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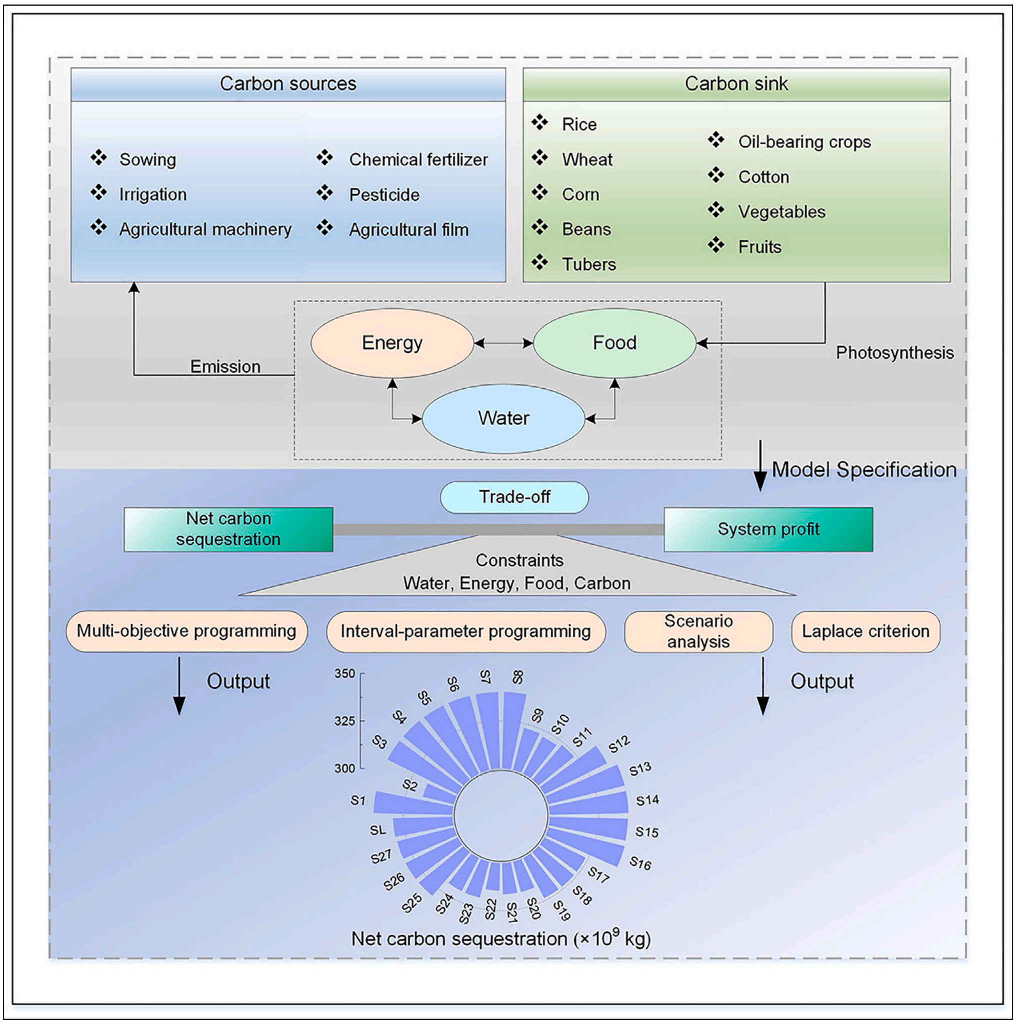

Qiting Zuo,
Qianwen Li, Lan
Yang, Rui Jing,
Junxia Ma, Lei Yu

yulei2018@zzu.edu.cn

## Highlights

Carbon sequestration is introduced to traditional water-energy-food nexus

An integrated multi-objective optimization approach under uncertainty is developed

Complexities of multi-objective and scenarios with unknown probabilities are tackled

Results can provide insights for the adjustment of crop planting structure

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# Incorporating carbon sequestration toward a water-energy-food-carbon planning with uncertainties

Qiting Zuo,[1,2] Qianwen Li,[1] Lan Yang,[3] Rui Jing,[4] Junxia Ma,[1] and Lei Yu[1,2,5,*]

## SUMMARY

**Water-energy-food nexus (WEFN) is the core content in the United Nations 2030 Agenda for Sustainable Development. However, the value of soil and crops' carbon sink function has not yet been fully considered in the managment practices of WEFN system. Here, we developed a water-energy-food-carbon nexus (WEFCN) planning framework that incorporates carbon sequestration and multiple mathematical optimization methods into the practical WEFN management for Henan Province, which is one of major grain-producing areas in China. Uncertainties from multiple objectives, scenarios, and different stakeholder interests are captured. We found that wheat has the largest carbon sequestration, followed by corn and oil-bearing crops, while other crops have implicit carbon sequestration. Since chemical fertilizer produces the most carbon emissions, the usage of chemical fertilizer needs to be reasonably controlled. Overall, the proposed framework supports optimal decision-making for regional-scale WEFCN management and further unlocks the hidden value of agricultural carbon mitigation.**

## INTRODUCTION

### Research background

Increasing greenhouse gas (GHG) emitted from human activities has exacerbated the global warming effect, becoming a major cause of climate change since the mid-20th century.[1] As one of the momentous components of global GHG emission, agricultural production activities directly contribute about 10%–12% to the global anthropogenic GHG emission[2] while the ratio has reached 17% in China.[3] In the meantime, as typical activities that directly consume water resources and energy to produce food for human survival, agricultural production practices are closely linked to multiple sectors, which form the water-energy-food nexus (WEFN).[4] WEFN is the core content in the United Nations 2030 Agenda for Sustainable Development.[5] It has received extensive attention since the 2011 Bonn Nexus Conference.[6] In WEFN, GHG is generated by agricultural production activities that lead to global warming; meanwhile, it can be absorbed by crops through photosynthesis to help mitigate climate change. To arrange reasonable agricultural production patterns and give full play to the ecological function of the farmland system to respond to complex climate change,[7] it is critical to quantify carbon emissions from production activities as well as carbon sequestrations through soil and crops' photosynthesis in WEFN. Integrating water, energy, food, and carbon into one framework enables us to explore a sustainable agriculture management pathway to coordinate food production, resource conservation, economic development, and farmland ecosystem protection.

### Literature review

Some research works have explored the carbon emission and sequestration in agriculture system. For instance, Bai et al. in 2019[8] calculated the agricultural carbon emission and sequestration in 142 counties in Hebei Province, China, and analyzed their spatial-temporal distribution from 2000 to 2010. Gonzalez-Sanchez et al. in 2019[9] estimated the annual and perennial crops' carbon sequestration potential in various agroclimatic zones of Africa and discovered that conservation agriculture would be helpful for climate change mitigation. Tongwane et al. in 2020[10] investigated the carbon emission from crop residues and nitrogen fertilizer usage in South Africa from 1911 to 2018 and found that carbon emission from crop residues would increase with expanded yields. These research studies mainly focused on the assessment of agricultural carbon footprint, simplex analysis of carbon structure or carbon sink function, while few of them integrated the agricultural emission with other sectors into planning models for a comprehensive evaluation.

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[1] School of Water Conservancy and Transportation, Zhengzhou University, Zhengzhou 450001, China
[2] Yellow River Institute for Ecological Protection & Regional Coordination Development, Zhengzhou University, Zhengzhou 450001, China
[3] Fudan Tyndall Center and Shanghai Key Laboratory of Atmospheric Particle Pollution and Prevention (LAP3), Department of Environmental Science & Engineering, Fudan University, Shanghai 200438, China
[4] College of Energy, Xiamen University, Xiamen 361005, China
[5] Lead contact
*Correspondence: yulei2018@zzu.edu.cn

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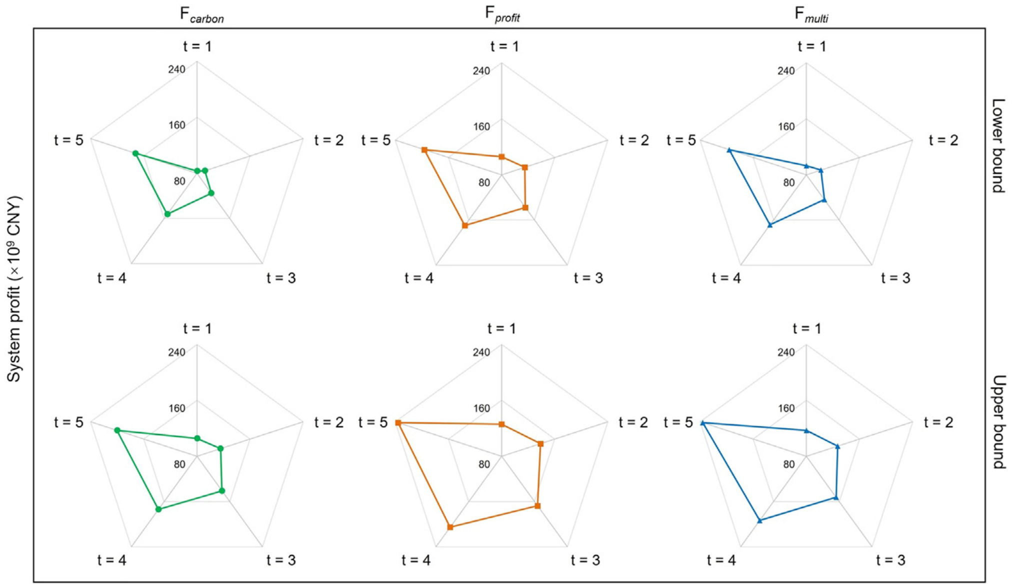

**Figure 1. System profit**

$F_{carbon}$, $F_{profit}$, and $F_{multi}$ represent the objectives of maximum carbon sink, maximum system profit, and multi-objective, respectively.

Recently, the WEFN research paradigm enables to explore the interlink among the agricultural emissions with water and energy sectors. Relevant research has been conducted from multiple perspectives previously, such as safety evaluation,[11] input-output analysis,[12] and system comprehensive optimization.[13] As an extension of typical WEFN, the water-energy-food-carbon nexus (WEFCN) further captures the carbon emission from agriculture and energy production. For example, Sušnik et al. in 2021[14] integrated carbon emission as a climate change factor into the system simulation of land, water, energy, and food and researched the policy implications on the nexus system in Latvia. Chamas et al. in 2021[15] developed an optimal resources allocation model for WEFN management with consideration of GHG emission from energy and agriculture sectors and generated optimized resources allocation under various technical and policy constraints. Ghiat et al. in 2021[16] proposed an integrated bioenergy with carbon capture and storage or utilization (BECCS/U) system to realize food production security and reduce $CO_2$ emission, in which the effectiveness of the proposed BECCS/U was evaluated under the concept of WEFN. Although these studies were of great significance for exploring the nexus of water, energy, food, and carbon, few of them assessed the hidden value for the soil and crops' carbon sink function. In specific, carbon sequestration was rarely considered in comprehensive optimization problem of WEFN.

