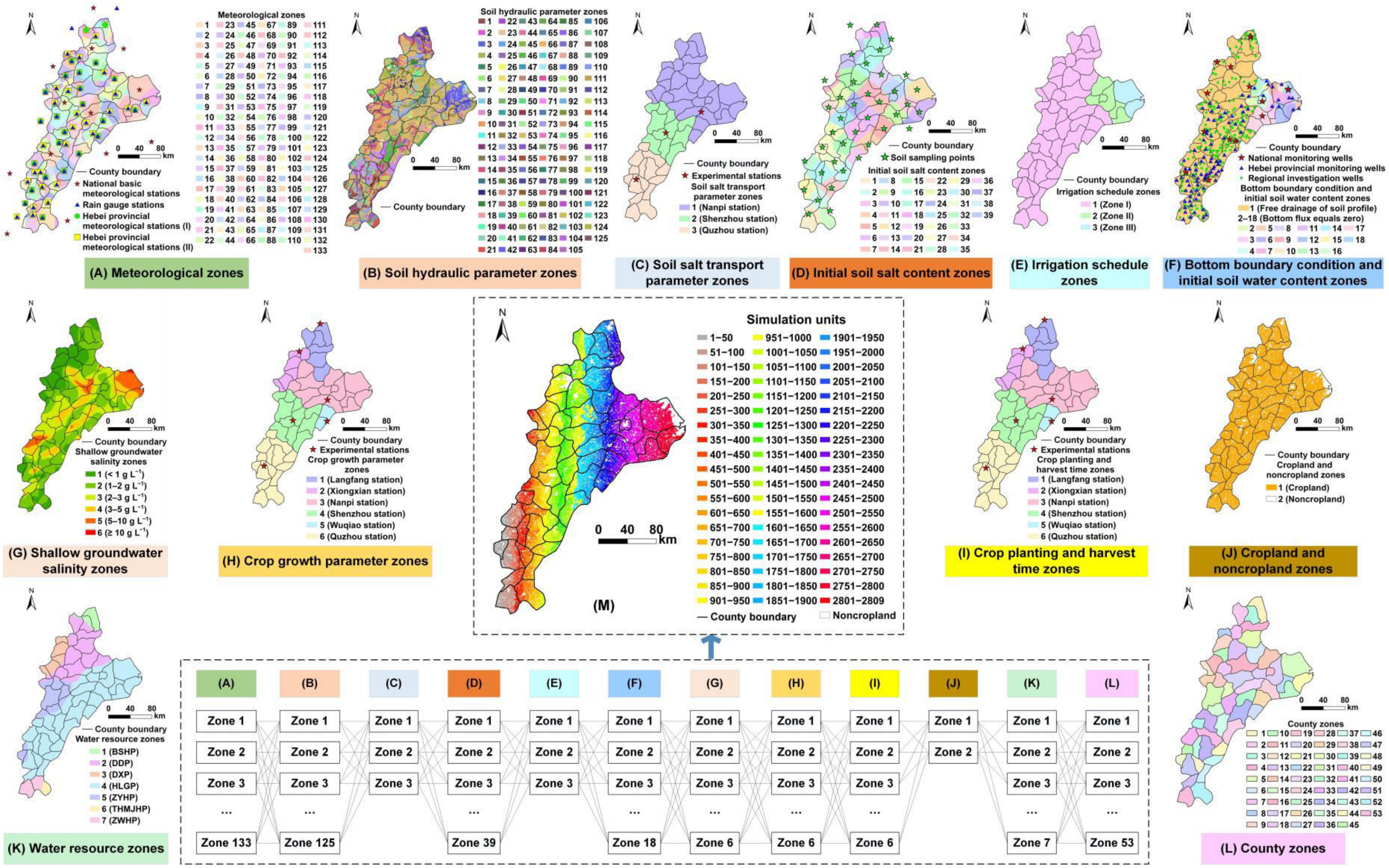
A need of study

-at the regional scale.

-for different irrigation strategies.

-under the framework of simulation-optimization-evaluation

Materials and Methods



Establishment

Calibration:

–Soil water content
–Soil salt content
–Crop leaf area index
–Crop biomass
–Crop yield

Validation:

–Soil water content
–Soil salt content
–Evapotranspiration
–Crop leaf area index
–Crop biomass
–Crop yield

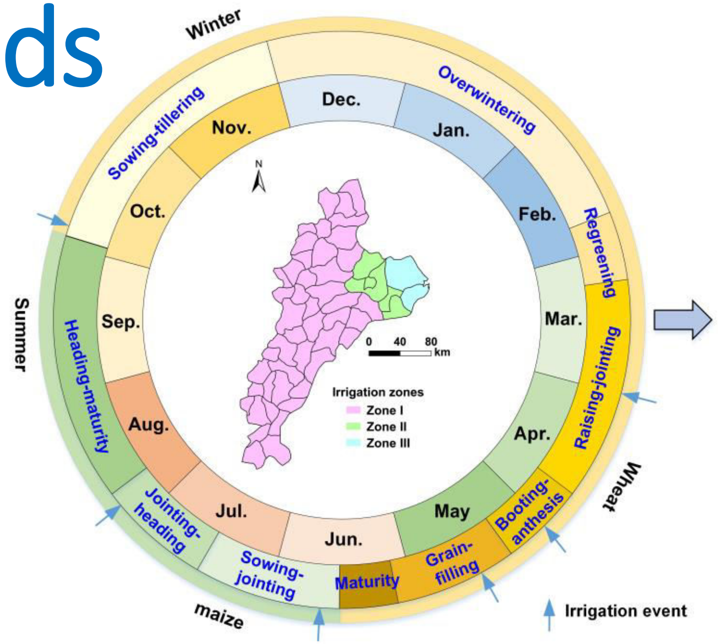
Source: Li and Ren (2019a)

Materials and Methods

	Scenario	Irrigation frequency	Irrigation timing
225 mm	L1	3	Pre-sowing + recovery-jointing + booting-anthesis
	L2	3	Pre-sowing + recovery-jointing + early grain-filling
	L3	3	Pre-sowing + booting-anthesis+ early grain-filling
150 mm	L4	2	Pre-sowing + recovery-jointing
	L5	2	Pre-sowing + booting-anthesis
	L6	2	Pre-sowing + early grain-filling
75 mm	L7	1	Pre-sowing
	L8	1	Recovery-jointing
	L9	1	Booting-anthesis
	L10	1	Early grain-filling
0 mm	L11	1	Early grain-filling

Note: 1) the irrigation amount for each application was 75 mm .

