Crop switching can enhance environmental sustainability and farmer incomes in China

XIE W, ZHU A, ALI T, et al. (Nature, 2023)

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Outline

Abstract

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 production efficiency and reduce environmental impacts[3], there is little understanding of whether crop switching can achieve more sustainable cropping systems and whether coordinated action is needed to avoid tradeoffs. Here we combine high-resolution data on crop-specific yields, harvested areas, environmental footprints and farmer incomes to first quantify the current state of crop-production sustainability. Under varying levels of inter-ministerial and central coordination, we perform spatial optimizations that redistribute crops to meet a suite of agricultural sustainable development targets. With a siloed approach—in which each government ministry seeks to improve a single sustainability outcome in isolation—crop switching could realize large individual benefits but produce tradeoffs for other dimensions and between regions. In cases of central 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%). These outcomes of centrally coordinated crop switching can contribute substantially (23–40% across dimensions) towards China's 2030 agricultural sustainable development targets and potentially produce global resource savings. This integrated approach can inform feasible targeted agricultural interventions that achieve sustainability co-benefits across several dimensions.

Motivation

- Post-Green Revolution, a few high-yield crops and intensive farming practices have spread globally.
- Continuous agricultural production increases have led to multidimensional environmental challenges.
- In China, issues include:
  - Declining groundwater levels
  - Increased greenhouse gas emissions
  - Intensive fertilizer usage
  - Pesticide pollution

Current interventions and limitations

- Chinese government interventions:
  - High-standard farmland construction
  - Water-saving projects
  - Soil testing and formulated fertilization
- Limitations of current policies:
  - Focus on single-department policy benefits
  - Assumption that current crop distribution is most efficient for climate and resource use

Research status

- Recent literature reviews (e.g., India, USA, North China Plain) have indicated that crop transition can effectively promote sustainability.
- There is a lack of **quantitative research** on whether crop transition can benefit that well in China.

Main contribution

- Employ a linear optimization model combined with coordinated actions at three different levels of government to assess the impact of crop transition on:
  - Production quantity
  - Water demand
  - Greenhouse gas(GHG) emissions
  - Fertilizer use
  - Pesticide use
  - Economic output of crop production

Three scenario summaries

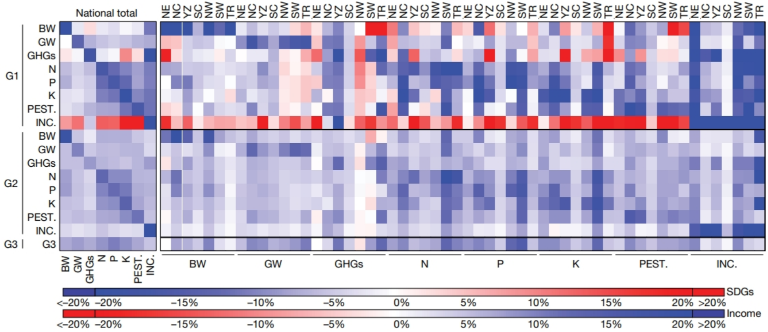
<table>
<tr><th>Scenarios</th><th>Sustainability dimension of objective function</th><th>Other sustainability dimensions</th><th>Farmer incomes</th><th>Crop production</th></tr>
<tr><td>G1</td><td>Optimized individually</td><td>May degrade on both national and grid levels</td><td rowspan="3">May not decrease at grid level</td><td rowspan="3">May not decrease on national level</td></tr>
<tr><td>G2</td><td>Optimized individually</td><td>May not degrade on national/grid levels</td></tr>
<tr><td>G3</td><td colspan="2">All sustainable dimensions are optimized</td></tr>
</table>

G1 (no coordination): siloed approach assigning priority to a single sustainability objective at a time; G2 (cross-ministry coordination): assigning priority to one sustainability dimension while not degrading outcomes for the other sustainability dimensions at the national/grid levels; G3 (central coordination): assigning priority to the improvement margins in all dimensions being as high as possible while their between-dimension differences are as low as possible.

Table S5. Detail properties of the optimization scenarios.