As a powerful tool to explore the interlinks and uncertainties among various factors in a system and help make informed decisions, the integrated optimization model has been widely applied for nexus system research. For instance, Zhang and Vesselinov in 2016[17] developed an integrated model to solve the trade-offs and support decisions for comprehensive management of energy-water nexus (EWN). Yu et al. in 2020[18] developed an integrated optimizing model to manage the EWN system of Henan Province, China. These research studies mainly focused on single-objective optimization (e.g., maximization or minimization of generated electricity, water consumption, and the associated system cost), while the trade-off between multiple objectives, e.g., environmental effects and economic benefit in WEFCN, has not been explored. The method of multi-objective programming (MOP) could further be applied to WEFCN system management. Previously, Si et al. in 2019[19] used a multi-objective optimization approach to reveal the WEFN in the Upper Yellow River Basin, in which the trade-off among multi-benefits was solved. Li et al. in 2019a[20] proposed a stochastic multi-objective model to optimize WEFN in irrigated agriculture, in which complex uncertainties of random boundary intervals were addressed. Although these studies weighed the conflicts among different objectives and dealt with uncertainties such as inaccurate statistics and imprecise model parameters, challenges remain in handling possible alternative scenarios due to the volatilities of human demands and natural resources supply. Scenario analysis (SA) is an effective way to address these challenges, which can deal with uncertainties under various scenarios.[21] Since the probabilities of various alternative scenarios are unknown and difficult to be measured with concrete data, the Laplace criterion (LC) can tackle this problem by assuming that the probability of each scenario is equal.[22] Therefore, it is essential to develop a more robust optimization method to synthetically handle uncertainties and complexities in WEFCN.

## Motivation and contribution

As reviewed above, previous research works have widely explored the WEFN.[11–13] Although the direct carbon emission from agriculture sector has been considered,[14–16] the vital carbon sink function by soil and crops' carbon sequestration is usually overlooked. Moreover, multiple sources of uncertainties exist in the WEFCN system, such as inaccurate statistics of economy and society and various scenarios related to fluctuant natural resources and uncertain human demand with unknown probability. Previous methods could only handle part of these uncertainties,[20,22] and more comprehensive methods are needed for handling the uncertainties systematically.

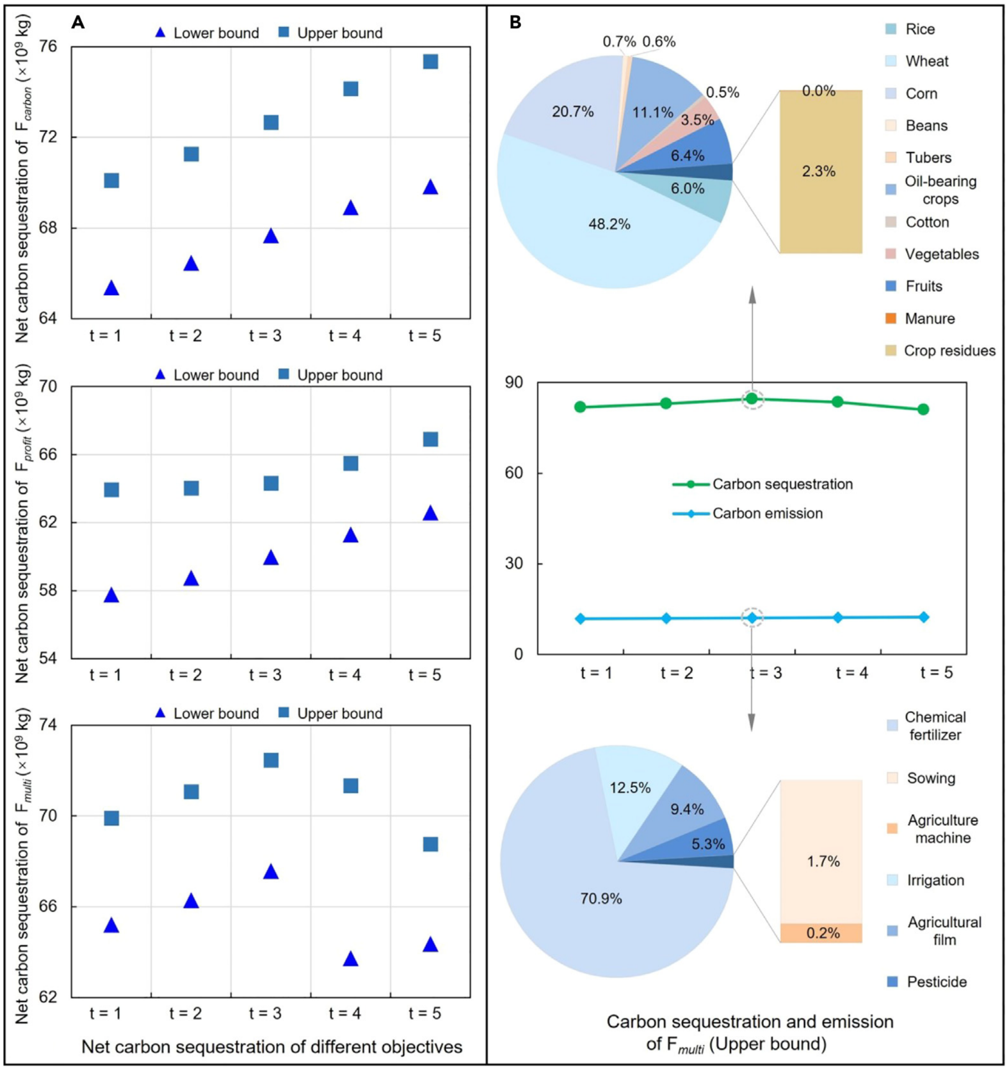

**Figure 2. Net carbon sequestration**

$F_{carbon}$, $F_{profit}$, and $F_{multi}$ represent the objectives of maximum carbon sink, maximum system profit, and multi-objective, respectively.

To address the above knowledge gap, we firstly incorporate the carbon sequestration of soil and crops into a typical WEFN planning model to establish the WEFCN model and investigate the impact of soil and crops' carbon sink function for carbon mitigation. Then, we further enable the WEFCN model to handle the complex uncertainties by reformulating the model through a multi-objective interval programming with scenario analysis under Laplace criterion (MOIP-SAL) method. The WEFCN is applied to a case study in Henan Province, China; valuable insights have been generated as discussed in the following sections.

The contribution of this study is as follows: (1) incorporating soil and crops' carbon sequestration into traditional WEFN toward the WEFCN; (2) addressing systemic uncertainties by MOIP-SAL and assessing the trade-off between carbon sink maximization and system economic benefit maximization by a non-linear multi-objective algorithm under consideration of decision makers' preference from both optimistic and pessimistic views; (3) providing decision-making supports for greener agricultural development pattern in response to carbon mitigation and transformation.

## RESULTS AND DISCUSSION

This section discusses the results obtained from the WEFCN optimization model for the Henan Province. The analysis was carried out from the following aspects: a) results comparison under multiple-objective ($F_{multi}$) and two single objectives ($F_{profit}$ and $F_{carbon}$) , including food production, water resources allocation, energy consumption; b) two different views of optimism and pessimism considered in the non-linear multi-objective solutions; and c) comparison among different scenarios.

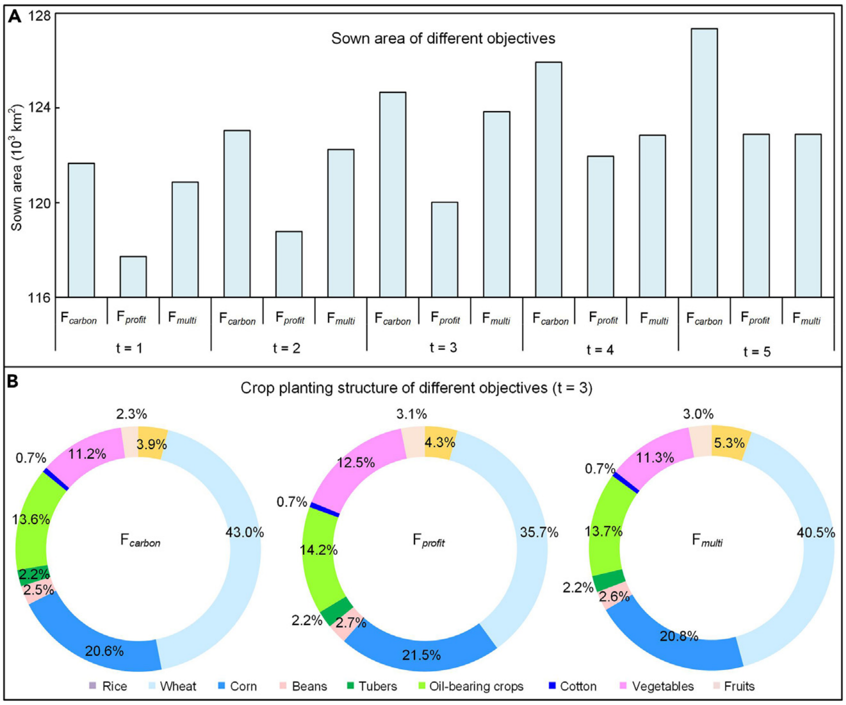

**Figure 3. Sown area and crop planting structure**

$F_{carbon}$, $F_{profit}$, and $F_{multi}$ represent the objectives of maximum carbon sink, maximum system profit, and multi-objective, respectively.

In this study, a WEFCN optimal planning model is established, and it is further reformulated by the MOIP-SALC method consisting of 27 scenarios for higher, moderate, and lower levels, respectively, for water resources availability, electricity availability, and food demand. Taking Henan Province as a case study, a series of insights are found as discussed below.