Eleven limited surface irrigation scenarios



Irrigation zone	PEP	Winter wheat				Summer maize	
		Pre-sowing	Raising-jointing	Booting-anthesis	Early grain-filling	Sowing	Heading
Zone I	25%	√	☆	☆	×	×	×
	50%	√	☆	☆	☆	×	×
	75%	√	☆	☆	☆	√	×
	95%	√	☆	☆	☆	√	√
Zone II	25%	√	☆	×	×	×	×
	50%	√	☆	☆	×	×	×
	75%	√	☆	☆	×	×	×
	95%	√	☆	☆	×	√	×
Zone III	25%	×	×	×	×	×	×
	50%	×	☆	×	×	×	×
	75%	×	☆	×	×	×	×
	95%	×	☆	×	×	×	×

Note: (1) "√" represents freshwater irrigation; "☆" represents saline water irrigation; and "×" represents no irrigation. (2) Under scenarios 1, 2, 3, 4 and 5, the irrigation water salinity in the winter wheat growing season was 2.0 g L^{-1}, 3.0 g L^{-1}, 4.0 g L^{-1}, 5.0 g L^{-1} and 6.0 g L^{-1}, respectively, and the irrigation water salinity at the winter wheat pre-sowing and during the summer maize growing season was still 1.0 g L^{-1}. (3) PEP means precipitation exceedance probability.

Five saline water irrigation scenarios

Fixed sprinkler irrigation scenario	Irrigation quota (mm)	Irrigation frequency	Irrigation amount at different stages of winter wheat (mm)					
			Before winter dormancy	Recovery	Jointing	Booting	Anthesis	Grain-filling
Scenario 1 (S1)	225	6	30	30	30	45	45	45
Scenario 2 (S2)		5	45	-	45	45	45	45
Scenario 3 (S3)	150	5	30	-	30	30	30	30
Scenario 4 (S4)		4	30	-	30	-	45	45
Scenario 5 (S5)		3	-	-	50	-	50	50
Scenario 6 (S6)	75	2	-	-	30	-	-	45

(A)

Scheduled sprinkler irrigation scenario	Value of f_3 at different DVS of winter wheat				
	DVS=0	DVS=0.5	DVS=1.0	DVS=1.5	DVS=2.0
Scenario 7 (S7)	0.90	0.90	0.70	0.70	0.80
Scenario 8 (S8)	0.90	0.90	0.75	0.75	0.85
Scenario 9 (S9)	0.90	0.90	0.80	0.80	0.90
Scenario 10 (S10)	0.90	0.90	0.85	0.85	0.90
Scenario 11 (S11)	0.90	0.90	0.90	0.90	0.90

(B)

Note: 1) "-" represents no irrigation at this growth stage; 2) f_3 is a user-defined factor depletion fraction, sprinkler irrigation is applied when the depletion of water in the root zone exceeds fraction f_3 of the available water; 3) DVS represents development stage, which values of 0, 0.5, 1.0, 1.5 and 2.0 indicate the seedling, middle vegetative, anthesis, middle reproductive and mature stages, respectively; and 4) the irrigation amount for each application under the scheduled sprinkler irrigation scenarios was 30 mm.

Eleven sprinkler irrigation scenarios

Source:
Li and Ren
(2019b, 2021, 2022)