Scenario		Optimization objective	Constraints: Sustainable dimensions	Constraints: Farmer incomes	Constraints: Crop production
G1	S1	Minimize blue water use	Blue water (P)	May not decrease in any grid cell	May not decrease on national level
	S2	Minimize green water use	Green water (A)		
	S3	Minimize GHGs emissions	GHGs (N)		
	S4	Minimize nitrogen fertilizer use	Nitrogen (P)		
	S5	Minimize phosphorus fertilizer use	Phosphorus (P)		
	S6	Minimize potash fertilizer use	Potash (N)		
	S7	Minimize pesticides use	Pesticides (A)		
	S8	Maximize farmer incomes	—		
G2	S9	Minimize blue water use	Blue water (P); Green water (A); GHGs (N); Nitrogen (P); Phosphorus (P); Potash (N); Pesticides (A);		
	S10	Minimize green water use			
	S11	Minimize GHGs emissions			
	S12	Minimize nitrogen fertilizer use			
	S13	Minimize phosphorus fertilizer use			
	S14	Minimize potash fertilizer use			
	S15	Minimize pesticides use			
	S16	Maximize farmer incomes			
G3	S17	Ensures that the improvement margins in all dimensions are as high as possible while their between-dimension differences are as low as possible	Blue water (P); Green water (A); GHGs (N); Nitrogen (P); Phosphorus (P); Potash (N); Pesticides (A);		

Fig. 1 | National and regional changes



G1 Scenario: optimized individually

Indicator	Maximum change
Blue water demand	-27.8%
Green water demand	-12.6%
GHG emissions	-17.1%
Nitrogen fertilizer use	-15.9%
Phosphorus fertilizer use	-15.5%
Potassium fertilizer use	-20.6%
Pesticide use	-15.6%
Farmer income	90.5%

- When maximizing income as a single objective, the other environmental sustainability benefits at the national and regional levels are significantly reduced.

G2 Scenario: optimized individually with more constraint

Indicator	Maximum change
Blue water demand	-18.5%
Green water demand	-9.5%
GHG emissions	-7.9%
Nitrogen fertilizer use	-12.0%
Phosphorus fertilizer use	-11.4%
Potassium fertilizer use	-13.0%
Pesticide use	-10.8%
Farmer income	20.2%

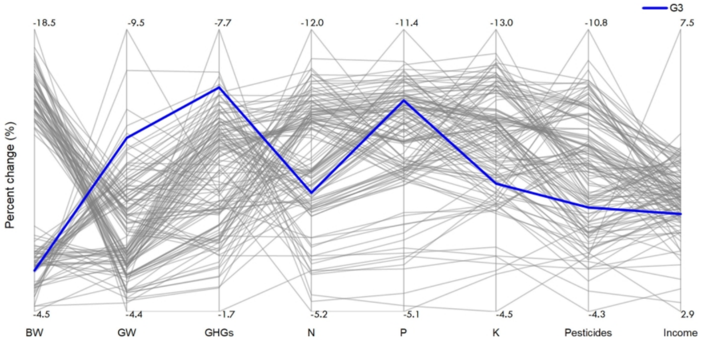
- Despite G2 scenario also offering multiple dimensions of sustainability benefits, prioritizing a single objective yields minimal contributions to sustainability benefits in other sectors.

G3 Scenario: Central collaboration

Indicator	Pareto optimal for all dimensions
Blue water demand	-6.5%
Green water demand	-7.5%
GHG emissions	-6.5%
Nitrogen fertilizer use	-8.1%
Phosphorus fertilizer use	-9.8%
Potassium fertilizer use	-8.3%
Pesticide use	-6.7%
Farmer income	4.5%

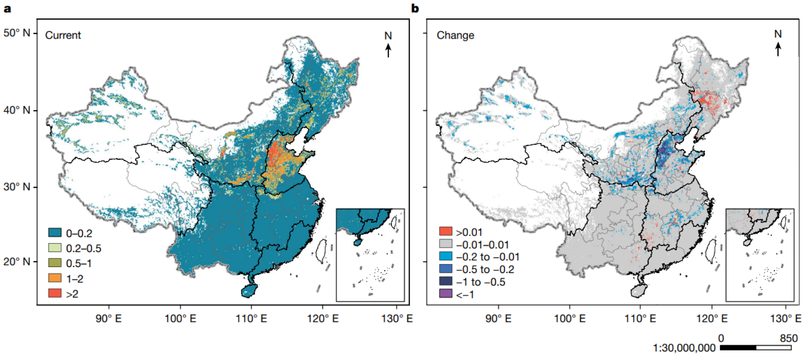
- The research findings indicate that crop switching can serve as an effective strategy to address the current situation of resource depletion or unsustainable utilization