## Trade-off between profit and carbon sequestration

### Optimal solutions

Figures 1 and 2 compare the system profits and net carbon sequestrations under different objectives. In general, the results would be distinguishable at different objectives, and the optimal economic and ecological benefits would be obtained under $F_{profit}$ and $F_{carbon}$. For instance, the system profit over the entire planning period of multiple-objective ($F_{multi}$) would be [67.9, 89.6]$\times 10^9$ CNY higher than that of $F_{carbon}$, but [41.2, 47.5] $\times$ $10^9$ CNY lower than that of $F_{profit}$ (Figure 1). Diametrically, the total net carbon sequestration of $F_{multi}$ would be [10.0, 11.1]$\times 10^9$ kg lower than that of $F_{carbon}$, but [26.7, 28.8]$\times 10^9$ kg higher than that of $F_{profit}$ (Figure 2A). These implied that the high-level economic development usually comes at the cost of the ecological environment. On the contrary, it was inevitable to give up certain economic profits for the development of environment-friendly agriculture. It could also be demonstrated that a comprehensive consideration of the two individual objectives would help achieve the balance between economic development and agricultural ecosystem protection. Especially, in terms of different time periods, the system profit under $F_{multi}$ would increase by [103.3, 119.1]$\times 10^9$ CNY from t = 1 to t = 5. This disclosed optimization results would help realize the balance between the economic benefits of crop planting and agricultural ecosystem protection in the long run.

The net carbon sequestration was calculated by subtracting carbon emission from the soil and crops' carbon sequestration. As shown in Figure 2B, the crop photosynthesis accounted for the largest share of carbon sequestration (i.e., 97.7%), followed by crop residues in soil and carbon offsets by livestock manure into field. Besides, among the crop photosynthesis, wheat has the largest carbon sequestration followed by corn and oil-bearing crops, while other crops have implicit carbon sequestration. Among all carbon emissions from crop production activities, chemical fertilizer usage produced the most emissions, which is consistent with the findings by Cao et al. in 2018.[23] The reason lies in the fact that Henan Province is an agricultural province, and abundant food production would inevitably consume vast chemical fertilizer, resulting in the largest carbon emissions from chemical fertilizer. Corresponding measures for carbon emission reduction and cleaner agricultural production such as lessening chemical fertilizer usage should be considered in the future planning formulation of Henan Province. However, this might bring grain reduction and profits decline. Whether and to what extent these measures should be taken would be the key issues for further policy making.

### Food production

By the end of 2019, Henan Province has achieved a harvest in grain production, ranking first in China on the total summer grain output and unit area yield with a recorded high value. Figures 3 and 4 show the cultivated area and crop yield under different objectives. In general, different

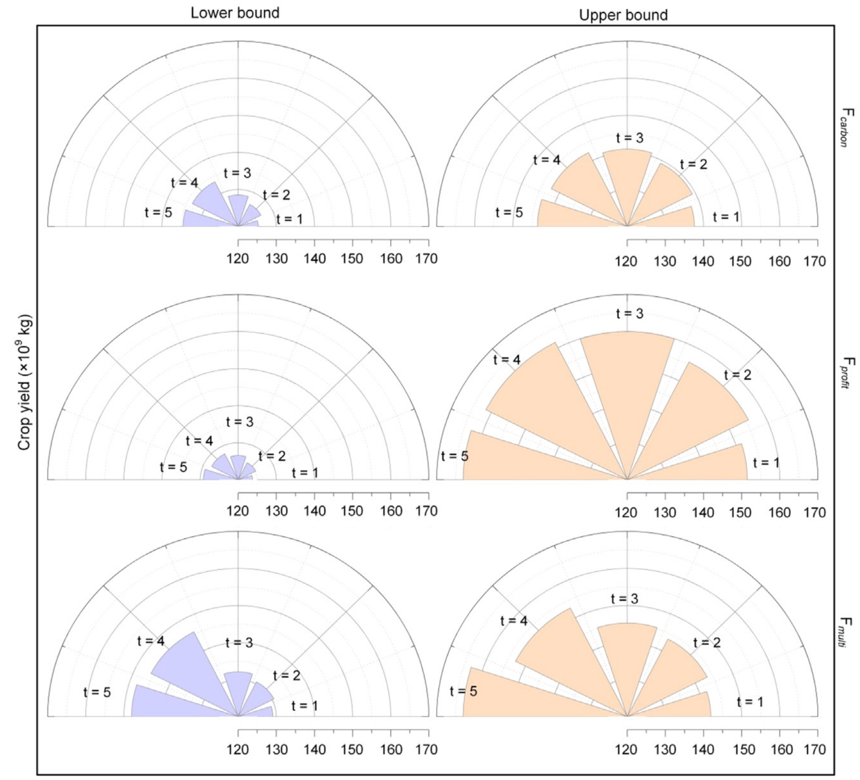

**Figure 4. Crop yield**

$F_{carbon}$, $F_{profit}$, and $F_{multi}$ represent the objectives of maximum carbon sink, maximum system profit, and multi-objective, respectively.

objective orientations would generate disparate plantation structures and crop yield. Specifically, the average sown area under $F_{carbon}$, $F_{profit}$, and $F_{multi}$ would be 124.7 × $10^3$ km,$^2$ 120.0 × $10^3$ km,$^2$ and 123.8 × $10^3$ km$^2$, respectively, at t = 3 (Figure 3A). This was because that, under $F_{carbon}$, cultivated area would be expanded to increase crops' carbon sequestration, as found in Cao et al. in 2018.[23] The main reason for the increase of agricultural carbon sink in Henan Province is the growth of planting area and agricultural production capacity. Under $F_{profit}$, the seeded area would be properly controlled for the consideration of various input costs. In comparison, the results of $F_{multi}$ would be more eclectic and reasonable compared with those of single-objective cases. Specifically, more vegetables and fruits would be planted under $F_{profit}$ due to the higher economic coefficients, while more wheat with a higher carbon sequestration rate would be arranged under $F_{carbon}$ (Figure 3B). For instance, the proportion of wheat planting area at t = 3 in the upper bound under $F_{carbon}$ was 2.5% higher than that of $F_{multi}$, while that of vegetables and fruits was 0.9% lower. As for every crop, wheat had a distinct advantage in planting structure and cotton took the least share. These results could help decision makers formulate planting plans reasonably according to various goal orientations and develop conservation tillage plans to increase crops' carbon sequestration and reduce adverse impacts on the environment.

## *Water resources consumption*

Water resources are vital for food production, especially for such a large agricultural province as Henan Province. In 2018, the agricultural water consumption in Henan Province was 12 × $10^9$ m$^3$, accounting for up to 51% of the total water consumption. As shown in Figure 5A, the total water resources consumption under $F_{multi}$ would be [9.1, 9.5]×$10^9$ m$^3$, which is lower than that under single-objective cases. This could be caused by the fact that, when considering economic benefit and net carbon sequestration simultaneously, more crops with both higher carbon sequestration rate (i.e., wheat) and higher economic coefficients (i.e., vegetables and fruits) would be planted, and these crops would lead to higher water consumption. This also implied that the total water resources consumption under $F_{multi}$ would be not much different from that under $F_{carbon}$ compared with $F_{profit}$. More water consumption is needed for Henan Province to maintain a balanced agricultural ecosystem to some extent. Among each crop, wheat would consume the most water resources, while cotton (Figure 5B) would consume the least. The results could provide decision-making support to manage agricultural water resources rationally by adjusting crop portfolio.

## *Energy consumption*

In addition to water resources, energy is another significant resource in a WEFCN model. Direct (i.e., electricity) and indirect energy (i.e., chemical fertilizer, pesticide, and agricultural film) were considered in the WEFCN model. Figure 6 shows the results of chemical fertilizer

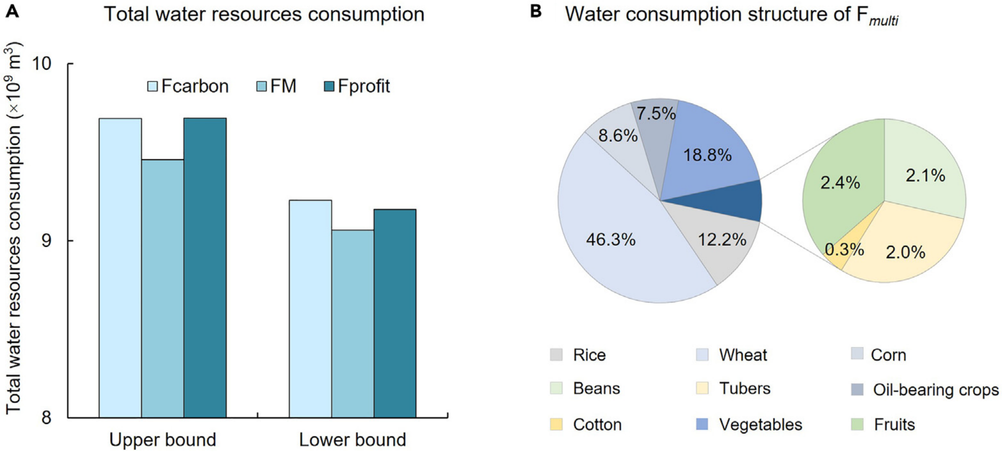

**Figure 5. Average water resources consumption over the planning period**

$F_{carbon}$, $F_{profit}$, and $F_{multi}$ represent the objectives of maximum carbon sink, maximum system profit, and multi-objective, respectively.

and pesticide consumption of $F_{multi}$. Among all the cultivated crops in Henan Province, wheat would be the largest user for pesticide and chemical fertilizer consumption, while cotton would consume the least chemical fertilizer and tubers would consume the least pesticide (Figures 6A and 6B). In addition, the pesticide consumption in the upper bound would decrease by 11.4 × $10^6$ kg during the planning period (Figure 6B) due to government controls of pesticide usage. Hence, the identified optimal solution in this study would deliver a positive feedback for environmental protection.

