Crop switching: A viable solution for water savings and environmental sustainability in China

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Outline

- **Background**
- Methods
- Results

China has made great achievements in ensuring food security

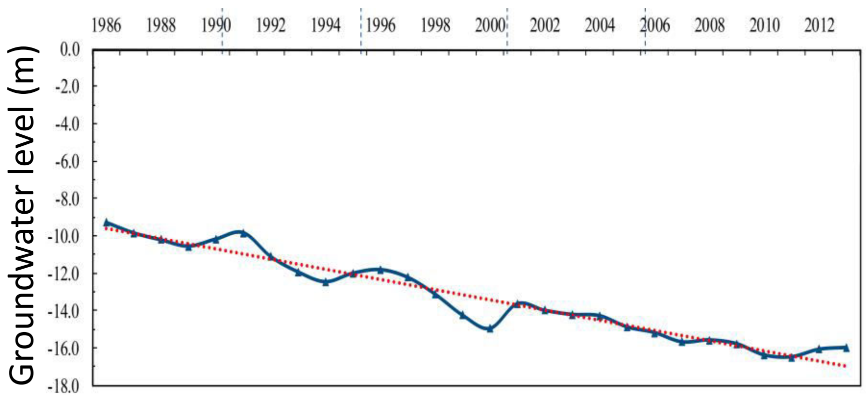
- **Population:** 1.375 billion

  ≈ 20% world population
- **Water availability:** ≈ 5% of world total
- **Arable land:** ≈ 8% of world total
- **Crop production:** ↑214% since 1990
- **Food self-sufficiency: ≈ 95% in 2019**

  (28.2%, 17.6%, and 22.9% of global rice, wheat, and maize)

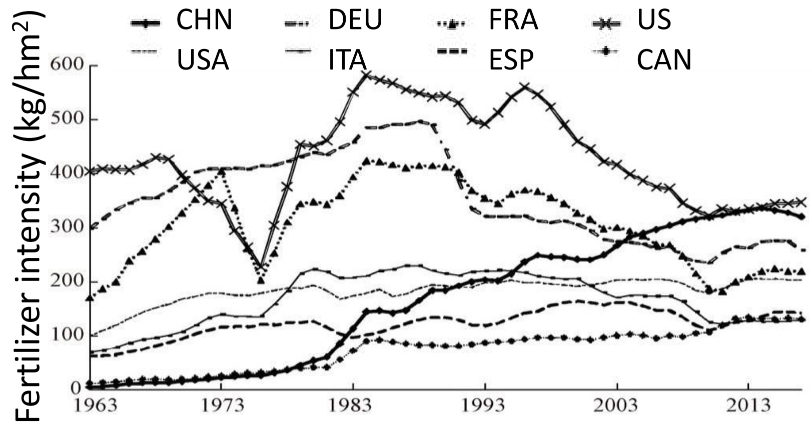
Agricultural expansion was at the expense of sustainable development

➢ **The groundwater level dropped alarmingly**



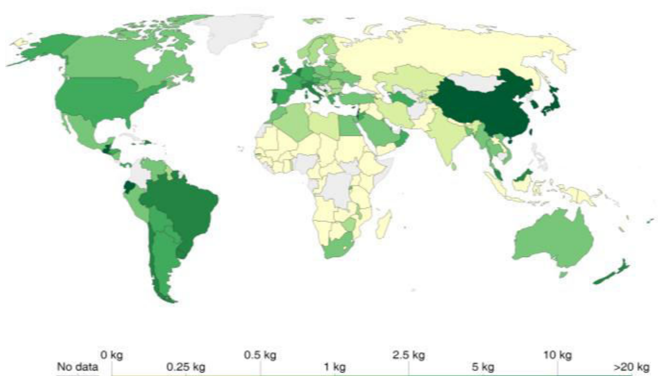
(MWR, 2012)

➢ **Fertilizer intensity continued to increase**



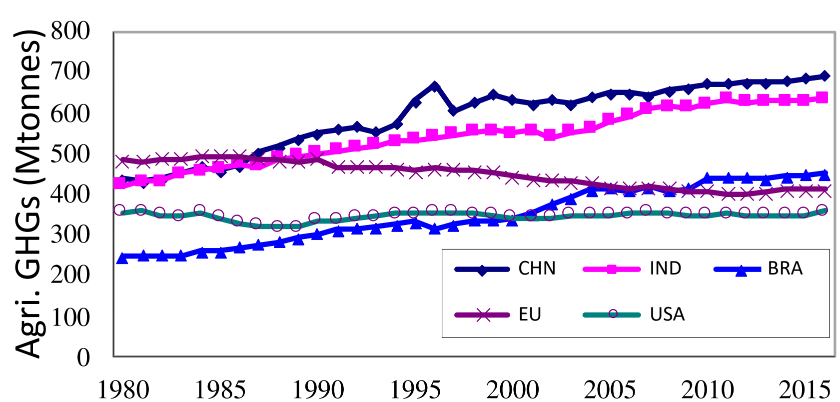
(Liu et al, 2020)