Extended Data Fig. 1



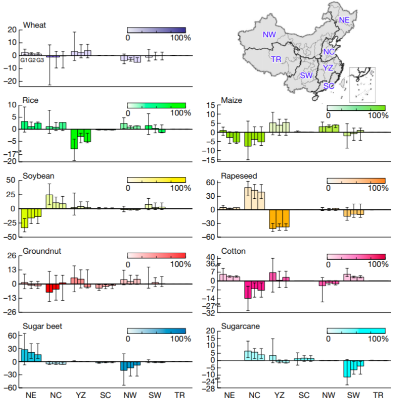
Extended Data Fig. 1 | Parallel coordinate plot with crop-switching strategies that are Pareto optimal for all dimensions. Each coordinate corresponds to a sustainability dimension and each line connecting different values between the coordinates corresponds to a single Pareto-optimal solution. The bold blue line shows the crop-switching solution under G3. BW, blue water; GW, green water; GHGs, greenhouse gas emissions; N, nitrogen fertilizers; P, phosphorus fertilizers; K, potash fertilizers.

Fig. 2 | Changes in blue-water scarcity through optimized crop switching



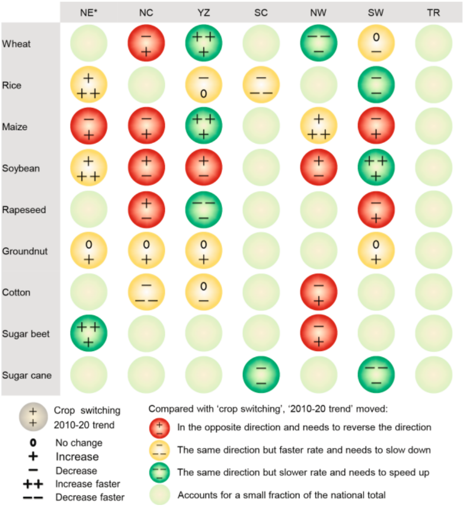
- Crop switching significantly reduces blue-water scarcity in North China.

Fig. 3 | Proposed changes in crop-production distribution



- Consistency of specific crops
- Moderate crop rotation in these regions can achieve sustainable benefits.

Crop Switching and 2010-20 Trend Comparison



Comparison of crop-switching benefits with China's 2030 agricultural sustainability targets

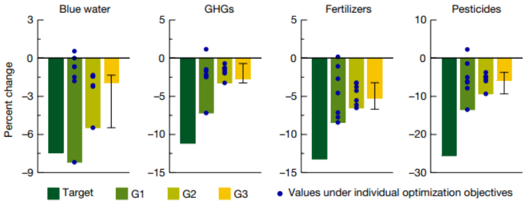


Fig. 4 | Comparison of crop-switching benefits with China's 2030 official agricultural sustainability targets. The dark-green bars ('Target') show the difference between the baseline projection and China's official agricultural sustainability targets in 2030. Under the baseline, the projection of blue water is based on existing literature[23]. As the projections of other sustainable dimensions for China were unavailable in the literature, we multiplied projected crop production in 2030 (ref. [36]) and current resource-use intensities (see 'Current state of sustainability outcomes' in Methods) 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 (see Extended Data Fig. 1).

Conclusion

Conclusion

This study provides detailed, actionable scientific evidence for the Chinese government's efforts to promote crop switching, meeting the information needs of recent government planning. Under the G3 centralized coordination scenario, crop switching could contribute substantially (23–40% across dimensions) towards China's 2030 agricultural sustainable development targets.