Materials and Methods

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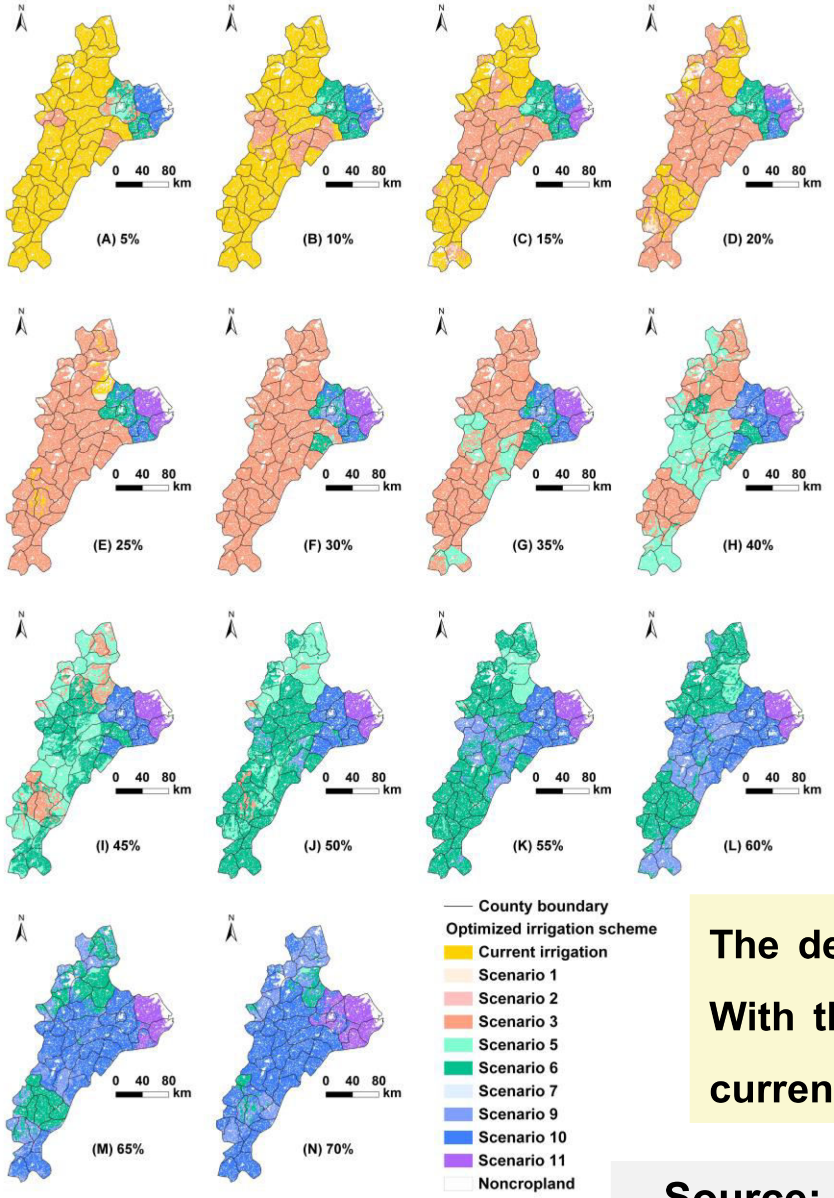
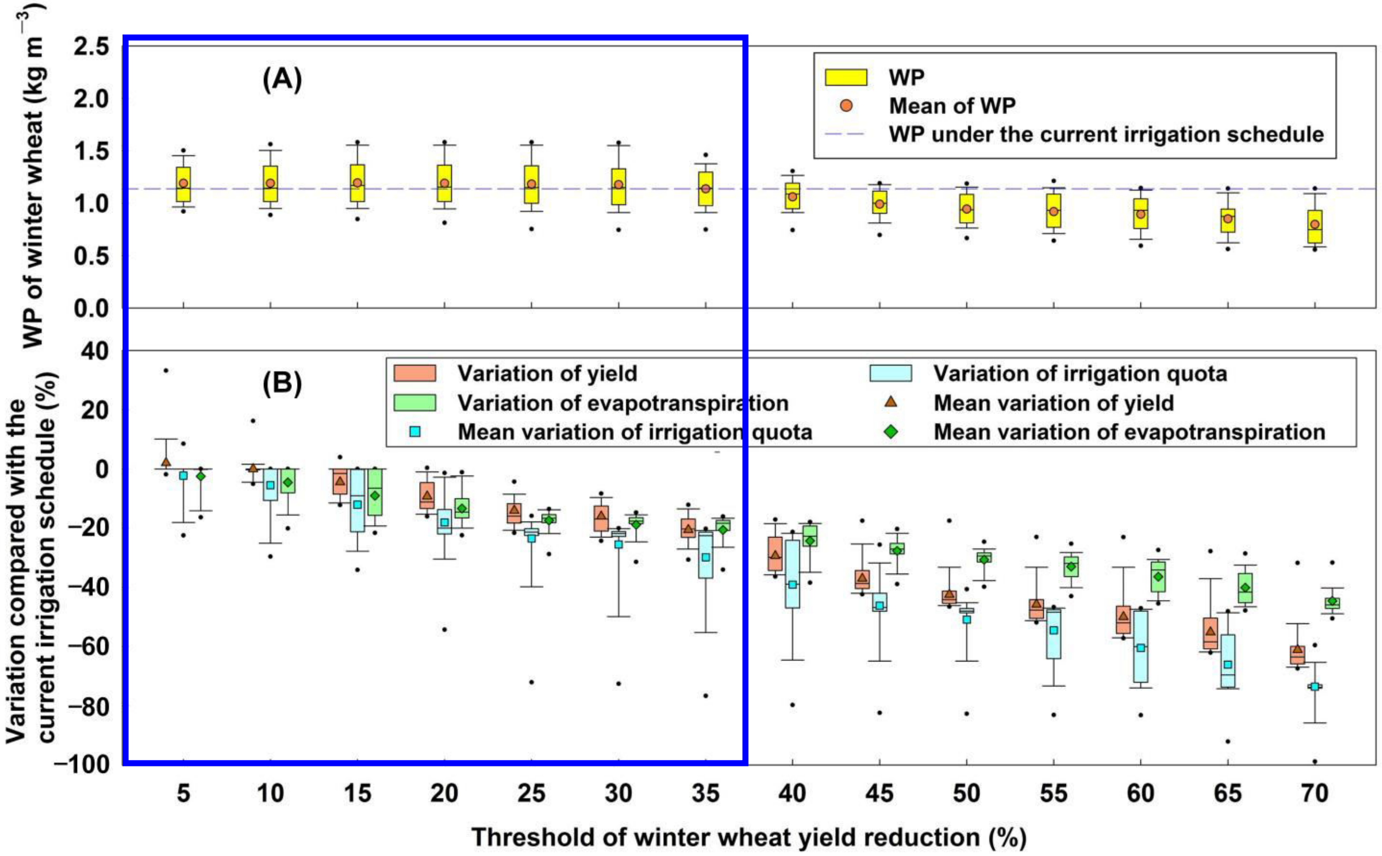
	Limited surface irrigation	**Saline water irrigation**	**Sprinkler irrigation**
Objective function	$\min z = \sum_{i=0}^{11} p_i x_i$	$\max z = \sum_{i=0}^{5} c_i x_i$	$\max z_j = \sum_{i=1}^{11} \mathrm{WP}_{i,j} x_{i,j} \quad (i=1,\cdots,11;\ j=1,2,3)$
Constraints	$\begin{cases} \sum_{i=0}^{11} y_i x_i \le b & (i=0,1,\cdots,11) \\ x_i = 0 \text{ or } 1 & (i=0,1,\cdots,11) \end{cases}$	$\begin{cases} \sum_{i=0}^{5} y_i x_i \le a & (i=0,1,\cdots,5) \\ \sum_{i=0}^{5} \mathrm{s}_i x_i < b & (i=0,1,\cdots,5) \\ x_i = 0 \text{ or } 1 & (i=0,1,\cdots,5) \end{cases}$	$\begin{cases} \sum_{i=1}^{11} I_{i,j} x_{i,j} \ge b & (i=1,\cdots,11;\ j=1,2,3) \\ \sum_{i=1}^{11} x_{i,j} = 1 & (i=1,\cdots,11;\ j=1,2,3) \\ x_{i,j} = 0 \text{ or } 1 & (i=1,\cdots,11;\ j=1,2,3) \end{cases}$
	Minimize evapotranspiration under the constraint of **yield reduction** (i.e., 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%, 55%, 60%, 65% and 70%).	**Maximize irrigation water salinity** under the constraints of **crop yield reduction** (i.e., 500 kg hm^{-2}, 1000 kg hm^{-2}, 1500 kg hm^{-2} and 2000 kg hm^{-2}) and **soil salt content** (3.0 g kg^{-1}).	**Maximize water productivity (WP)** under the constraint of **irrigation quota reduction** (i.e., 10%, 20%, 30%, 40%, 50% and 60%).