## Optimistic versus pessimistic

According to the non-linear multi-objective optimal solution, two different views of optimism and pessimism were evaluated. Figure 7 shows the comparison results between optimistic and pessimistic views. In specific, Figure 7A shows the satisfaction degree of optimistic and

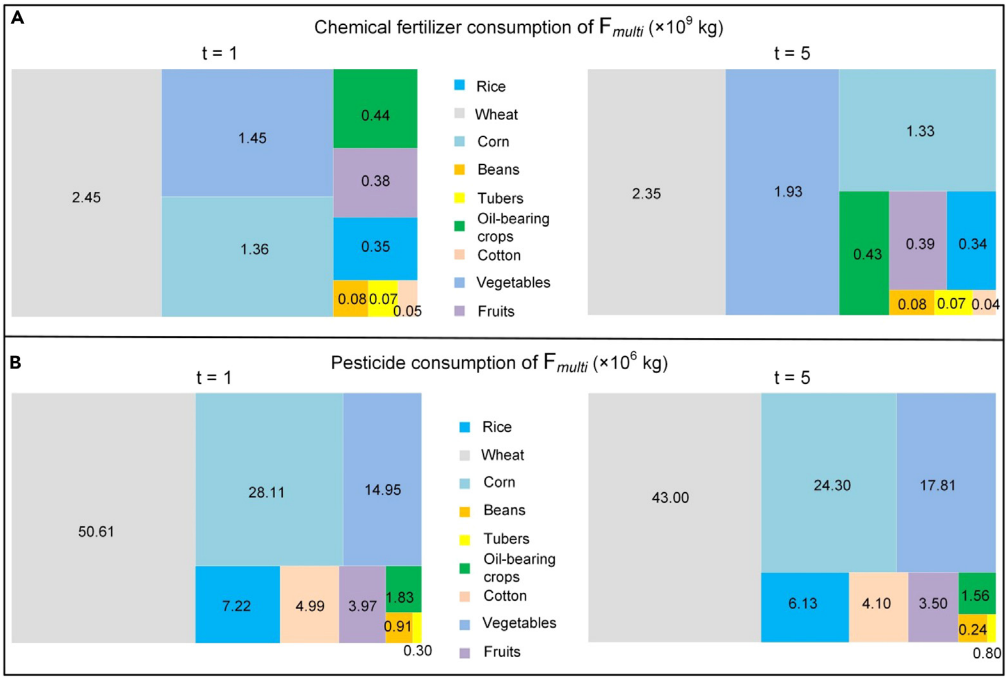

**Figure 6. Chemical fertilizer consumption and pesticide consumption of $F_{multi}$**

$F_{multi}$ represents the multi-objective.

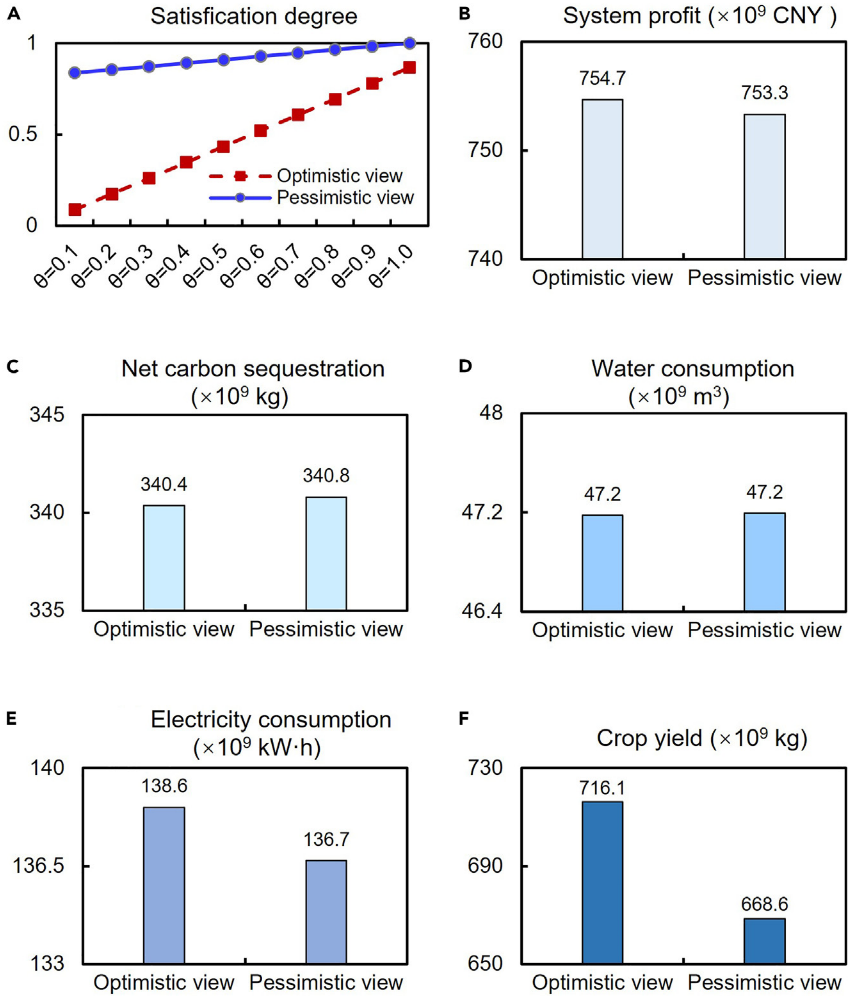

**Figure 7. Comparison of the results between optimistic and pessimistic views**

pessimistic view. Compared with the optimistic view, the satisfaction degree of the pessimistic view would be higher. This is because both the two objectives were to be maximized, and thus the satisfaction degree would increase if each objective reached the corresponding upper bound. The decision makers holding the optimistic view would tend neither to accept the values below the minimum value of each objective

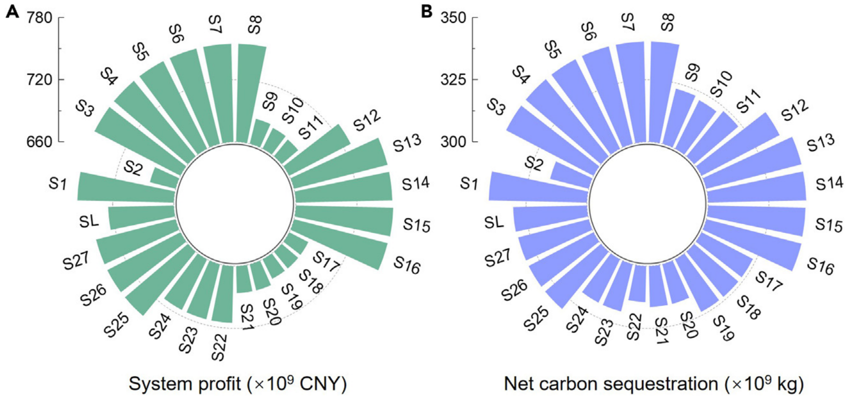

**Figure 8. Results of different scenarios**

S1–S27 represent the designed scenarios, and SL is the scenario under the Laplacian criterion.

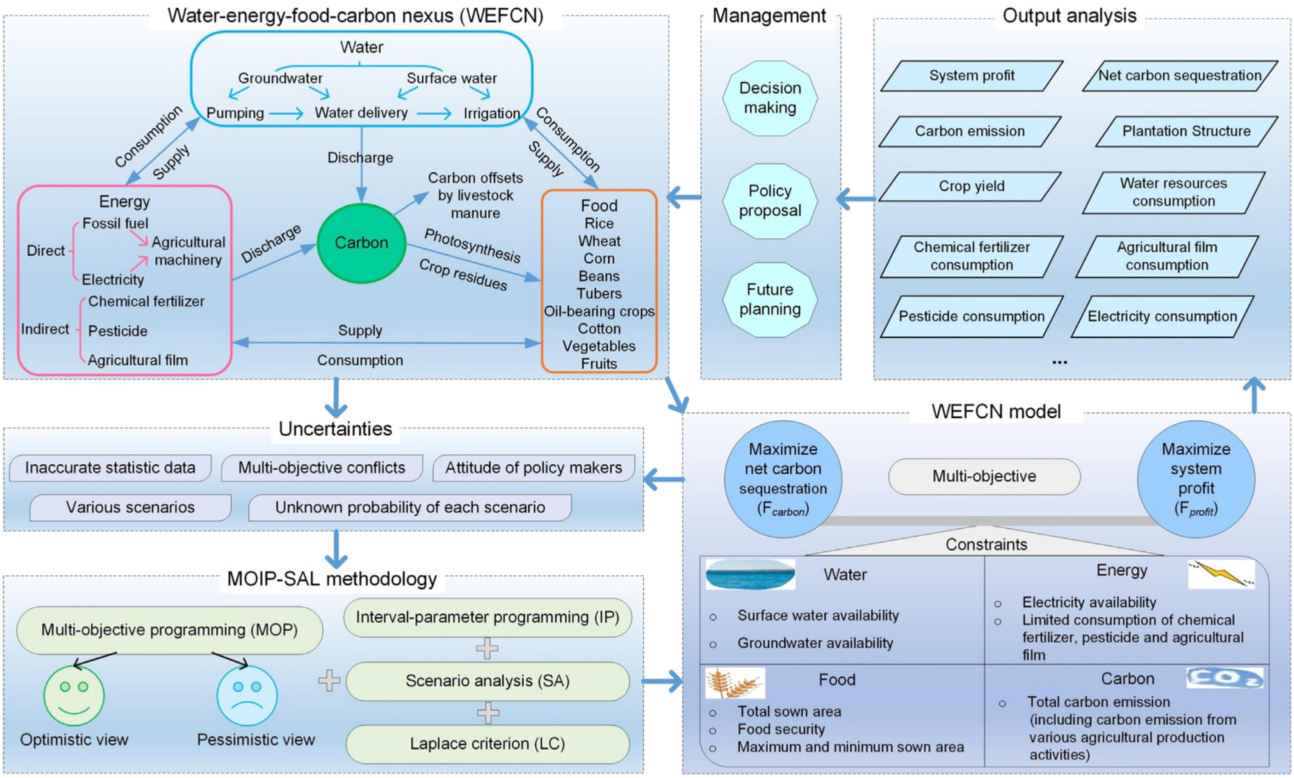

**Figure 9. The framework of WEFCN model**

nor to reject them absolutely within a certain range. In contrast, the decision makers holding the pessimistic view would neither reject the values exceeding the minimum value plus tolerance nor accept them absolutely. Objectives would have more advantages to reach their upper bounds under the pessimistic view. It is also indicated that as the value of $\theta$ increased from 0.1 to 1 gradually, the satisfaction degree increased accordingly, which would be consistent with previous study from Li et al. in 2019b.[24] In addition, for the realization of two objectives and the allocation of different resources, optimistic and pessimistic views would produce distinguishable results (Figures 7B, 7C, 7D, 7E, and 7F). For instance, the system profit of the optimistic view was $1.4 \times 10^9$ CNY higher than that of the pessimistic view, while the net carbon sequestration was $0.4 \times 10^9$ kg lower than that of the pessimistic view (Figures 7B and 7C). Moreover, the optimistic view would result in lower water resources consumption and higher crop yield although it had higher electricity consumption (Figures 7D–7F). Results indicated that choosing the optimistic view would help achieve more system profit, while the pessimistic view would lead to more net carbon sequestration. Results could provide a reference for decision makers to choose a reasonable view and appropriate value of $\theta$ to reach the balance among economic benefit and net carbon sink.