Outline

Framework

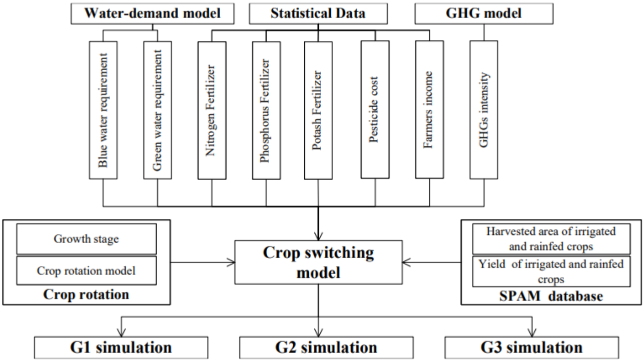


Figure S2 | The overall framework of our method

Method

- **Linear Programming**
- **Objective Function**:
  - Maximize income
  - Minimize SDG (Sustainable Development Goals) usage
- **Constraints**:
  - Yield constraints
  - Income constraints
  - Sustainability indicator constraints
- **Variables**:
  - IVS: Planting ratio of 9 crops in China
  - DVS: 8 Sustainable Development Indicators

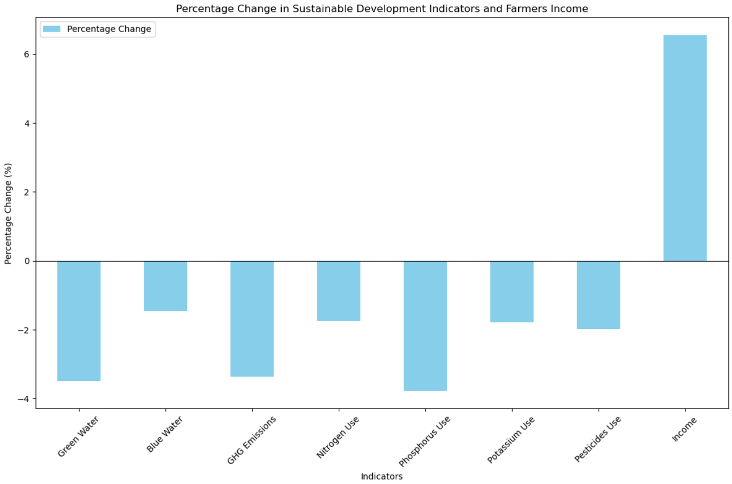
G1 Scenario: maximize income

- **Objective**: Maximize farmer income
- **Constraints**:
  - Crop yield constraint (National level)
  - Farmer income constraint (Grid level)
- **Outcome**: Maximizing farmer income alone (without considering other sustainability indicators) can lead to a **69.93%** increase in income.

G2 Scenario: maximize income with more constraints

- **Objective**: Maximize farmer income
- **Constraints**:
  - Crop yield constraint (National level)
  - Farmer income constraint (Grid level)
  - Other 7 sustainability indicators cannot decrease (National level)
  - Other 7 sustainability indicators cannot decrease (Grid level)
- **Outcome**: Maximizing farmer income alone with more constraints can lead to a **6.55%** increase in income.

Crop switching results in G2 scenario



G3 Scenario: Centralized Coordination

Improvement Value for Each Dimension (G_{Dim})

$$G_{\mathrm{Dim}} = \left(1 - \frac{\sum_{\{\mathrm{irr},\mathrm{ra}\},i,j,z} \mathrm{CA}_{\mathrm{irr/ra},i} \cdot x_{\mathrm{irr/ra},i,j} \cdot R_{j,z} \cdot \mathrm{UI}_{\mathrm{Dim},i,z}}{\sum_{\{\mathrm{irr},\mathrm{ra}\},i} \mathrm{CURRENT}_{\mathrm{Dim},\mathrm{irr/ra},i}}\right) \times 100\%$$

Objective Function

$$\text{Maximize} \quad \mathrm{Aver}(G_{Dim})/\mathrm{Var}(G_{Dim})$$

G3 Scenario: Centralized Coordination

Method: Weighted Sum Method

- Assign weights of 0 or 1 to each of the seven indicators, resulting in $2^7 = 128$ Pareto optimal solutions.
- Weights represent whether the indicator is least or most important.

Single Objective Optimization

$$\text{Maximize } \lambda \sum_{i=1}^{n} G_{\mathrm{Dim},i} - (1-\lambda) \cdot \mathrm{Var}\left(G_{\mathrm{Dim}}\right)$$

Constraints

- Same as G2 scenario.

