Optimization of uncertain agricultural management considering the framework of water, energy and food

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Abstract

Synergetic development of water, energy and food is prerequisite for coping with issues of increment of global population, deterioration of ecological environment and aggravation of climate change. This study aims to develop a scenario-based type-2 fuzzy interval programming (STFIP) approach for planning agricultural water, energy and food (WEF) as well as crop cultivation. Both single uncertainties (presented as interval numbers, scenarios and fuzzy sets) and dual uncertainties (i.e. interval-scenario and type-2 fuzzy interval) can be effectively tackled by STFIP method. Then, a STFIP-WEFN model is developed to maximize net agricultural profit with integrated management of productive resources for Henan Province, China. Solutions of different water resources, diverse energy resources and multiple agricultural crops in association with various water supply structures between current situation and future policy orientation are examined. Results disclose that: over the entire planning horizon, a) the total planting area of crops can increase from [129.3, 133.6] × 10^3 km^2 to [132.0, 135.6] × 10^3 km^2 by optimizing resources allocation; b) uncertainties existing in WEFN system can lead to a change rate of the system benefit by 16.93%; c) the total planting area can increase by [4.00, 6.05] % when the groundwater ratio changes from 40 % to 55 %. These findings can help effectively optimize the existing planting structure and coordinate the development of Henan Province among water, energy, food, economy, society and environment.

Keywords: Decision making; Optimal planting structure; Resources allocation; Uncertainty analysis; Water-energy-food

1. Introduction

Water, energy and food (WEF) are three strategic supporting elements for sustainable development of national economy (Purwanto et al., 2019). Under the compound influence of climate change, population growth, changing diets, urbanization and aging infrastructure, intensifying challenge are observed for ensuring adequate WEF (Zhang et al., 2018; Alcon et al., 2019). Global demand for WEF is expected to increase by 40 %, 50 % and 35 % respectively by 2030, which would undoubtedly become a "short plank", restricting the development of modern society and posing a serious threat to national security and social stability (NIC, 2012; Li et al., 2019b). WEF has complex interactions, which are not only interdependent but also competitive among each other (Cai et al., 2018). Specifically, the whole process of energy production from fossil fuel extraction to electricity generation is accompanied with the actions of water extraction, cooling and transmission whilst different stages of crop growth also need to take water as the input factor (Ricart and Rico, 2019). Energy provides basic guarantee for the various links (e.g., extraction, distribution, transportation) of water exploitation and utilization while the grain production cannot be mechanized, processed, stored and transported without its support (Pahl-Wostl, 2019). In addition, food also provides the basic material for socio-economic development and energy production (Niu et al., 2019; Alcon et al., 2020). These compound interactions constitute a complex system, which is subject tothe competition of limited resources, and thus make the synergetic development of WEF into a dilemma (Mercure et al., 2019).

Agriculture, taking land, water and energy as production factors, supplies basic food and raw materials to other sectors (e.g., life, manufacturing, service), which is the solid foundation of mankind survival and economy development (Fernández et al., 2020; Guan et al., 2020). However, the contradiction between demand growth of food andenergy and supply reduction of agricultural water is increasingly fierce in recent years (Egea et al., 2017). It is estimated that about 70% of the world's freshwater resources are used for agricultural irrigation and even up to 90% in many developing countries (Lim et al., 2019). The occurrence of water depletion seriously restricts the increase of crop yield, which is also a common problem in the agricultural development worldwide (Daher et al., 2019; Fernández et al., 2019). Energy is an essential element for crop growth and grain production to support production of agricultural energy (e.g., fertilizer, agricultural machinery, plastic film). A large amount of water and energy input will lead to the increase of agricultural output, while it is not conducive to the coordinated development of WEF resources (Moradi et al., 2015; Sadeghi et al., 2018). Facing the dilemma of water shortage and fossil energy exhaustion, it is of great significance to propose an integrated optimization method for achieving scientific agricultural management (i.e., planting structure adjustment, resources optimal allocation), which can guarantee the efficient utilization of water and energy resources in the process of grain production to achieve the balance state of the three elements (Tidwell., 2016).

Previously lots of studies have been implemented for agricultural WEF management by understanding water-energy-food nexus (WEFN) (Ilhan, 2017; Ethan Yang and Wi, 2018; Guan et al., 2020; Sadeghi et al., 2020b; Zhang et al., 2020). For instance, Ilhan (2017) used the pooled least squares regression, pooled fixed effects, and pooled random effects regression techniques to investigate the linkages between agricultural sustainability and WEF shortage in Sub-Saharan African countries. Guan et al. (2020) formulated a Water Evaluation and Planning (WEAP) platform to optimize water resources allocation by quantifying the interactions of WEFN. However, the above studies mainly focused on the WEFN analysis through deterministic methods, which might encounter difficulties in dealing with complex uncertainties from inherent, extrinsic and interactive aspects (Li et al., 2018; Ravar et al., 2020). Currently, many researchers have concentrated on analyzing the complexities and uncertainties of WEFN with inexact optimization approaches (Mannan et al., 2018; Osman et al., 2018; Yousefi et al., 2018; Chen et al., 2019; Guo et al., 2019; Ji et al., 2019; Sun et al., 2019; Zeng et al., 2019). Among them, stochastic programming (SP) can effectively tackle random variables that could not definitely know but could be conveyed with probability distributions; nevertheless, a large number of samples must be obtained initially (Yu et al., 2017; Gholizadeh et al., 2020). Multi-objective programming (MOP) has its effectiveness in obtaining integrated decisions, but it has difficulties in identifying optimal solutions because subjective elements and tradeoff relationships could be involved (e.g., weight definition) (Nematian and Movahhed, 2019). Interval parameter programming (IPP) can effectively deal with uncertain parameters expressed as interval values, while it has limitations in expressing possible degree of event occurrence (Kemal, 2020). Fuzzy programming (FP) can effectively handle the ambiguous parameters through fuzzy sets [e.g., (b_1, b_2, b_3)], while it could be incapable of tackling the membership functions that were also expressed as fuzzy sets (Melin and Castillo, 2014).