## Performance comparison for 27 scenarios and Laplace criterion

Figure 8 shows the optimal results of the basic scenario (i.e., S1), other 26 scenarios (i.e., S2–S27), and the scenario with Laplace criterion (i.e., SL). Generally, scenarios with a lower level of water resources availability (i.e., S2, S9–S11 and S17–S21) would generate lower system profit and

**Table 1. Carbon emission coefficient**

| Carbon emission source | Coefficient | Unit |
|---|---|---|
| Sowing | 1647.00 | $kg/km^2$ |
| Irrigation | 266.48 | kg/ha |
| Agricultural machinery | 0.18 | kg/kW |
| Chemical fertilizer | 0.86 | kg/kg |
| Pesticide | 4.70 | kg/kg |
| Agricultural film | 5.18 | kg/kg |

**Table 2. Carbon sequestration rate and economic coefficient of crops**

| Crops | Carbon sequestration rate | Economic coefficient |
|---|---|---|
| Rice | 0.41 | 0.45 |
| Wheat | 0.48 | 0.40 |
| Corn | 0.47 | 0.40 |
| Beans | 0.45 | 0.34 |
| Tubers | 0.42 | 0.70 |
| Oil-bearing crops | 0.45 | 0.32 |
| Cotton | 0.45 | 0.10 |
| Vegetables | 0.45 | 9.50 |
| Fruits | 0.45 | 1.75 |

net carbon sequestration. In contrast, higher system profit and net carbon sequestration would be achieved with adequate water resources availability (i.e., S3–S5, S12–S14, and S25–S27). Therefore, it could be preliminarily inferred that compared with energy and food, water resources would be the most critical factor. This finding is consistent with previous research studies of Stockholm Environmental Institute and Asian Development Bank, and they thought that water resources were the key element of WEFN.[25] Note that different viewpoints exist in terms of the central factors in WEFN. For example, food was considered to be the most critical by Food and Agriculture Organization (FAO) of the United Nations, and energy was prioritized by the International Energy Agency (IEA). When water resources availability and food demand were fixed, diverse electricity availabilities would generate significantly different results (i.e., S7 and S23). It could be speculated that energy was another key constraint. If electricity availability and water resources availability were stable, the change of results caused by different food demands was not obvious (i.e., S15 and S16). Relatively speaking, food would not be a critical constraint in the WEFCN model. Since the Laplacian criterion comprehensively considered the occurrence possibility of various scenarios, the results of SL would be more appropriate, avoiding too high or too low results with a small probability.

## Conclusions

Food production activities in WEFN are one of dominating sources of GHG emission, while the carbon sink function of soil and crops contributes to the mitigation of climate change. However, the agricultural carbon sink was rarely considered in the WEFN so far; the carbon

**Table 3. Carbon emission of Henan Province**

| Year | Total carbon emission (Mt $CO_2$) | Agricultural carbon emission (Mt $CO_2$) | Percentage of agricultural carbon emission (%) |
|---|---|---|---|
| 1997 | 154.3 | 10.2 | 6.6 |
| 1998 | 155.8 | 9.0 | 5.8 |
| 1999 | 157.2 | 9.6 | 6.1 |
| 2000 | 162.1 | 9.2 | 5.7 |
| 2001 | 181.3 | 9.3 | 5.1 |
| 2002 | 194.3 | 8.8 | 4.5 |
| 2003 | 215.7 | 8.6 | 4.0 |
| 2004 | 277.6 | 7.6 | 2.7 |
| 2005 | 336.2 | 10.2 | 3.0 |
| 2006 | 379.0 | 10.2 | 2.7 |
| 2007 | 426.2 | 9.6 | 2.3 |
| 2008 | 435.6 | 10.9 | 2.5 |
| 2009 | 450.7 | 10.8 | 2.4 |
| 2010 | 504.7 | 9.8 | 1.9 |
| 2011 | 548.5 | 12.2 | 2.2 |
| 2012 | 520.7 | 14.7 | 2.8 |
| 2013 | 483.9 | 9.2 | 1.9 |
| 2014 | 535.4 | 9.7 | 1.8 |
| 2015 | 517.8 | 10.1 | 2.0 |

**Table 4. Nomenclatures for parameters and variables**

| | |
|---|---|
| $\pm$ | The interval values with lower and upper bounds |
| $t$ | Planning periods, t = 1–5 is the year of 2021–2025 |
| $v$ | Variety of crops, v = 1–9 is rice, wheat, corn, beans, tubers, oil-bearing crops, cotton, vegetables, and fruits |
| $\delta$ | Effective utilization proportion of irrigation water |
| $\alpha$ | Effective utilization coefficient of chemical fertilizer |
| $\vartheta$ | Effective utilization coefficient of spraying pesticide |
| $\varphi$ | Effective utilization coefficient of agricultural machinery |
| $\theta$ | Limited proportion of water resources for agriculture |
| $A$ | Coefficient of carbon emission from chemical fertilizer usage (kg/kg) |
| $A_{m,t}$ | Fresh base weight of livestock manure applied to crops in period t (kg) |
| $AWQ_{t,v}^{\pm}$ | Agricultural water requirement quota to crop v in period t ($m^3/km^2$) |
| $ASCS_{residue}$ | Soil carbon sequestration of crop residues in soil per unit area (kg C/ha) |
| $B$ | Coefficient of carbon emission from sowing ($kg/km^2$) |
| $C$ | Coefficient of carbon emission from agricultural machinery (kg/kW) |
| $CS_{crop,t}^{\pm}$ | Carbon sequestration of crop photosynthesis (kg) |
| $CS_{manure,t}$ | Carbon sequestration of carbon offsets by livestock manure into field (kg) |
| $CS_{residue,t}^{\pm}$ | Carbon sequestration of crop residues in soil (kg) |
| $CSR_v$ | Carbon sequestration rate of crop v |
| $CCFA_{t,v}^{\pm}$ | Unit consumption of chemical fertilizers to crop v in period t ($kg/km^2$) |
| $CCPA_{t,v}^{\pm}$ | Unit consumption of pesticide to crop v in period t ($kg/km^2$) |
| $CE_t^{\pm}$ | Carbon emission in year t (kg) |
| $CEC_t^{\pm}$ | Shadow price of unit carbon emission in year t (CNY/kg) |
| $CEM_t^{\pm}$ | Limited carbon emission of agriculture system in year t (kg) |
| $CEU_t^{\pm}$ | Unit price of electricity in year t (CNY/kWh) |
| $CFP_t^{\pm}$ | Unit price of chemical fertilizer in period t (CNY/kg) |
| $CGU_t^{\pm}$ | Unit price of groundwater in period t ($CNY/m^3$) |
| $CGWS_t$ | Supply ratio of groundwater for agriculture in period t |
| $CPP_t^{\pm}$ | Unit price of pesticide in period t (CNY/kg) |
| $CS_t^{\pm}$ | Total carbon sequestration by various crops in period t (kg) |
| $CSU_t^{\pm}$ | Unit price of surface water in period t ($CNY/m^3$) |
| $CSWS_t$ | Supply ratio of surface water for agriculture in period t |
| $D$ | Coefficient of carbon emission from irrigation (kg/ha) |
| $E$ | Coefficient of carbon emission from agricultural film usage (kg/kg) |
| $F$ | Coefficient of carbon emission from pesticide usage (kg/kg) |
| $F_{carbon}{}^{\pm}$ | The objective of net carbon sequestration (kg) |
| $F_{profit}{}^{\pm}$ | The objective of system benefits (CNY) |
| $FD_{t,v}^{\pm}$ | Food demand of crop v in period t (kg) |
| $GWA_t^{\pm}$ | Available amount of groundwater in year t ($m^3$) |
| $H_v$ | Economic coefficient of crop v |
| $OMFP_{t,v}^{\pm}$ | Output of crop v in period t ($kg/km^2$) |
| $OMP_{t,v}^{\pm}$ | Unit production price of crop v in period t (CNY/kg) |
| $OC_{content-manure,t}$ | Organic carbon content of livestock manure (g/kg) |
| $PAME_t^{\pm}$ | Total available electricity for agricultural machinery in year t (kWh) |
| $PAJ_{t,v}^{\pm}$ | Purchased amount of crop v in period t (kg) |
| $PFAP_t^{\pm}$ | Unit price of agricultural films in period t ($CNY/km^2$) |
| $R_v$ | Grain-straw ratio (%) |
| $RS$ | Crop residues return per unit area (kg/ha) |

(*Continued on next page*)

**Table 4. *Continued***

| | |
|---|---|
| $SAF_{t,v}^{\pm}$ | Sown areas of crop v in period t (km$^2$) |
| $SAF_{t,v}^{min\pm}$ | The minimum sown areas of crop v in period t (km$^2$) |
| $SAF_{t,v}^{max\pm}$ | The maximum sown areas of crop v in period t (km$^2$) |
| $SEDP_{t,v}^{\pm}$ | Unit price of seeds to crop v in period t (CNY/km$^2$) |
| $SWA_{t}^{\pm}$ | Available amount of surface water in period t (m$^3$) |
| $TAF_{t}^{\pm}$ | Total consumption of agricultural film in period t (kg) |
| $TEF_{t}^{\pm}$ | Total limited consumption of chemical fertilizer in period t (kg) |
| $TEC_{t}^{\pm}$ | Total limited consumption of pesticide in period t (kg) |
| $TEAF_{t}^{\pm}$ | Total limited consumption of agricultural film in period t (kg) |
| $TEIA_{t}^{\pm}$ | Total irrigated area in period t (ha) |
| $TPAM_{t}^{\pm}$ | Total power of agricultural machinery in period t (kW) |
| $TSAF_{t}^{\pm}$ | Total available sown area in period t (km$^2$) |
| $U_v$ | Direct crop residues return rate (%) |
| $UAM_{t}^{\pm}$ | Unit electricity consumption of agricultural machinery in period t (kWh/km$^2$) |
| $W_o$ | Water content of livestock manure (%) |

sequestration potential in WEFN system is not yet clear. In this research, a WEFCN optimization framework has been developed to unlock the value of carbon sequestration and capture the interlinks between water, energy, food, and carbon emission. In order to handle the comprehensive uncertainties in the WEFCN system, an MOIP-SAL method has been developed to reflect uncertainties as interval numbers and generate scenarios with unknown probabilities considering the trade-offs among multiple conflicting objectives. An illustrative case study in Henan Province, China, has been performed leading to the following results.

(1) More vegetables and fruits would be planted if only aimed at economic benefit, while more wheat with a higher carbon sequestration rate would be arranged with the net carbon sequestration as the objective.
(2) Chemical fertilizer use would be the largest carbon emission source in Henan Province, and control of total fertilizer application should be emphasized in the future planning formulation.
(3) The developed optimization-based framework can provide practical support for the study area in cleaner and developing environmental-friendly agricultural practices with complexities and uncertainties, and the framework is applicable to similar regions at parallel scale.