➢ **The country with the highest pesticides intensity**



(FAO, 2017)

➢ **The country with the largest Agri. GHGs emissions**



(FAO, 2017)

Sustainable farm management solutions

- **China:** "high-standard farmland" to improve agriculture productivity while reducing input use, implementing "water-saving projects" to improve water use efficiency etc.
- These solutions assume that crops are already grown in the locations where they are most agro-climatically suited and most resource-efficient.
- There is little understanding of whether the current distribution of crops is best for achieving more sustainable agricultural systems in China.
- **Global:** studies show reduced irrigation (i.e., blue) water demand and blue water scarcity, protect the natural environment and biodiversity

Crop switching is a promising strategy to complement other sustainable farm management solutions

- **India:** replacing rice areas with alternative cereals (e.g., millets and sorghum) enhances dietary nutrient supply, reduces natural resource use and GHG emissions, and improves climate resilience without compromising calorie supply or expanding cropland (Davis et al., 2018).
- **USA:** crop switching can reduce blue water demand (Davis et al., 2017) and climate-related crop losses (Rising et al., 2020).
- **Crop switching** is a promising strategy, in China, previous policies have mainly depended on qualitative analyses.

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Crop switching is a promising strategy to complement other sustainable farm management solutions

- We construct a linear optimization model to simulate the contribution of crop switching to sustainable agricultural development and assess tradeoffs and co-benefits across multiple dimensions.
- Constraints:
  1) national supply of all crops cannot decrease—a constraint reflecting national self-sufficiency targets
  2) farmer incomes within each grid cell cannot decrease
  3) only crops currently grown within a grid cell can be planted there
  4) arable land and harvested area within each grid cell are kept as current levels
  5) cropping calendars of rotating crops cannot overlap in time.

Agricultural BIG Data

✓ Irrigated and Rainfed Crops (13*2):

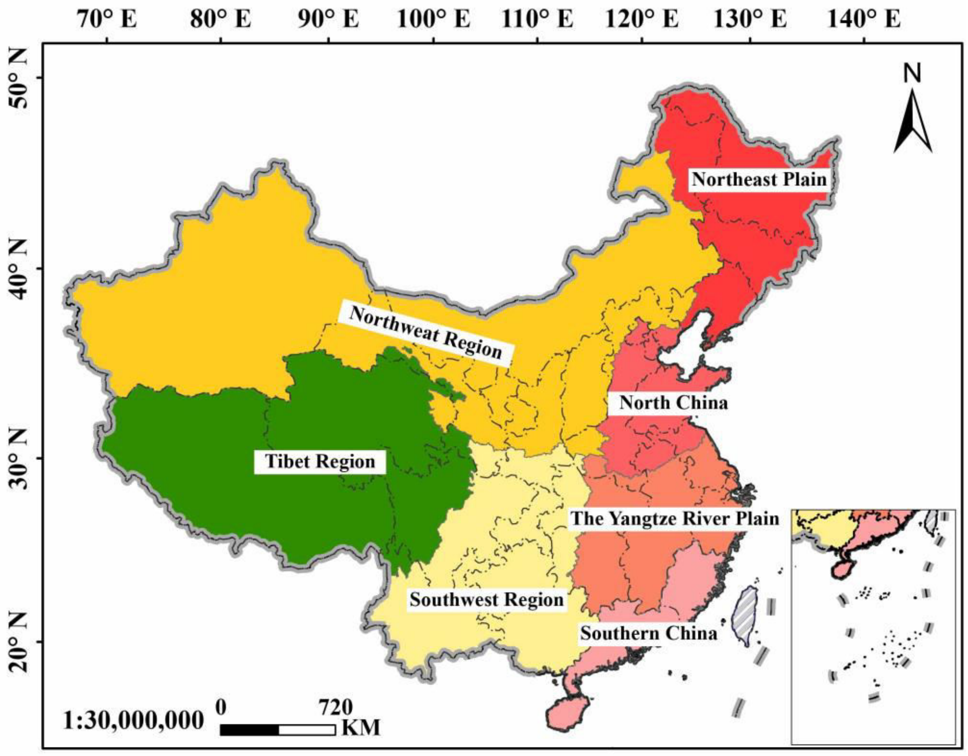
- Wheat (Spring Wheat, Winter Wheat), Rice (Early-Rice, Mid-Rice, Late-Rice), Maize (Spring Maize, Summer Maize), Soybean, Rapeseed, Groundnut, Cotton, Sugar Beet, Sugar Cane. (~94% crop production; ~88% of harvested land)

✓ Multi-source Data (5 arc minute; 1/12° ; ~10-km resolution)

1. Crop-specific information of irrigated/rainfed yields and harvested area in 2010 (grid level), *SPAM database (v 1.2)*.
2. Crop-specific blue and green water intensity (grid level), *Crop-Water Demand model*.
3. Crop-specific GHGs emissions intensity (grid level), *DNDC model*.
4. Crop-specific fertilizers intensity (Nitrogen, Phosphorous, Potash and Compound fertilizer), pesticides intensity and farmer incomes (provincial level), *Agricultural costs and profits statistical yearbook*.
5. Growing season of crops (778 stations in China), *China meteorological data service center*.