Source: Li and Ren (2019b, 2021, 2022)

Results and Discussion

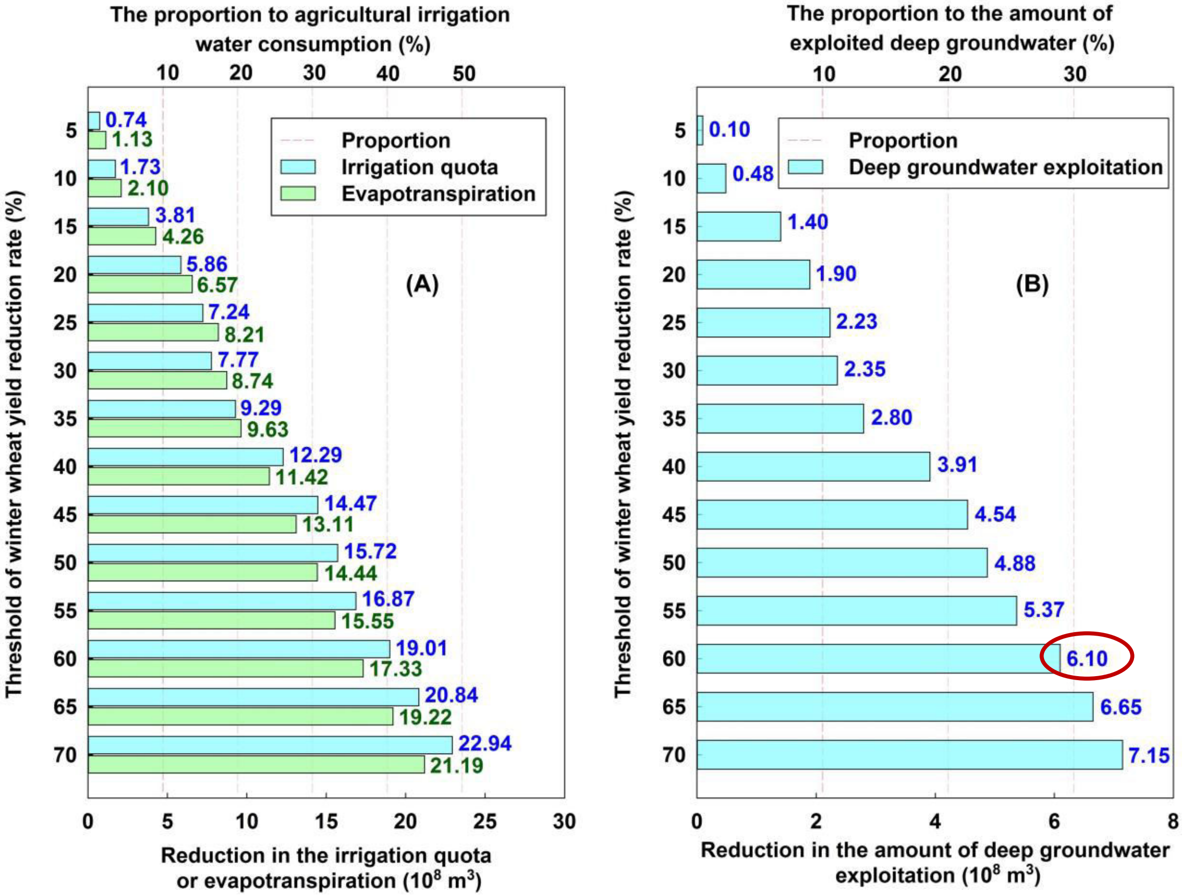


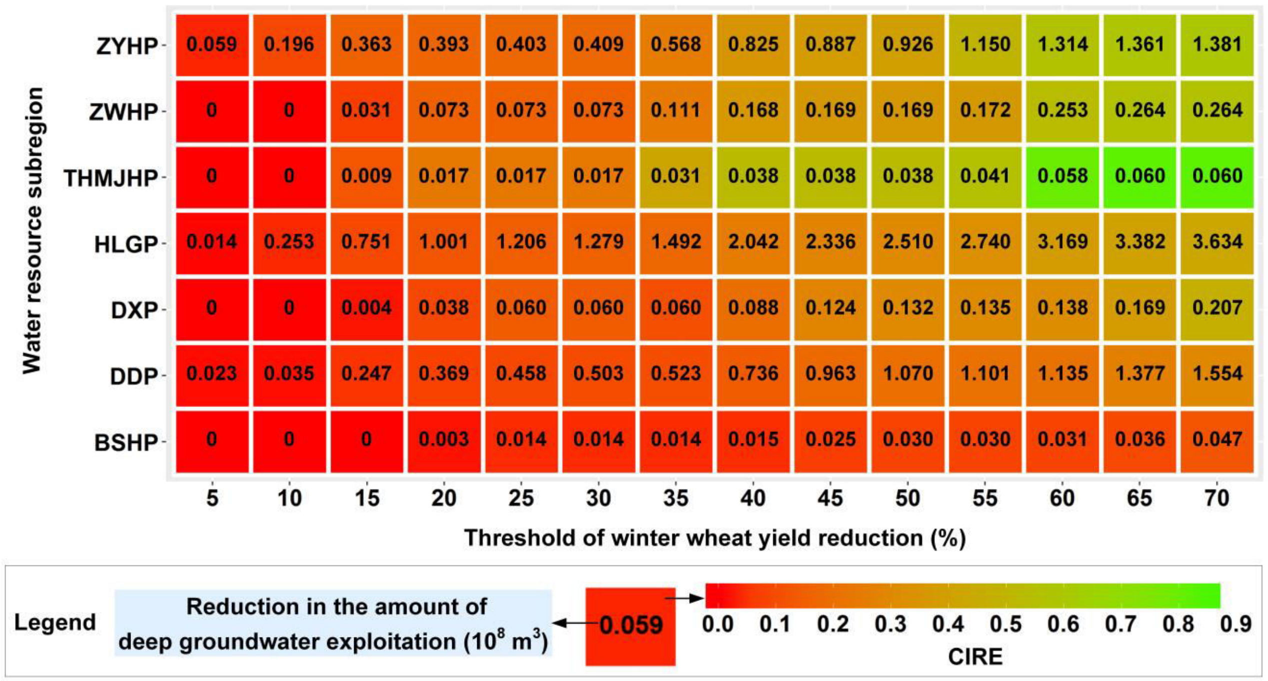


The decrease in irrigation quota led to the yield and evapotranspiration reductions. With the yield reduction less than 21%, the WP remained stable compared with the current irrigation schedule.