G3 Scenario: Example

Example Weight Vector: $[1, 0, 0, 0, 0, 0, 0]$

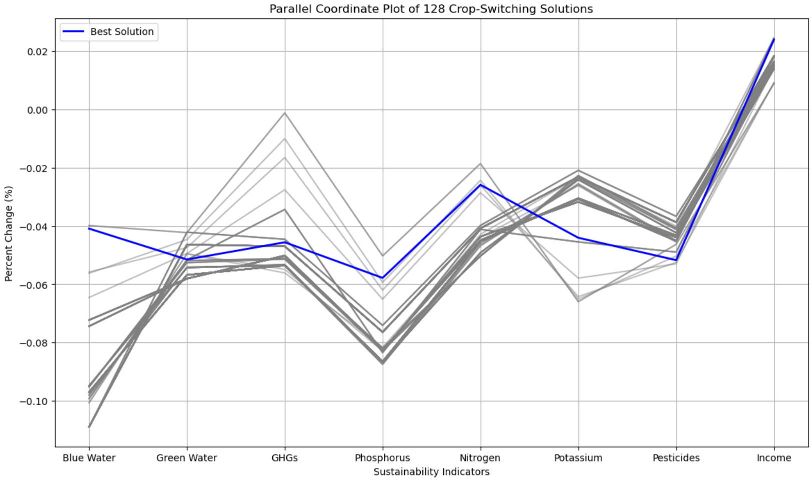
- This vector represents optimizing only blue-water usage.
- Same constraints as in the G2 scenario.

Example Weight Vector: $[1, 1, 1, 1, 1, 1, 1]$

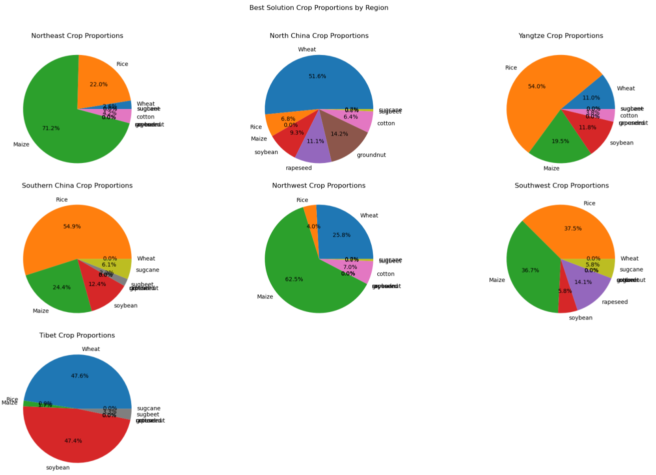
- Optimizing all sustainability indicators simultaneously.
- Balances the improvement across all indicators to achieve comprehensive sustainability.

Provides flexibility for planners and decision-makers to place greater weight on specific sustainability outcomes

G3 Scenario: Result



Optimal grain distribution



Conclusion

- **Regional Crop Adjustments:**
  - **Northeast:** Decrease soybean; increase maize and cotton.
  - **North China Plain:** Decrease maize; increase rapeseed, and rice.
  - **Yangtze River Plain:** Decrease rapeseed and rice; increase wheat, soybean and maize.
  - **Southern China:** Increase soybean; decrease rice.
  - **Northwest:** Decrease wheat; increase maize.
  - **Southwest:** Decrease wheat; increase maize and rice.
  - **Tibet:** Increase soybean; decrease rice.
- **Sustainability Impact:**
  - blue water (-4% to -11%), green water (-4% to -6%), greenhouse gases (GHGs) (-0.1% to -5.6%), fertilizers (-5.0% to -8.7%), pesticides (-3.6% to -5.3%) and increased farmer incomes ($+0.9\%$ to $+2.5\%$)

Outline

1 Summary of the paper

2 Method

3 Future work

Future Work

- **Data:** Update from 2010 data to recent data for calculations.
- **Model:** Re-evaluate the 1998 standards from Allen et al. for calculating green and blue water.
- **Granular Analysis:** Shift from macro-level grain adjustments to finer regional details, considering conversion costs, etc.
- **Yield Predictions:** Use machine learning to predict crop yields and better address sustainability goals.