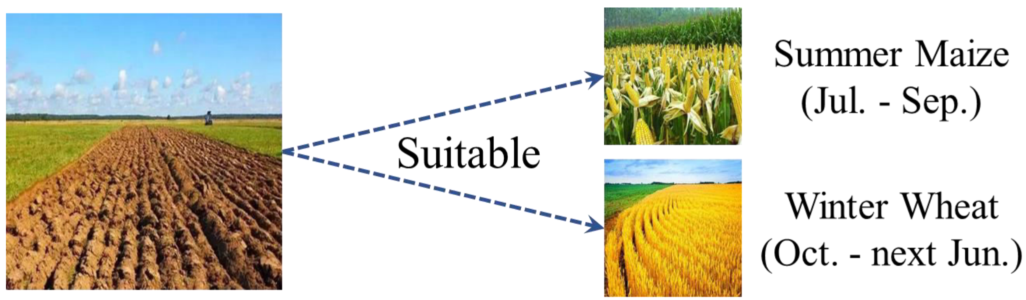
Regions divided by agro-ecological zones (AEZ)

Region	Administrative areas included
North China	Beijing, Tianjin, South central Hebei, Henan, Shandong, Northern Anhui, Northern Jiangsu
Northeast Plain	Liaoning ,Jilin, Heilongjiang, Eastern Inner Mongolia
The Yangtze River Plain	Jiangxi, Shanghai, Zhejiang, South central Anhui, South central Jiangsu, Most of Hubei, Most of Hunan
Southern China	Fujian, Guangdong, Hainan
Southwest Region	Guangxi, Chongqing, Guizhou, Southern Shaanxi, Eastern Sichuan, Most of Yunnan, Western Hubei, Western Hunan
Northwest Region	Xinjiang, Ningxia, North central Shaanxi, Most of Gansu, Shanxi, West central Inner Mongolia, Northern Hebei
Tibet Region	Tibet, Qinghai, Western Sichuan, Northwest Yunnan



Crop Rotations

- Rice: South (2-3 seasons per year) → Northeast (1 season per year)
- The 72,000 grid points were divided into 7 regions, and 1,352 crop rotation patterns were constructed based on crop growing season data (planting times do not conflict). 153 crop rotation patterns were further selected through expert judgment and field surveys.



Region	Number of grids	Number of cropping rotations				
		1 crop per year	2 crops per year	3 crops per 2 years	5 crops per 3 years	Total
Northeast	11698	10	0	0	0	10
North	6314	13	3	4	0	20
Yangtze	9769	13	1	9	0	23
South	4193	13	14	6	14	47
Northwest	19122	11	1	0	0	12
Southwest	17255	13	4	11	0	28
Tibet	3649	13	0	0	0	13
Total	72000	86	23	30	14	153

Rotation Examples

Region	Crop 1	Crop 2	Crop 3	Crop 4	Crop 5	Rotation
North	Winter Wheat					1 crop per year
North	Summer Maize					1 crop per year
North	Winter Wheat	Summer Maize				2 crops per year
North	Winter Wheat	Soybean				2 crops per year
North	Winter Wheat	Summer Maize	Soybean			3 crops per 2 years
North	Winter Wheat	Rapeseed	Soybean			3 crops per 2 years
North	Summer Maize	Rapeseed	Soybean			3 crops per 2 years
North	Winter Wheat	Summer Maize	Rapeseed	Soybean	Groundnut	5 crops per 3 years
North	Winter Wheat	Summer Maize	Winter Wheat	Summer Maize	Rapeseed	5 crops per 3 years
North	Winter Wheat	Soybean	Groundnut	Rapeseed	Soybean	5 crops per 3 years

Method: Large Liner Optimization Model

Min/Max SDG_{Dim} (minimize national use of blue water or other 7 sustainable dimensions, or maximize national farmer income)

***s.t.* *(More than 1.5 million constraints)*:**

$\sum_{i,j} CA_{irr,i} * x_{i,j} * R_{j,z} * YLD_{irr,i,z} \geq P_{Cur,irr,z}$ **(1) Production (national level)**

$\sum_{j,z} CA_{irr,i} * x_{i,j} * R_{j,z} * YLD_{irr,i,z} * UI_{INC,i,z} \geq TFI_{Cur,irr,i}$ **(2) Farmer's income (grid level)**