Source: Li and Ren (2019b)

Results and Discussion





Water resource subregion	5	10	15	20	25	30	35	40	45	50	55	60	65	70
ZYHP	0.059	0.196	0.363	0.393	0.403	0.409	0.568	0.825	0.887	0.926	1.150	1.314	1.361	1.381
ZWHP	0	0	0.031	0.073	0.073	0.073	0.111	0.168	0.169	0.169	0.172	0.253	0.264	0.264
THMJHP	0	0	0.009	0.017	0.017	0.017	0.031	0.038	0.038	0.038	0.041	0.058	0.060	0.060
HLGP	0.014	0.253	0.751	1.001	1.206	1.279	1.492	2.042	2.336	2.510	2.740	3.169	3.382	3.634
DXP	0	0	0.004	0.038	0.060	0.060	0.060	0.088	0.124	0.132	0.135	0.138	0.169	0.207
DDP	0.023	0.035	0.247	0.369	0.458	0.503	0.523	0.736	0.963	1.070	1.101	1.135	1.377	1.554
BSHP	0	0	0	0.003	0.014	0.014	0.014	0.015	0.025	0.030	0.030	0.031	0.036	0.047

Threshold of winter wheat yield reduction (%)

Legend: Reduction in the amount of deep groundwater exploitation (10^8 m^3) ← 0.059 → CIRE 0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9

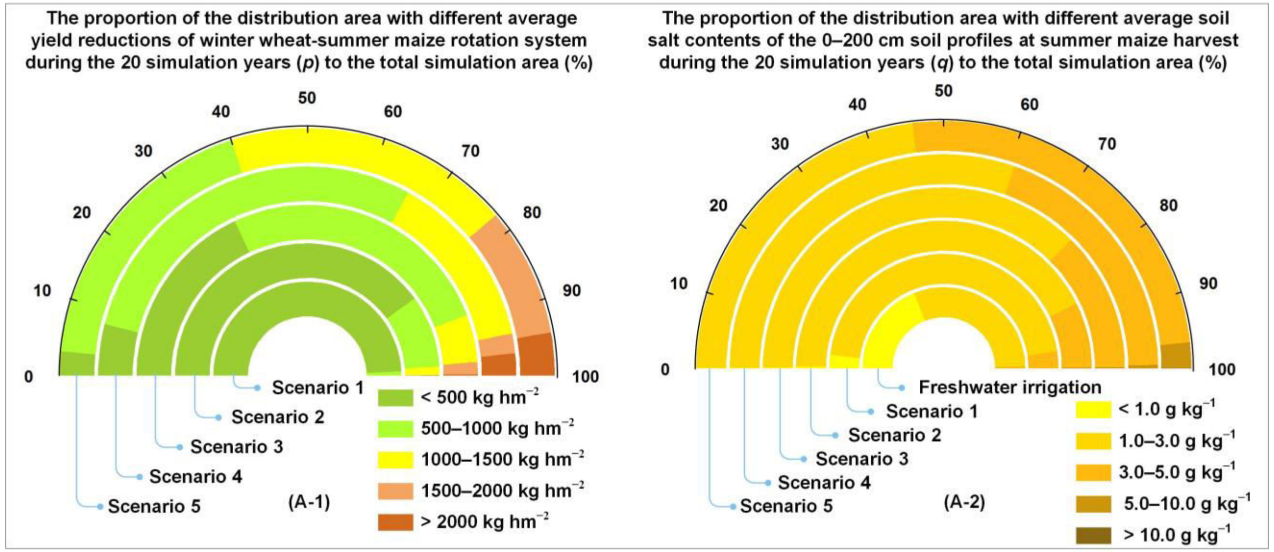
Note: BSHP indicates the plain downstream of the Beisi River basin; DDP indicates the Diandong plain of the Daqing River basin; DXP indicates the Dianxi plain of the Daqing River basin; HLGP indicates the Heilonggang Yundong plain; THMJHP indicates the Tuhai and Majia Rivers plain; ZWHP indicates the plain of the Zhangwei River basin; ZYHP indicates the plain of the Ziya River basin; and CIRE represents the contribution index of reducing exploitation.

With an increase in yield reduction from 4% to 61%, the reduction in the amount of deep groundwater exploitation under the optimized irrigation scheme increased from approximately 1.40×10^8 m^3 to 7.15×10^8 m^3.

To achieve the target value of 6.05×10^8 m^3, the yield decreased by approximately 50%.

Source: Li and Ren (2019b)

Results and Discussion

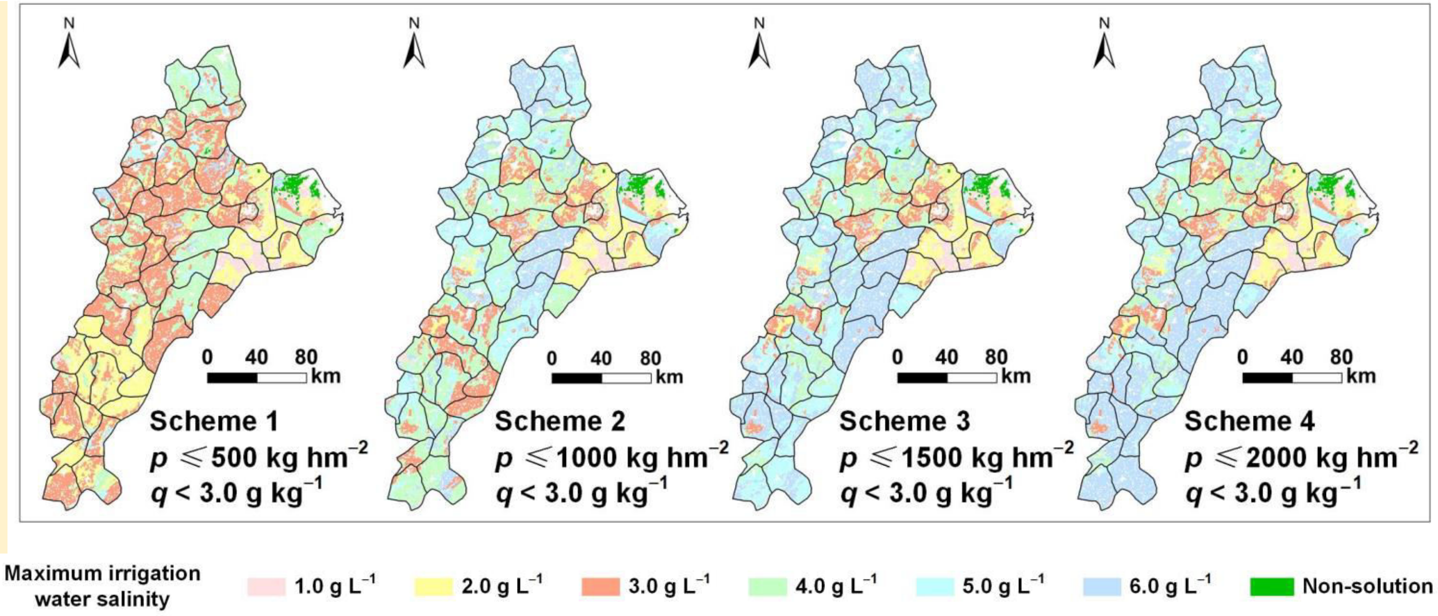

The proportion of the distribution area with different average yield reductions of winter wheat-summer maize rotation system during the 20 simulation years (p) to the total simulation area (%)

The proportion of the distribution area with different average soil salt contents of the 0–200 cm soil profiles at summer maize harvest during the 20 simulation years (q) to the total simulation area (%)

The yield reduction of the rotation system was less than or equal to 2000 kg hm^{-2} in more than 94% of the simulation area under the five scenarios.