## The way forward

This research offers valuable insights for planning of crop planting to achieve a balance between economic benefit and farmland ecosystem services in the long run. Based on the proposed optimization model, future research can further explore the more complex mechanism of carbon emission and sequestration in the real-world agroecosystem. In addition to carbon emission from human agricultural production activities, other natural emissions, such as $CH_4$ emission from paddy, soil respiration, and nitrification could also be considered in future research.[23] Meanwhile, scenarios related to different levels of water, energy, and food constraints on the WEFCN system were only presumed simply; more comprehensive approaches to effectively handle soft constraints under uncertainties, such as flexible programming,[26] could be adopted.

## Limitations of study

Within the proposed WEFCN system in the present study, the carbon emission in the process of food production, i.e., human agricultural production activities, is counted including the irrigation, sowing, investment of agricultural machinery, as well as the usage of chemical fertilizer, pesticide, and agricultural film. It is also noted that, in a balanced system where food production matches food consumption, carbon just cycles back and forth between the atmosphere and biomass. The boundary of the system would be vital. Thus, we considered relevant avenues, i.e., crop residues in soil and carbon offsets by livestock manure into field, for sequestration to address this flaw. Carbon sequestration mainly includes crop photosynthesis, crop residues in soil, and carbon offsets by livestock manure into field.[27,28]

## STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

- KEY RESOURCES TABLE
- RESOURCE AVAILABILITY

Table 5. Scenario design

| Scenario | Electricity availability | Water resources availability | Food demand |
|---|---|---|---|
| S1 | E | W | F |
| S2 | E-Low | W-Low | F-Low |
| S3 | E-High | W-High | F-High |
| S4 | E-High | W-High | F |
| S5 | E-High | W-High | F-Low |
| S6 | E-High | W | F-High |
| S7 | E-High | W | F |
| S8 | E-High | W | F-Low |
| S9 | E-High | W-Low | F-High |
| S10 | E-High | W-Low | F |
| S11 | E-High | W-Low | F-Low |
| S12 | E | W-High | F-High |
| S13 | E | W-High | F |
| S14 | E | W-High | F-Low |
| S15 | E | W | F-High |
| S16 | E | W | F-Low |
| S17 | E | W-Low | F-High |
| S18 | E | W-Low | F |
| S19 | E | W-Low | F-Low |
| S20 | E-Low | W-Low | F-High |
| S21 | E-Low | W-Low | F |
| S22 | E-Low | W | F-High |
| S23 | E-Low | W | F |
| S24 | E-Low | W | F-Low |
| S25 | E-Low | W-High | F-High |
| S26 | E-Low | W-High | F |
| S27 | E-Low | W-High | F-Low |

W-High, W, and W-Low represent higher, moderate, and lower levels of water resources availability, respectively. E-High, E, and E-Low represent higher, moderate, and lower levels of electricity availability, respectively. F-High, F, and F-Low represent higher, moderate, and lower levels of food demand, respectively.

  - ○ Lead contact
  - ○ Materials availability
  - ○ Data and code availability
- METHOD DETAILS
  - ○ Methodology
  - ○ Case study: Model application in Henan Province of China

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## AUTHOR CONTRIBUTIONS

Q.Z. and Q.L. designed the study. L.Y. and Q.L. built the integrated model and performed analyses. L.Y. and R.J. contributed to the model and performed the analysis. J.M. coordinated the project. All authors contributed to the manuscript.

## DECLARATION OF INTERESTS

The authors declare no competing interests.

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## STAR★METHODS

### KEY RESOURCES TABLE

| REAGENT or RESOURCE | SOURCE | IDENTIFIER |
|---|---|---|
| Deposited data | | |
| Economic and social data | Henan Statistical Yearbook: http://oss.henan.gov.cn/sbgt-wztipt/attachment/hntjj/hntj/lib/tjnj/2019/zk/indexch.htm | N/A |
| | The 13th Five-year Plan for various industries of Henan Province: http://www.henan.gov.cn/2017/05-24/270609.html,<br>http://fgw.henan.gov.cn/2017/03-01/721102.html | N/A |
| | Government reports: https://www.henan.gov.cn/2019/03-02/736255.html | N/A |
| Data of irrigation water for crops | Agricultural Basic Water Quota of Henan Province: http://www.jsgg.com.cn/Index/Display.asp?NewsID=23080 | N/A |
| Data related to carbon emission | Bai et al.[8] | N/A |
| Historical agricultural carbon emission | Shan et al.[34] | N/A |
| Parameters related to crop residues in soil and carbon offsets livestock manure into field | Xu et al.[35]; Wu et al.[36] | N/A |
| Software and algorithms | | |
| Lingo 11.0 | LINDO Systems: https://www.lindo.com/lindoforms/downlingo.html | N/A |

## RESOURCE AVAILABILITY

### Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Lei Yu (yulei2018@zzu.edu.cn).

### Materials availability

This study did not generate new unique materials.

### Data and code availability

The data used in this study are all available from public resources that have been appropriately cited within the manuscript. All custom code can be available on request from the lead contact. Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

In this study, some basic economic and social data such as crop yield, water resources consumption, as well as consumption of electricity, chemical fertilizer and pesticide were collected from Henan Statistical Yearbook,[29] the 13th Five-year Plan for various industries of Henan Province[30,31] and relevant government reports,[32] data of irrigation water for crops were collected from Agricultural Basic Water Quota of Henan Province.[33] Data related to carbon emission such as carbon emission coefficients of various carbon sources, carbon sequestration rate and economic coefficient of crops were extracted from the pertinent literature,[8] as shown in Tables 1 and 2. Historical agricultural carbon emission was obtained from Shan et al. in 2017,[34] as depicted in Table 3. Parameters related to crop residues in soil and carbon offsets livestock manure into field were extracted from Xu et al. in 2013[35] and Wu et al. in 2021.[36]

## METHOD DETAILS

### Methodology

*Overview of the framework*

This study establishes a WEFCN optimal planning model to unlock the interlinks among water, energy, food, carbon emission and carbon sequestration in agricultural systems. The WEFCN model can also assess the trade-off between carbon sink maximization and system economic benefit maximization subject to a set of constraints. By identifying the uncertainties in the authentic WEFCN system, the model is further reformulated by the MOIP-SALC optimization method to address multiple uncertainties. Finally, taking Henan Province, a major grain-producing area in China as a case study, a series of optimization results are generated including food production, energy, and water resources consumption, etc. These results offer valuable guidence for future grain production planning in Henan Province. The detailed method and framework are shown in Figure 9.

### Objectives of the WEFCN optimization model

There are two widely adopted objectives been considered in the WEFCN model, one pursues maximum system profit (i.e. $F_{profit}$) for economic development, while the other targets maximum net carbon sequestration (i.e. $F_{carbon}$) in the agricultural ecosystem with the driving force of developing green low-carbon agriculture. The main constraints include water resources and energy consumption, food production and carbon emission. And the decision variable is $SAF_{t,\ v}{}^{\pm}$, which is the sown area of crop $v$ in period $t$. Specific nomenclature for variables and parameters are described in Table 4.

The two objectives are expressed as follows: Firstly, for the objective of net carbon sequestration, it can be calculated by the carbon emission and carbon sequestration. In detail, carbon emission in the agriculture system mainly comes from human agricultural production activities such as irrigation, sowing, and investment of agricultural machinery, as well as the usage of chemical fertilizer, pesticide and agricultural film. Carbon sequestration mainly includes crop photosynthesis, crop residues in soil and carbon offsets by livestock manure into field.[27,28] The detailed calculation methods of these three parts mainly refer to Xu et al. in 2013[35] and Wu et al. in 2021.[36]

$$\text{Max } F_{carbon}{}^{\pm} = \sum_{t=1}^{5}\left(CS_t^{\pm} - CE_t^{\pm}\right) \tag{Equation 1a}$$

$$CS_t^{\pm} = CS_{crop,t}^{\pm} + CS_{residue,t}^{\pm} + CS_{manure,t} \tag{Equation 1b}$$

$$CS_{crop,t}^{\pm} = \sum_{v=1}^{9} CSR_v \times SAF_{t,v}^{\pm} \times OMFP_{t,v}^{\pm} \div H_v \tag{Equation 1c}$$

$$CS_{residue,t}^{\pm} = ASCS_{residue} \times \sum_{v=1}^{9}\left(SAF_{t,v}^{\pm} \times OMFP_{t,v}^{\pm} \times R_v \times U_v\right) \div RS \times \frac{44}{12} \tag{Equation 1d}$$

$$CS_{manure,t} = 10.0\% \times A_{m,t} \times (1 - W_o) \times OC_{content-manure,t} \times 10^{-6} \times \frac{44}{12} \tag{Equation 1e}$$

$$\begin{aligned} CE_t^{\pm} = {} & \sum_{v=1}^{9} CCFA_{t,v}^{\pm} \times SAF_{t,v}^{\pm} \times A_t + \sum_{v=1}^{9} SAF_{t,v}^{\pm} \times B_t + TPAM_t^{\pm} \times C_t \\ & + TEIA_t^{\pm} \times D_t + TAF_t^{\pm} \times E_t + \sum_{v=1}^{9} CCPA_{t,v}^{\pm} \times SAF_{t,v}^{\pm} \times F_t \end{aligned} \tag{Equation 1f}$$

Secondly, for the objective of system profit, the incomes come from food production, and the costs include water and energy use, seed purchase, and carbon emission control.

$$\text{Max } F_{profit}{}^{\pm} = (1) - [(2) + (3) + (4) + (5) + (6) + (7) + (8) + (9)] \tag{Equation 2a}$$

(1) *Incomes from food production*

$$\sum_{t=1}^{5}\sum_{v=1}^{9} SAF_{t,v}^{\pm} \times OMFP_{t,v}^{\pm} \times OMP_{t,v}^{\pm} \tag{Equation 2b}$$

(2) *Surface water cost*

$$\sum_{t=1}^{5}\left(\sum_{v=1}^{9} SAF_{t,v}^{\pm} \times AWQ_{t,v}^{\pm}\right) \times CSWS_t \times CSU_t^{\pm} \times \delta \tag{Equation 2c}$$

(3) *Groundwater cost*

$$\sum_{t=1}^{5}\left(\sum_{v=1}^{9} SAF_{t,v}^{\pm} \times AWQ_{t,v}^{\pm}\right) \times CGWS_t \times CGU_t^{\pm} \times \delta \tag{Equation 2d}$$

(4) *Chemical fertilizer cost*

$$\sum_{t=1}^{5}\sum_{v=1}^{9}\left(SAF_{t,v}^{\pm} \times CCFA_{t,v}^{\pm}\right) \times CFP_{t}^{\pm} \times \alpha \tag{Equation 2e}$$