$\sum_{j} x_{i,j} \leq 1$ **(3) Cultivated Area (grid level)**

$\sum_{j} CA_{irr,i} * x_{i,j} * R_{j,z} = CA_{Cur,irr,i}$ **(4) Harvested Area (grid level)**

$\sum_{j,z} CA_{irr,i} * x_{i,j} * R_{j,z} * UI_{Dim,i,z} \leq \begin{cases} CURRENT_{Dim,irr,i} \mid (Ind_{Dim,i} \geq BD_{Dim,i}) \\ UPBOUND_{Dim,irr,i} \mid (Ind_{Dim,i} < BD_{Dim,i}) \end{cases}$ **(5) SDG (grid level)**

$SDG_{Dim} = \sum_{i,j,z} CA_{irr,i} * x_{i,j} * R_{j,z} * UI_{Dim,i,z}$ **(6) Optimization Object**

SDG_{Dim} = total national use of Dim; Dim = nine agricultural sustainable dimensions;

$CA_{irr,i}$ = cultivated area of irrigated croplands in grid i

$x_{irr,i,j}$ = proportion of the cultivated land applying crop rotation j in grid i

$R_{j,z}$= rotation number that crop z is planted per year in the feasible crop rotation $j_{zlist,i,s}$;

- **All these optimizations were duplicated on rainfed cropland except minimizing the blue water use scenario, and then we aggregated the results with irrigated optimizations to get the optimization of all lands.**

Method: The properties of the scenarios

Scenarios *	Sustainability dimensions under study	All other sustainability dimensions	Farmer incomes	Crop production
G1	Optimized individually	May degrade on both national and grid level	May not decrease in any grid cell	May not decrease on national level
G2	Optimized individually	May not degrade in any grid cell		
G3	All sustainable dimensions are optimized			

*G1 (No coordination): Silo-ed approach prioritizing a single sustainability objective at a time; G2 (Cross-ministry coordination): prioritizes one sustainability dimension while not degrading outcomes for any of the other sustainability dimensions at the national level and grid level; G3 (Central coordination): prioritizes that the average improvement of all sustainable dimensions is the largest while the variance among these improvements is the smallest

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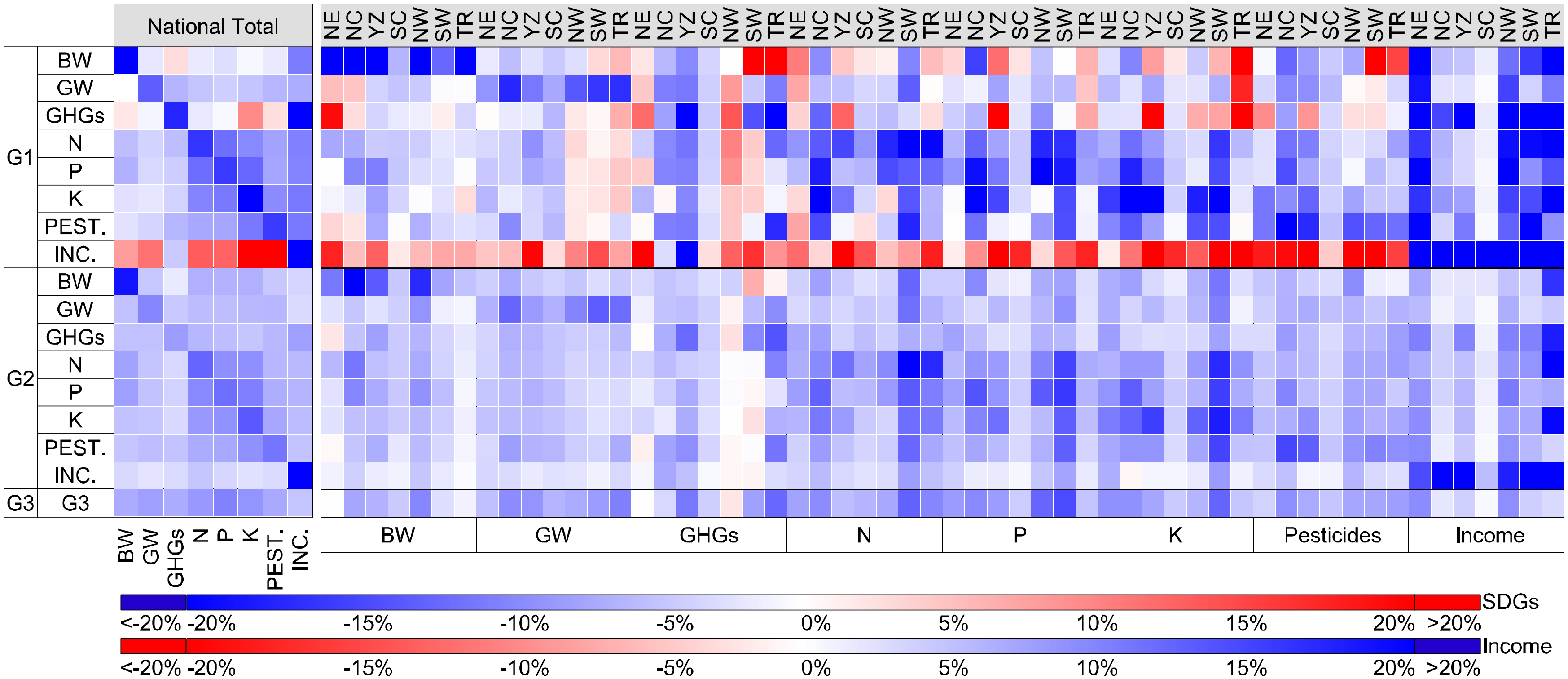
Changes in resource use, environmental losses, and farmer incomes under crop switching