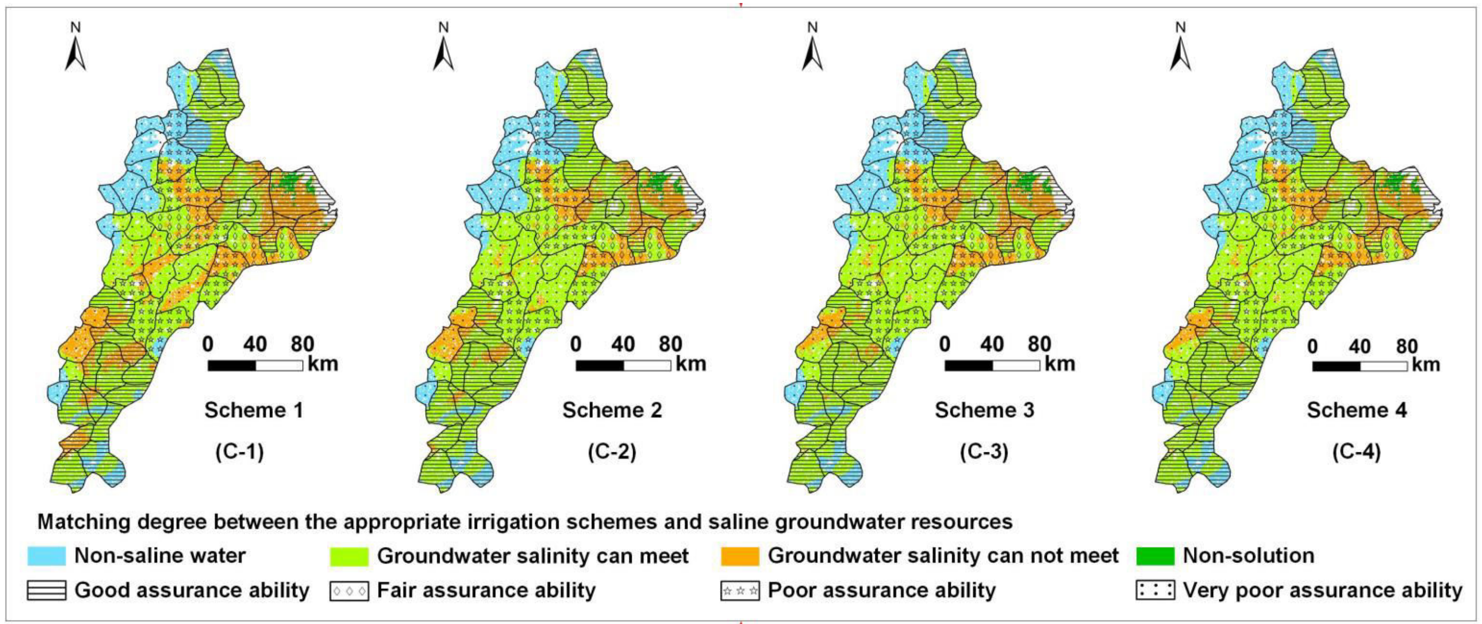
The salt content of the 2-m soil profile at summer maize harvest was less than or equal to 5 g kg^{-1} in more than 96% of the simulation area under the five

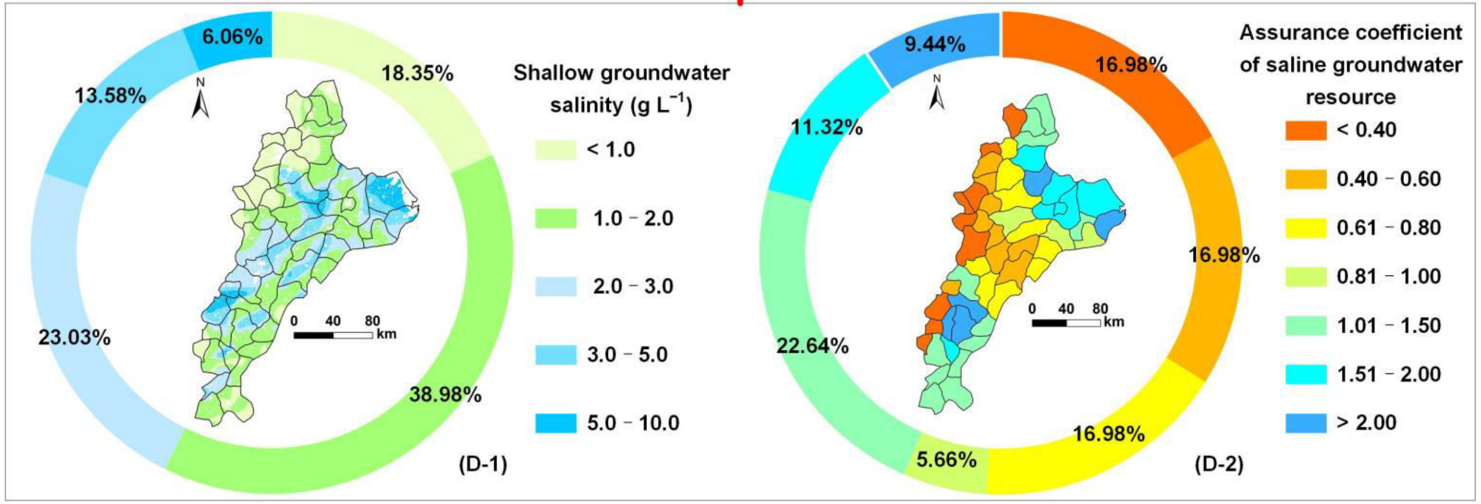
On the premise that the salt content of 2-m soil profile was less than 3 g kg^{-1}, if the average crop yield reduction in the range of ≤500 kg hm^{-2}, ≤1000 kg hm^{-2}, ≤1500 kg hm^{-2} and ≤2000 kg hm^{-2} was permitted, the dominant maximum irrigation water salinity in the study area was 3 g L^{-1}, 4 g L^{-1}, 6 g L^{-1} and 6 g L^{-1}, respectively.