(5) *Pesticide cost*

$$\sum_{t=1}^{5}\sum_{v=1}^{9}\left(SAF_{t,v}^{\pm} \times CCPA_{t,v}^{\pm}\right) \times CPP_{t}^{\pm} \times \vartheta \tag{Equation 2f}$$

(6) *Agricultural film cost*

$$\sum_{t=1}^{5}\left(\sum_{v=1}^{9} SAF_{t,v}^{\pm}\right) \times PFAP_{t}^{\pm} \tag{Equation 2g}$$

(7) *Electricity consumption cost from agricultural machinery*

$$\sum_{t=1}^{5}\left(\sum_{v=1}^{9} SAF_{t,v}^{\pm}\right) \times UAM_{t}^{\pm} \times CEU_{t}^{\pm} \times \varphi \tag{Equation 2h}$$

(8) *Seed purchase cost*

$$\sum_{t=1}^{5}\sum_{y=1}^{9} SAF_{t,v}^{\pm} \times SEDP_{t,v}^{\pm} \tag{Equation 2i}$$

(9) *Carbon emission control cost*

$$\sum_{t=1}^{5} CE_{t}^{\pm} \times CEC_{t}^{\pm} \tag{Equation 2j}$$

### *Constraints of a basic WEFCN optimization model*

Constraints can be mainly grouped into four aspects: water resources, energy, food, and carbon emission. The water resources related constraints are:

(1) *Constraint on surface and groundwater supply*

$$\sum_{v=1}^{9}\left(SAF_{t,v}^{\pm} \times AWQ_{t,v}^{\pm}\right) \times CSWS_{t} \times \delta \le SWA_{t}^{\pm} \tag{Equation 3a}$$

$$\sum_{v=1}^{9}\left(SAF_{t,v}^{\pm} \times AWQ_{t,v}^{\pm}\right) \times CGWS_{t} \times \delta \le GWA_{t}^{\pm} \tag{Equation 3b}$$

For energy, the related constraints are:

(2) *Constraint on electricity availability of agricultural machinery*

$$\sum_{v=1}^{9} SAF^{\pm}_{t,v} \times UAM^{\pm}_{t} \leq PAME^{\pm}_{t} \tag{Equation 4}$$

(3) *Constraint on indirect energy use, including chemical fertilizer, pesticide and agricultural film*

$$\sum_{v=1}^{9} \left( SAF^{\pm}_{t,v} \times CCFA^{\pm}_{,v} \right) \times \alpha \leq TEF^{\pm}_{t} \tag{Equation 5a}$$

$$\sum_{v=1}^{9} \left( SAF^{\pm}_{t,v} \times CCPA^{\pm}_{t,v} \right) \times \vartheta \leq TEC^{\pm}_{t} \tag{Equation 5b}$$

$$\sum_{v=1}^{9} \left( SAF^{\pm}_{t,v} \times CAF^{\pm}_{t,v} \right) \leq TEAF^{\pm}_{t} \tag{Equation 5c}$$

For food, the related constraints are:

(4) *Constraint on food assurance*

$$SAF^{\pm}_{t,v} \times OMFP^{\pm}_{t,v} + PAJ^{\pm}_{t,v} \geq FD^{\pm}_{t,v} \tag{Equation 6}$$

(5) *Constraint on the total sown area*

$$\sum_{v=1}^{9} SAF^{\pm}_{t,v} \leq TSAF^{\pm}_{t} \tag{Equation 7}$$

(6) *Land use constraint*

$$SAF^{\min}_{t,v} \leq SAF^{\pm}_{t,v} \leq SAF^{\max}_{t,v} \tag{Equation 8}$$

For carbon emission, the related constraints are:

(7) *Carbon emission constraint*

$$CE^{\pm}_{t} \leq CEM^{\pm}_{t} \tag{Equation 9a}$$

$$\begin{aligned} CE^{\pm}_{t} = {} & \sum_{v=1}^{9} CCFA^{\pm}_{t,v} \times SAF^{\pm}_{t,v} \times A_t + \sum_{v=1}^{9} SAF^{\pm}_{t,v} \times B_t + TPAM^{\pm}_{t} \times C_t \\ & + TEIA^{\pm}_{t} \times D_t + \sum_{v=1}^{9} CAF^{\pm}_{t,v} \times SAF^{\pm}_{t,v} \times E_t + \sum_{v=1}^{9} CCPA^{\pm}_{t,v} \times SAF^{\pm}_{t,v} \times F_t \end{aligned} \tag{Equation 9b}$$

(8) *Non-negative constraint*

$$SAF_{t,v}^{\pm} \geq 0 \tag{Equation 10}$$

### Reformulate WEFCN model by MOIP-SALC method

*Multi-objective program with interval parameters (MOIP).* Considering various uncertainties exist in a real-world WEFCN system, e.g., inaccurate statistical data, as well as decision makers might have different preference towards certain objectives, the multi-objective programming (MOP) method with interval parameters (IP) can be applied. Its general form can be described as follows:[37]

$$\text{Min } f_i^{\pm}(x), 1 \leq i \leq I' \tag{Equation 11a}$$

$$\text{Max } f_i^{\pm}(x), I' + 1 \leq i \leq I \tag{Equation 11b}$$

subject to:

$$g_j^{\pm}(x) \leq c_j^{\pm}, 1 \leq j \leq J' \tag{Equation 11c}$$

$$g_j^{\pm}(x) \geq c_j^{\pm}, J' + 1 \leq j \leq J'' \tag{Equation 11d}$$

$$g_j^{\pm}(x) = c_j^{\pm}, J'' + 1 \leq j \leq J \tag{Equation 11e}$$

$$x \geq 0 \tag{Equation 11f}$$

where, $x$ is the decision variable, $f_i^{\pm}(x)$ and $g_j^{\pm}(x)$ are the i-th objective and the j-th constraint with interval parameters.

Due to the fluctuant natural resources and uncertain human demand, various scenarios related to different levels of water, energy and food constraints that may occur with unknown occurrence probability were also considered. The above MOIP method can express dynamical and inaccurate statistical data as interval values and consider multiple objectives in realistic decision problems. Note that due to specific reality and related policy considerations, decision-makers may show specific preferences for certain objectives. The traditional multi-objective programming based on the linear membership functions may not be effective, thus, the non-linear membership functions for different objectives should be defined in this case. To address the decision-makers' preference issue more efficiently, a non-linear multi-objective algorithm from both optimistic and pessimistic views can be adopted. The membership and non-membership functions under optimistic and pessimistic views could refer to Rani et al. in 2016.[38] In this case, we further convert the non-linear multi-objective program with interval parameters (MOIP) into a single-objective programming problem as follows:

From the optimistic view,

$$\text{Max } \lambda^{\pm} \tag{Equation 12a}$$

subject to:

$$(1-\theta)\frac{\left(U_i^{\pm}\right)^{\varepsilon} - \left[f_i^{\pm}(x)\right]^{\varepsilon}}{\left(U_i^{\pm}\right)^{\varepsilon} - \left(L_i^{\pm}\right)^{\varepsilon}} - \theta\frac{\left[f_i^{\pm}(x)\right]^{\varepsilon} - \left(L_i^{\pm}\right)^{\varepsilon}}{\left(U_i^{\pm}+\alpha_i^{\pm}\right)^{\varepsilon} - \left(L_i^{\pm}\right)^{\varepsilon}} + \theta \geq \lambda^{\pm}, 1 \leq i \leq I' \tag{Equation 12b}$$

$$\theta - \theta\frac{\left[f_i^{\pm}(x)\right]^{\varepsilon} - \left(L_i^{\pm}\right)^{\varepsilon}}{\left(U_i^{\pm}+\alpha_i^{\pm}\right)^{\varepsilon} - \left(L_i^{\pm}\right)^{\varepsilon}} \geq \lambda^{\pm}, 1 \leq i \leq I' \tag{Equation 12c}$$

$$\theta\frac{\left(U_i^{\pm}\right)^{\varepsilon} - \left[f_i^{\pm}(x)\right]^{\varepsilon}}{\left(L_i^{\pm} - \alpha_i^{\pm}\right)^{\varepsilon} - \left(U_i^{\pm}\right)^{\varepsilon}} + \theta \geq \lambda^{\pm}, I' + 1 \leq i \leq I \tag{Equation 12d}$$

$$(1-\theta)\frac{\left[f_i^{\pm}(x)\right]^{\varepsilon} - \left(L_i^{\pm}\right)^{\varepsilon}}{\left(U_i^{\pm}\right)^{\varepsilon} - \left(L_i^{\pm}\right)^{\varepsilon}} - \theta\frac{\left(U_i^{\pm}\right)^{\varepsilon} - \left[f_i^{\pm}(x)\right]^{\varepsilon}}{\left(U_i^{\pm}\right)^{\varepsilon} - \left(L_i^{\pm} - \alpha_i^{\pm}\right)^{\varepsilon}} + \theta \geq \lambda^{\pm}, I' + 1 \leq i \leq I \tag{Equation 12e}$$

$$g_j^{\pm}(x) \leq c_j^{\pm}, 1 \leq j \leq J' \tag{Equation 12f}$$

$$g_j^{\pm}(x) \geq c_j^{\pm}, J' + 1 \leq j \leq J'' \tag{Equation 12g}$$

$$g_j^{\pm}(x) = c_j^{\pm}, J'' + 1 \leq j \leq J \tag{Equation 12h}$$

$$0 \leq \lambda^{\pm} \leq 1 \tag{Equation 12i}$$

$$x \geq 0 \tag{Equation 12j}$$

From the pessimistic view,

$$\text{Max } \lambda^{\pm} \tag{Equation 13a}$$

subject to:

$$(1-\theta)\frac{\left(U_i^{\pm}\right)^{\varepsilon} - \left[f_i^{\pm}(x)\right]^{\varepsilon}}{\left(U_i^{\pm}\right)^{\varepsilon} - \left(L_i^{\pm}\right)^{\varepsilon}} + \theta \geq \lambda^{\pm}, 1 \leq i \leq I' \tag{Equation 13b}$$

$$(1-\theta)\frac{\left(U_i^{\pm}\right)^{\varepsilon} - \left[f_i^{\pm}(x)\right]^{\varepsilon}}{\left(U_i^{\pm}\right)^{\varepsilon} - \left(L_i^{\pm}\right)^{\varepsilon}} - \theta\frac{\left[f_i^{\pm}(x)\right]^{\varepsilon} - \left(U_i^{\pm} - \alpha_i^{\pm}\right)^{\varepsilon}}{\left(U_i^{\pm}\right)^{\varepsilon} - \left(U_i^{\pm} - \alpha_i^{\pm}\right)^{\varepsilon}} + \theta \geq \lambda^{\pm}, 1 \leq i \leq I' \tag{Equation 13c}$$