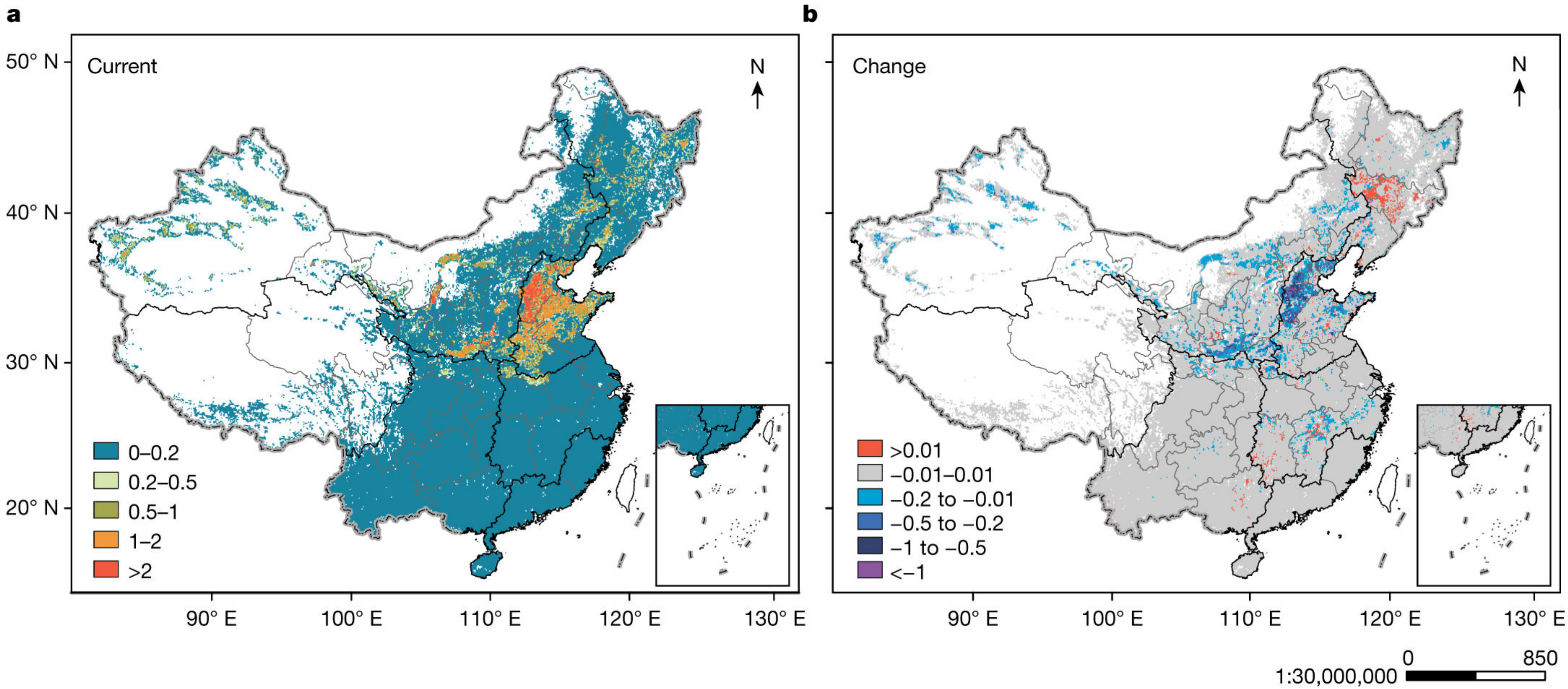


Each row represents a different optimization objective; **each column** represents the outcome for each sustainability dimension.