Source: Li and Ren (2021)

Results and Discussion





The average saline water amount needed for winter wheat irrigation was approximately 22.78×10^{8} m^{3}, which was approximately 9% more than the exploitable amount of saline groundwater.

In the 23 counties of the study area, the exploitable amount of saline groundwater could meet the needs of winter wheat irrigation. In most parts of these counties, the shallow groundwater salinity could also satisfy the appropriate irrigation schemes, showing a high matching degree.

Source: Li and Ren (2021)

Results and Discussion

2809 simulation units

×

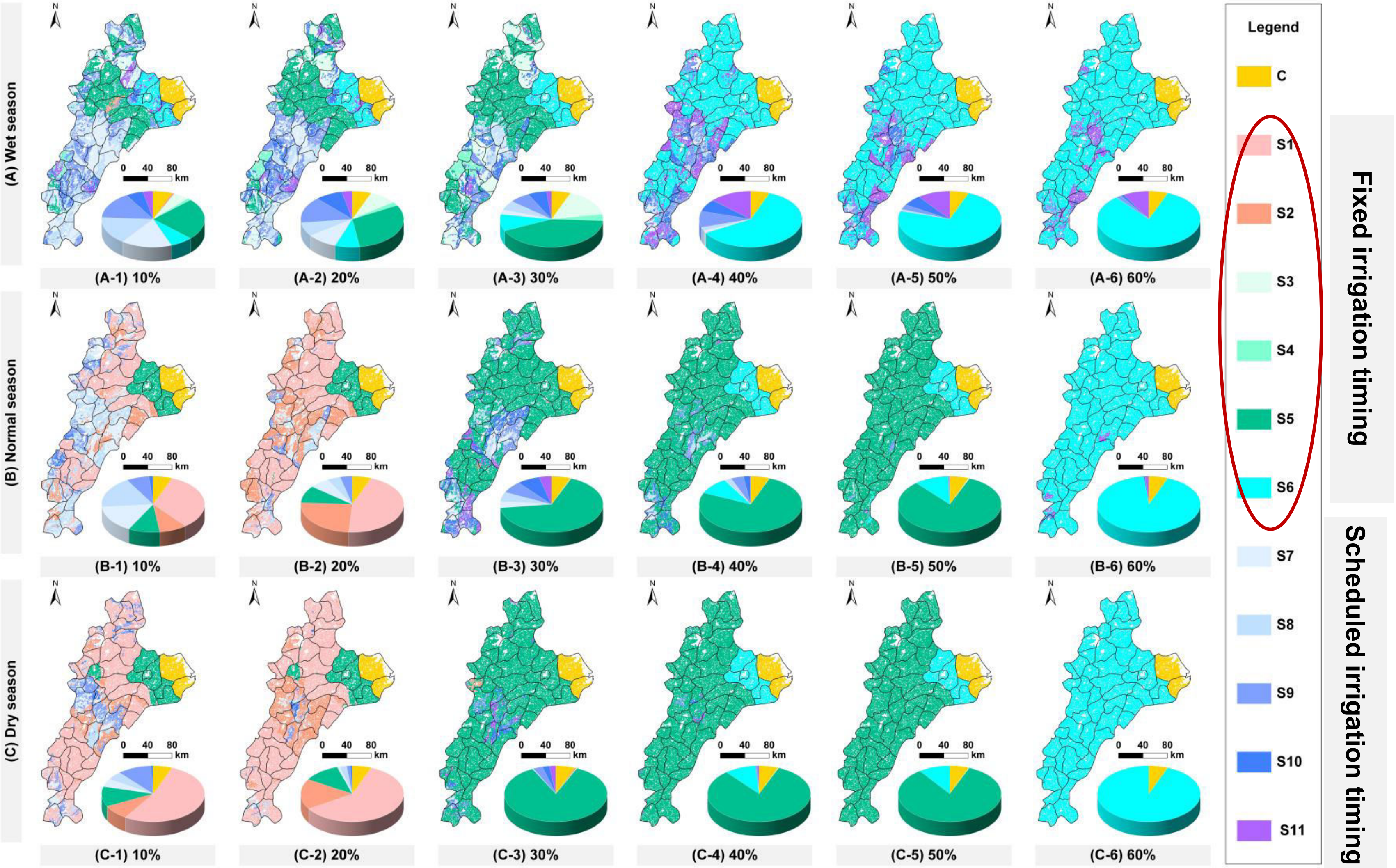
3 precipitation levels (wet, normal and dry)

×

6 threshold (10%, 20%,30%, 40%, 50% and 60%)