$$(1-\theta)\frac{\left[f_i^{\pm}(x)\right]^{\varepsilon} - \left(L_i^{\pm}\right)^{\varepsilon}}{\left(U_i^{\pm}\right)^{\varepsilon} - \left(L_i^{\pm}\right)^{\varepsilon}} - \theta\frac{\left(L_i^{\pm}+\alpha_i^{\pm}\right)^{\varepsilon} - \left[f_i^{\pm}(x)\right]^{\varepsilon}}{\left(L_i^{\pm}+\alpha_i^{\pm}\right)^{\varepsilon} - \left(L_i^{\pm}\right)^{\varepsilon}} + \theta \geq \lambda^{\pm}, I' + 1 \leq i \leq I \tag{Equation 13d}$$

$$(1-\theta)\frac{\left[f_i^{\pm}(x)\right]^{\varepsilon} - \left(L_i^{\pm}\right)^{\varepsilon}}{\left(U_i^{\pm}\right)^{\varepsilon} - \left(L_i^{\pm}\right)^{\varepsilon}} + \theta \geq \lambda^{\pm}, I' + 1 \leq i \leq I \tag{Equation 13e}$$

$$g_j^{\pm}(x) \leq c_j^{\pm}, 1 \leq j \leq J' \tag{Equation 13f}$$

$$g_j^{\pm}(x) \geq c_j^{\pm}, J' + 1 \leq j \leq J'' \tag{Equation 13g}$$

$$g_j^{\pm}(x) = c_j^{\pm}, J'' + 1 \leq j \leq J \tag{Equation 13h}$$

$$0 \leq \lambda^{\pm} \leq 1 \tag{Equation 13i}$$

$$x \geq 0 \tag{Equation 13j}$$

where $\lambda^{\pm}$ represents the degree of satisfaction under multiple-objective and constraints; $U_i^{\pm}$ and $L_i^{\pm}$ are the maximum and minimum values of $f_i^{\pm}(x)$; $\alpha_i^{\pm}$ is the respective tolerance; $\varepsilon > 0$ is prescribed by decision-makers, and usually $\varepsilon = 2$; $\theta \in (0,1)$ is an alterable auxiliary parameter.

*Integrating scenario analysis under Laplace criterion.* To capture the dynamic impacts of varying degrees of water, energy and food constraints for a WEFCN, a scenario analysis (SA) method were introduced to create a "space of possibilities" to explore the consequence of uncertainty.[39] While the probabilities related to the occurrence of various scenarios are random and usually difficult to be measured with concrete data. Laplace criterion (LC) assuming that the occurrence probability of each scenario is equal[40] can be embeded into SA to formulate a scenario analysis with Laplace criterion (SALC) method.[41] Finally, a multi-objective interval programming with scenario analysis under Laplace criterion (MOIP-SALC) approach could be formulated by integrating MOP, IP, SA, and LC into a framework as follows:

Take optimistic view as an example,

$$\text{Max } \lambda^{\pm} \tag{Equation 14a}$$

subject to:

$$UL_i^{\pm} = Max\left\{\frac{1}{m}\cdot\begin{pmatrix} R_{11}^{\pm} & R_{12}^{\pm} & \dots & R_{1n}^{\pm} \\ R_{21}^{\pm} & R_{22}^{\pm} & \dots & R_{2n}^{\pm} \\ \dots & \dots & \dots & \dots \\ R_{m1}^{\pm} & R_{m2}^{\pm} & \dots & R_{mn}^{\pm} \end{pmatrix}\cdot f_i^{\pm}(x)\right\} \tag{Equation 14b}$$

$$LL_i^{\pm} = Min\left\{\frac{1}{m}\cdot\begin{pmatrix} R_{11}^{\pm} & R_{12}^{\pm} & \dots & R_{1n}^{\pm} \\ R_{21}^{\pm} & R_{22}^{\pm} & \dots & R_{2n}^{\pm} \\ \dots & \dots & \dots & \dots \\ R_{m1}^{\pm} & R_{m2}^{\pm} & \dots & R_{mn}^{\pm} \end{pmatrix}\cdot f_i^{\pm}(x)\right\} \tag{Equation 14c}$$

$$(1-\theta)\frac{\left(UL_i^{\pm}\right)^{\varepsilon}-\left[f_i^{\pm}(x)\right]^{\varepsilon}}{\left(UL_i^{\pm}\right)^{\varepsilon}-\left(LL_i^{\pm}\right)^{\varepsilon}}-\theta\frac{\left[f_i^{\pm}(x)\right]^{\varepsilon}-\left(LL_i^{\pm}\right)^{\varepsilon}}{\left(UL_i^{\pm}+\alpha_i^{\pm}\right)^{\varepsilon}-\left(LL_i^{\pm}\right)^{\varepsilon}}+\theta\geq\lambda^{\pm},1\leq i\leq I' \tag{Equation 14d}$$

$$\theta-\theta\frac{\left[f_i^{\pm}(x)\right]^{\varepsilon}-\left(LL_i^{\pm}\right)^{\varepsilon}}{\left(UL_i^{\pm}+\alpha_i^{\pm}\right)^{\varepsilon}-\left(LL_i^{\pm}\right)^{\varepsilon}}\geq\lambda^{\pm},1\leq i\leq I' \tag{Equation 14e}$$

$$\theta\frac{\left(UL_i^{\pm}\right)^{\varepsilon}-\left[f_i^{\pm}(x)\right]^{\varepsilon}}{\left(LL_i^{\pm}-\alpha_i^{\pm}\right)^{\varepsilon}-\left(UL_i^{\pm}\right)^{\varepsilon}}+\theta\geq\lambda^{\pm},I'+1\leq i\leq I \tag{Equation 14f}$$

$$(1-\theta)\frac{\left[f_i^{\pm}(x)\right]^{\varepsilon}-\left(LL_i^{\pm}\right)^{\varepsilon}}{\left(UL_i^{\pm}\right)^{\varepsilon}-\left(LL_i^{\pm}\right)^{\varepsilon}}-\theta\frac{\left(UL_i^{\pm}\right)^{\varepsilon}-\left[f_i^{\pm}(x)\right]^{\varepsilon}}{\left(UL_i^{\pm}\right)^{\varepsilon}-\left(LL_i^{\pm}-\alpha_i^{\pm}\right)^{\varepsilon}}+\theta\geq\lambda^{\pm},I'+1\leq i\leq I \tag{Equation 14g}$$

$$g_{jR_{mn}}^{\pm}(x)\leq c_{jR_{mn}}^{\pm},1\leq j\leq J' \tag{Equation 14h}$$

$$g_{jR_{mn}}^{\pm}(x)\geq c_{jR_{mn}}^{\pm},J'+1\leq j\leq J'' \tag{Equation 14i}$$

$$g_{jR_{mn}}^{\pm}(x)=c_{jR_{mn}}^{\pm},J''+1\leq j\leq J \tag{Equation 14j}$$

$$0\leq\lambda^{\pm}\leq 1 \tag{Equation 14k}$$

$$x_{R_{mn}}\geq 0 \tag{Equation 14l}$$

where $UL_i^{\pm}$ and $LL_i^{\pm}$ are the maximum and minimum values of $f_i^{\pm}(x)$ with the consideration of LC; $\frac{1}{m}$ is the constant of Laplace criterion and $R^{\pm}$ represents the matrix of scenarios. Similarly, the solution from the pessimistic view can be also developed, without redundant repeat here.

Overall, the developed MOIP-SALC approach for optimal planning of a WEFCN system can be summarized as:

Step 1. Convert the original multi-objective model into two sub-models with lower and upper bounds., andeach sub-model is a multi-objective model as well.

Step 2. Convert each multi-objective sub-model into a single-objective model, then apply Equations 12a–12j and Equations 13a–13j to solve the single-objective model under the optimistic and pessimistic views. The specific resolution steps can be found in Rani et al. in 2016.[38] Note that these two steps were based on the basic scenario.

Step 3. Repeat Steps 1 and 2 to obtain the results under every scenario individually.

Step 4. Determine the value of $UL_i^{\pm}$ and $LL_i^{\pm}$ of all objectives by using LC and the results under all scenarios would be considered.

Step 5. Obtain the results under LC by solving Equations 14a–14l.

The models were solved by the Lingo 11.0 software. For each scenario among S1-S27, there are 428 variables in each sub-model with lower or upper bounds under the optimistic or pessimistic view, the solving run time was nearly 15 seconds. As for SL, there are 11,478 variables and the solving run time was more than 18 minutes.

## Case study: Model application in Henan Province of China

We applied the WEFCN planning framework to the Henan Province as it is the birthplace of ancient agricultural civilization of China, which is also known as the "Central Plain Granary" nowadays. As one of the major agricultural provinces in China, agriculture plays a dominant role in the development of Henan Province. By 2018, the agricultural gross output value was up to 497.4 billion CNY, accounting for about 10.4 % of the gross domestic production (GDP). And the rural population was 52.67 million, which also accounted for up to 48.3 % of the total resident population.[29] Such rapid economy and population growth inevitably require adequate food supply, which would impose greater stress on food production capacity. In 2018, the annual grain output was 66.49 million tonne, with an increase of 1.9 % over the previous year.[32] However, the agricultural land and water resources endowment of Henan Province are inherently inadequate. For instance, the per capita cultivated land and freshwater resources are only 4/5 and 1/5 of the national average and 1/4 and 1/20 of the world average.[30] Along with the large-scale use of chemical fertilizer, pesticide and agricultural film, not only the soil becomes thinner, but also non-point source pollution and white pollution are more serious. Meanwhile, large amont of carbon emission have been emitted from agricultural production activities.[31] Generally, the task of achieving green development and sustainable use of resources is arduous and not optimistic.

### *Scenario setting*

To explore the dynamic impacts of different levels of water, energy and food constraints on the WEFCN system and identify the key factor, 27 scenarios (i.e. S1-S27) combining higher, moderate and lower levels of water resources availability (i.e. W-High, W and W-Low), electricity availability (i.e. E-High, E and E-Low) and food demand (i.e. F-High, F and F-Low) were considered, as described in Table 5. The value of W was equal to the moderate water resources availability, W-High was defined as 1.1 × W, and W-Low was defined as 0.9 × W. Similarly, the definitions of E-High, E-Low, F-High, F-Low were 1.1 × E, 0.9 × E, 1.1 × F and 0.9 × F, respectively. And SL was scenario under Laplace criterion, it assumed that the probabilities of all scenarios were equal.