G3:

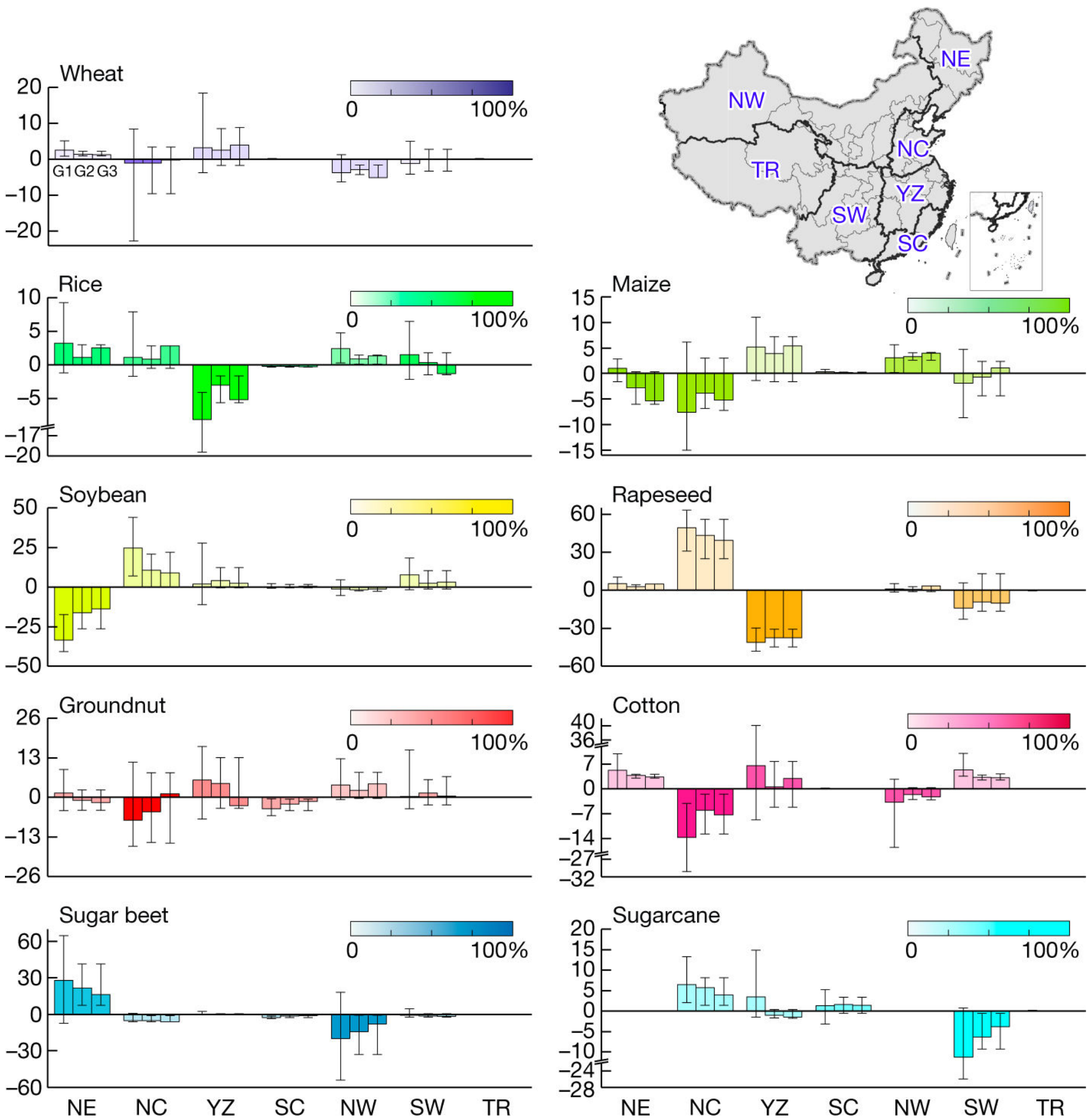
- **Blue Water, -6.5%; Green Water, -7.5%; GHGs, -6.5%;**
- **Nitrogen fertilizer, -8.1%; Phosphate fertilizer, -9.8%;**
- **Potassium fertilizer, -8.3%; Pesticides, -6.7%; Farmers' income, +4.5%**