=

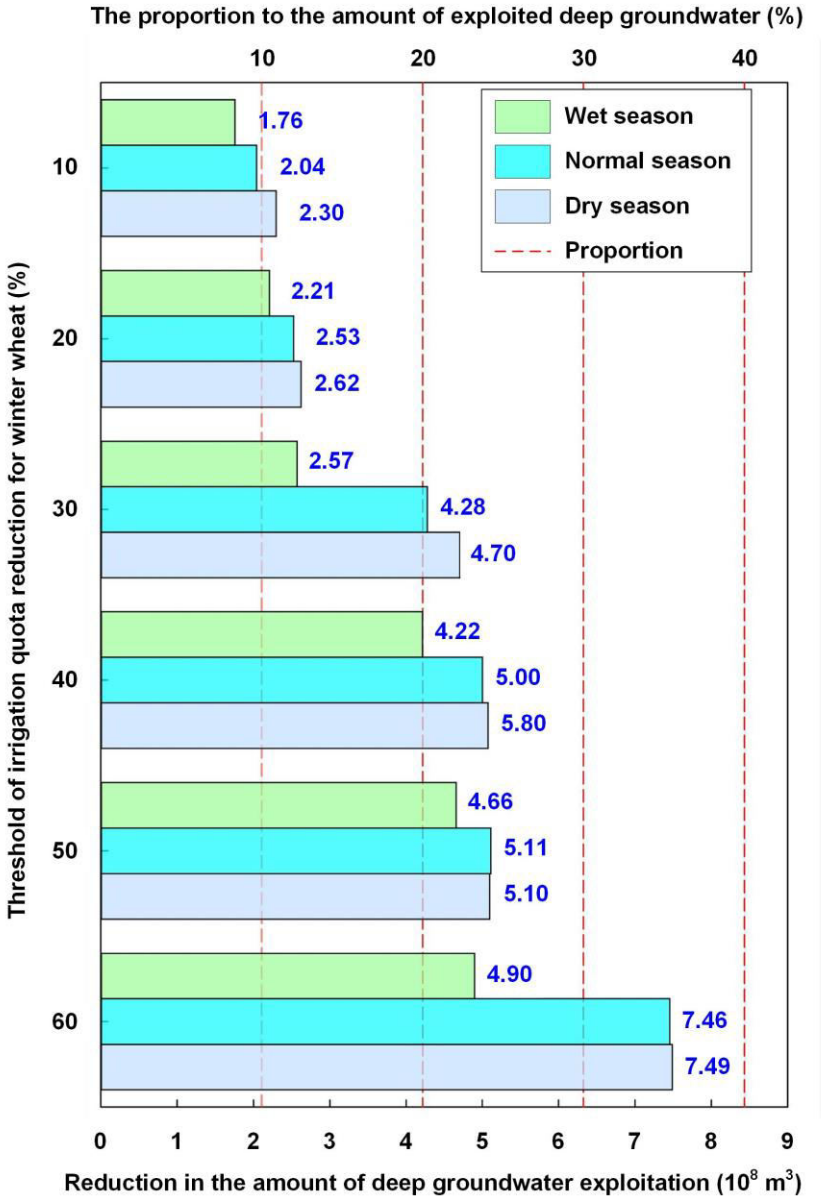
Solve 50562 times



Note: C represents the current irrigation schedule, S1 to S11 represent the sprinkler irrigation scenarios.

Source: Li and Ren (2022)

Results and Discussion



Precipitation level	Wet	Normal	Dry
Reduction in irrigation quota	15.59 ×10^8 m^3	23.89 ×10^8 m^3	24.00 ×10^8 m^3
Reduction in deep groundwater exploitation	4.90 ×10^8 m^3	7.46 ×10^8 m^3	7.49 ×10^8 m^3
Proportion to the target value of reducing deep groundwater exploitation	81%	123%	124%
Reduction in winter wheat yield	55.8%	74.3%	79.7%

Source: Li and Ren (2022)

Conclusions

1. If the irrigation quota was reduced to prevent deep groundwater overexploitation, the applications of sprinkler irrigation and limited surface irrigation led to reductions in yield and WP.
2. Under the current planting scale of most farmers, limited surface irrigation rather than sprinkler irrigation is recommended in the most study areas from the perspective of achieving a relatively high yield and a higher WP.

Conclusions

3. Saline groundwater is an important alternative water source for irrigation, and reasonable utilization would not cause significant soil salt accumulation and crop yield reduction. Only in half of the study area saline groundwater meets the irrigation requirements from the perspectives of water quantity and water quality.

- ➢ It is difficult to achieve groundwater sustainability only by changing irrigation methods and schemes, we suggest using other water sources (e.g., external transfer water and unconventional water) and field management measures.

Publications

Journal of Hydrology 574 (2019) 497–

Contents lists available at ScienceDi

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Research papers

Evaluating the effects of limited irrigation on crop w
reducing deep groundwater exploitation in the North
agro-hydrological model: I. Parameter sensitivity ana
model validation

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ARTICLE INFO

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Keywords:
Overexploited deep groundwater area
Distributed SWAP-WOFOST model
Regional heterogeneity
Multisource data
Multiscale validation
Global sensitivity analysis

ABSTRACT

1. Introduction

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Research papers

Evaluating the effects of limited irrigation on crop wa
reducing deep groundwater exploitation in the North
agro-hydrological model: II. Scenario simulation and

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Distributed SWAP-WOFOST model

ABSTRACT

1. Introduction

* Corresponding author at: No. 2 Yuanmingyuan West Road, Haidian District, Beijing 100193, PR
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Research papers

Evaluating the saline water irrigation schemes using
agro-hydrological model

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Matching degree
North China Plain

ABSTRACT

1. Introduction

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Research papers

Assessing the feasibility of sprinkler irrigation schemes a
using a distributed agro-hydrological model

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North China Plain

ABSTRACT

1. Introduction

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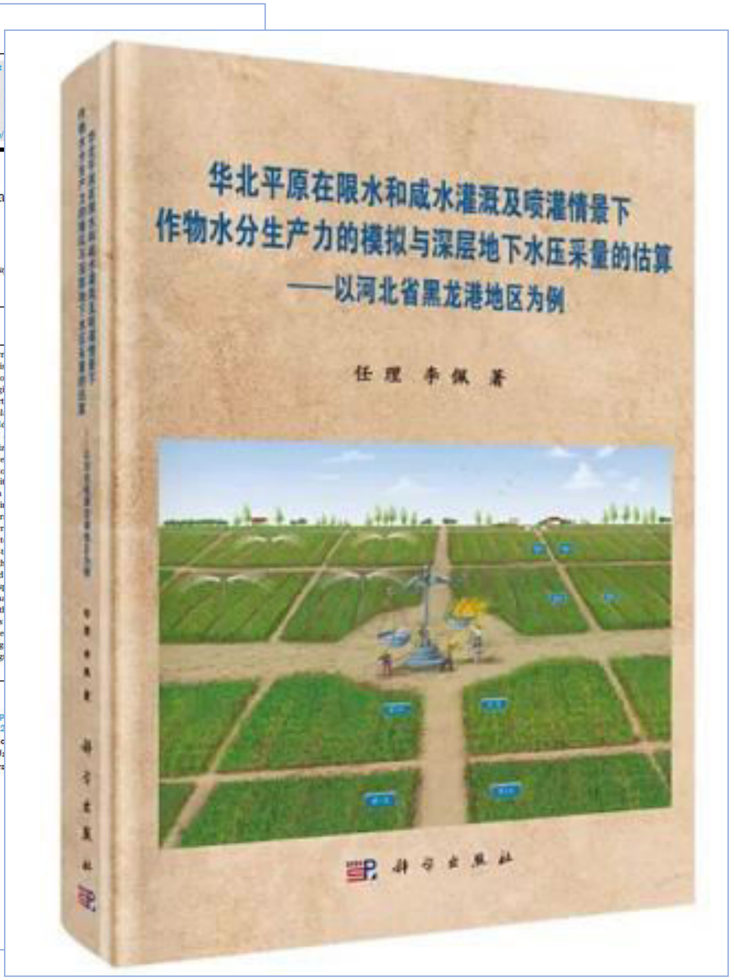

华北平原在限水和咸水灌溉及喷灌情景下
作物水分生产力的模拟与深层地下水压采量的估算
——以河北省黑龙港地区为例

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