Reductions in blue water scarcity through optimized crop switching



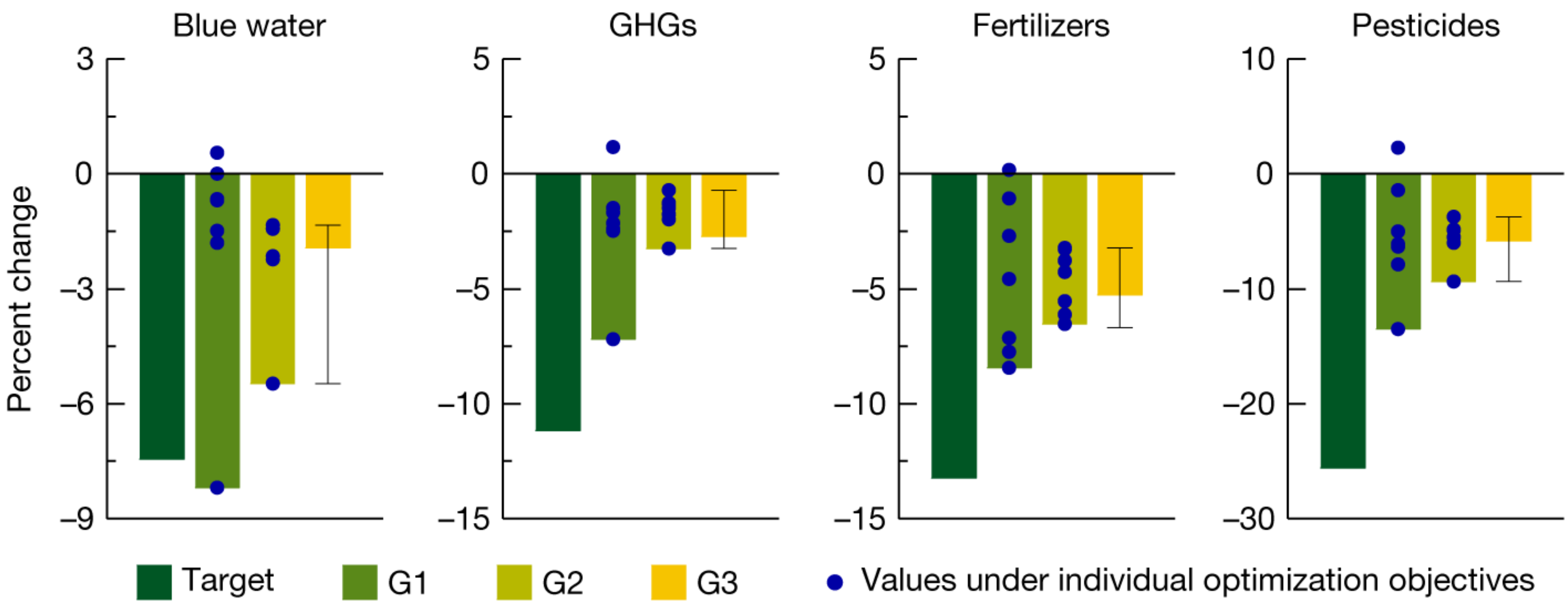
Changes in the spatial distribution of water scarcity under the optimization scenario (G3) that simultaneously saves resources, reduces environmental losses and increases farmer incomes. **a,** Ratio of current blue-water use to water availability (that is, water scarcity). **b,** Changes in blue-water scarcity after crop switching.

Changes in the spatial distribution of resource use and environmental losses



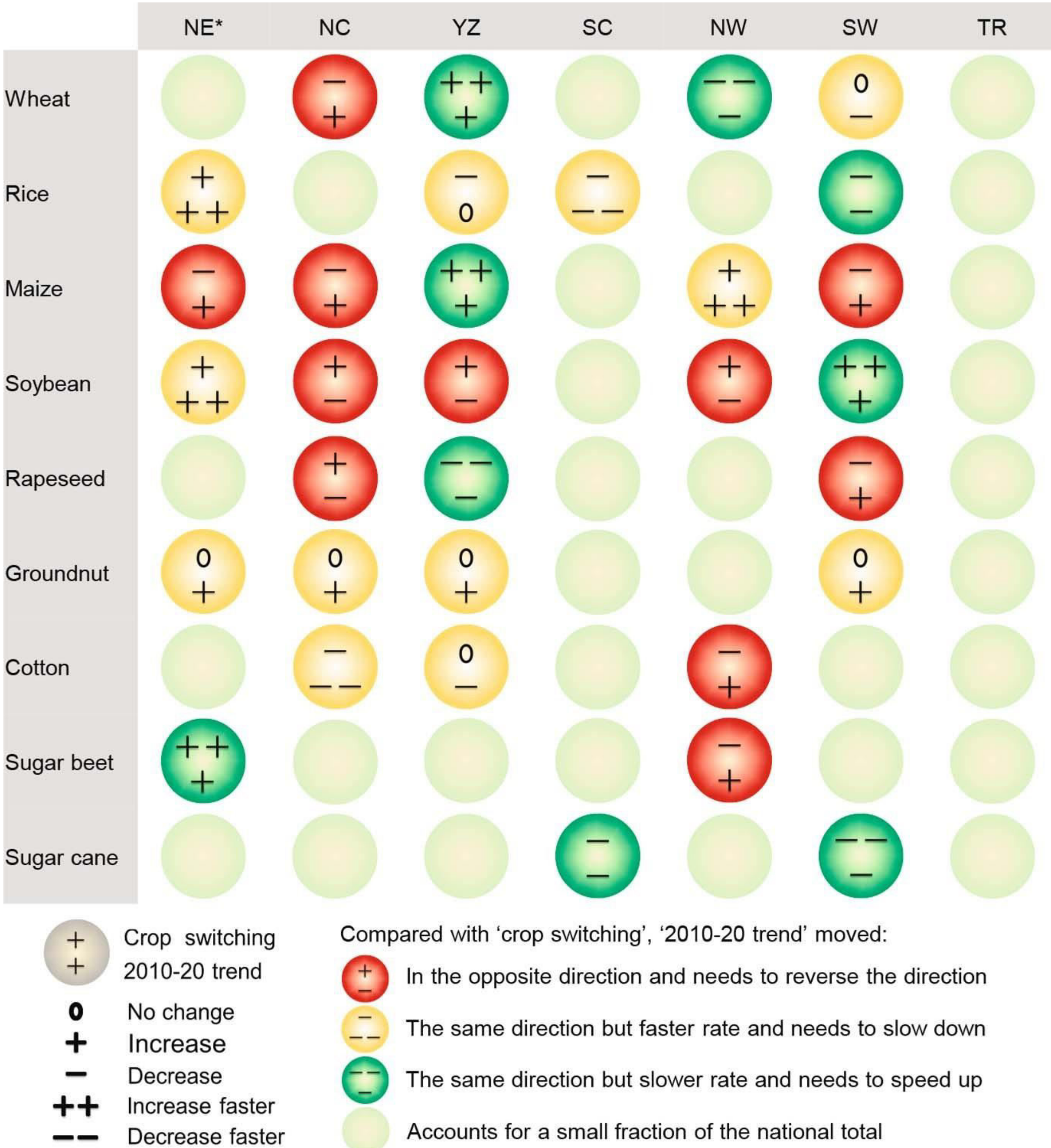
The **y-axis** indicates the percentage point differences between the shares (%) in the national production of a specific crop in each region before and after crop switching. In each group of three bars, the **left, middle, and right bars** are the average change of regional crop-production share under G1 (eight scenarios), G2 (eight scenarios), and G3 (one scenario), respectively. The **whiskers** indicate the minimum and maximum of all changes; the whiskers for G3 bars represent the range of Pareto-optimal outcomes. The **color scale of the bars** corresponds to the share of current crop production of each region to the national total; for instance, the darker shades of the bars for wheat in the North China Plain (NC) and rice in the Yangtze River Plain (YZ) indicate that these regions account for large shares in the total national production of those crops. The **map in the top-right** corner shows the distribution of the seven regions of China:

Contribution to official agricultural sustainability targets in 2030



The **dark green bars (‘Target’)** show the difference between the baseline projection and China’s official agricultural sustainability targets in 2030. Under the baseline, the projection of blue water is based on existing literature. As the projections of other sustainable dimensions for China were unavailable in the literature, we multiplied projected crop production in 2030 and current resource-use intensities to estimate their baseline projections. The **other three bars** represent the crop-switching benefits of the G1, G2, and G3 scenarios. The **blue points** represent the crop-switching benefits/costs of individual optimization objectives. The **whiskers for the G3** bars represent the range of Pareto-optimal outcomes.

Trend agreement between proposed and recently observed changes in cropping patterns



Circle colors denote whether—compared with our proposed crop switching (**G3**)—the observed distribution change of the crop in that region during the past ten years has moved in the **opposite direction** and needs to **reverse the direction (red),** the **same direction but faster rate** and needs to **slow down (yellow)** or the **same direction and the same/slower rate** and needs to **speed up (green)**. Faded circles indicate that a crop in that region accounts for a small fraction of the national production. The **top signs (+, −, 0)** inside each circle represent how the sowing area of the crop is **proposed to change** under our crop-switching scenarios, whereas the **bottom signs (+, −, 0)** show recent crop distribution changes **during 2010–2020**.

Concluding remarks

- Under a **siloed approach**, crop switching could realize large individual benefits but produce tradeoffs for other dimensions and among different regions.
- In cases of **enhanced coordination** –in which tradeoffs are prevented— we find marked co-benefits for environmental-impact reductions (blue water (−4.5% to −18.5%), green water (−4.4% to −9.5%), greenhouse gases (GHGs) (−1.7% to −7.7%), fertilizers (−5.2% to −10.9%), pesticides (−4.3% to −10.8%)) and increased farmer incomes (+2.9% to +7.5%).
- Outcomes of coordinated crop switching can contribute significantly (23% to 40% across dimensions) to **meeting China's agricultural sustainable development targets for 2030** and potentially produce global resource savings.
- Our integrated approach offers **feasible targeted agricultural interventions that achieve sustainability co-benefits across several dimensions.**

Thank You!

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Article

Crop switching can enhance environmental sustainability and farmer incomes in China

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Achieving food-system sustainability is a multidimensional challenge. In China, a doubling of crop production since 1990 has compromised other dimensions of sustainability[1,2]. Although the country is promoting various interventions to enhance

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