In the real-world agricultural management system, parameters may be affected by a series of factors (e.g., inaccuracy of statistical data, subjective experience), which would result in system errors and multiple uncertainties (Si et al., 2019). For example, during the entire planning horizon, prices of agricultural products and costs of agricultural production conditions may fluctuate under the influence of demand-supply relationship and policies (Hoolohan et al., 2019). Thus, it is necessary to describe these parameters and variables with interval numbers. Subject to the combined influences of subjective judgements and objective evaluation, the available surface water for agricultural irrigation may be expressed as Type-2 fuzzy sets [e.g., $\left(b_1,\ b_2,\ b_3,\ b_4,\ b_5\right)$] (Wang et al., 2017).Even though Type-2 fuzzy programming (TFP) can effectively address uncertain fuzzy membership functions by introducing the type-2 fuzzy theory (Starczewski, 2014; Tolga et al., 2020), it has not been applied to plan agricultural WEF management in previous studies. Besides, the coupling relationship among WEF may change under the influences of complex factors (e.g., varied policies, dynamic demand and supply), Thus the scenario analysis (SA) method can deal with such uncertainties with a variety of simulated scenarios (Namany et al., 2019; Noussan and Tagliapietra, 2020). Furthermore, parameters can be affected by the joint action of above uncertain factors, which would lead to dual uncertainties expressed as interval-scenario and type-2 fuzzy interval (Jiang et al., 2019).

Summarizing the existing literatures shows that an integrated uncertain optimization method has not emerged for both optimizing land and WEF resources allocation, and tackling the above uncertainties in agricultural management. Therefore, this paper develops a scenario-based type-2 fuzzy interval programming (STFIP) approach by integrating IPP, SA and TFP into one framework. STFIP has advantages of not only tackling uncertainties presented as interval numbers, scenarios and fuzzy sets, but also reflecting dual uncertainties expressed as interval-scenario and type-2 fuzzy interval. Then, a STFIP-WEFN model is developed and applied to Henan Province, China. A series of scenarios are considered for water resources, diverse energy resources and multiple agricultural crops in association with various water supply structures between current situation and future policy orientation. STFIP-WEFN model takes great superiorities in: a) adjusting the existing planting structure towards a more reasonable and high-efficient aspect; b) facilitating the dynamic analysis for decisions of water resources allocation, electricity distribution and crops production; c) coordinating the conflicting interactions among WEF elements, as well as other environmental and economic factors.

2. Methodology

The agricultural managers are charged with allocating multiple resources (e.g., land, water, energy) to meet the requirements for various crops under different periods. LP model can effectively solve above problem that involved with multivariable optimal decision making (Cai et al., 2001; Ji et al., 2018). However, in real-world agricultural management problems, there are multiple uncertainties resulted by series of factors and parameters should be described with interval numbers with lower and upper bound (i.e., LB and UB) value (Li et al., 2019a; Si et al., 2019). Thus, the IPP model can be generated by combining LP model with Interval parameter theory (Tong, 1994; Simić et al., 2017):

$$\text{Max } f^{\pm} = C^{\pm} X^{\pm} \tag{1a}$$

subject to

$$A^{\pm} X^{\pm} \leq B^{\pm} \tag{1b}$$

$$X^{\pm} \geq 0 \tag{1c}$$

where $C^{\pm} \in \left\{R^{\pm}\right\}^{n\times 1}$, $A^{\pm} \in \left\{R^{\pm}\right\}^{m\times n}$, $B^{\pm} \in \left\{R^{\pm}\right\}^{m}$, $f^{\pm}$ represents the objective function; $X^{\pm}$

are decision variables; $R^{\pm}$ represents the set of interval numbers (Ganjefar and Solgi, 2015). Obviously, IPP is capable of handling the parameters and variables that cannot be accurately described in determinate values. However, the LB and UB of interval numbers may be known without the distribution information for certain parameters and further in contact with type-2 fuzzy information (Karnik et al., 1999). From above considerations, Type-2 fuzzy sets (TFS) should be introduced to deal with such uncertainty and its membership function can be expressed as follows (Ali et al., 2015):

$$\tilde{\mu}_{\tilde{B}}(x,u)=\begin{cases}\left(0,\ \dfrac{x-b_1}{2(b_3-b_1)},\ \dfrac{x-b_1}{b_3-b_1}\right) & \text{if } b_1<x\le b_2\\ \left(\dfrac{x-b_2}{b_3-b_2},\ \dfrac{x-b_2}{b_3-b_2}+\dfrac{(b_3-x)(b_1-b_3)}{2(b_3-b_1)(b_3-b_2)},\ \dfrac{x-b_1}{b_3-b_1}\right) & \text{if } b_2<x<b_3\\ 1 & \text{if } x=b_3\\ \left(\dfrac{b_4-x}{b_4-b_3},\ \dfrac{b_4-x}{b_4-b_3}+\dfrac{(x-b_3)(b_5-b_4)}{2(b_5-b_3)(b_4-b_3)},\ \dfrac{b_5-x}{b_5-b_3}\right) & \text{if } b_3<x\le b_4\\ \left(0,\ \dfrac{b_5-x}{2(b_5-b_3)},\ \dfrac{b_5-x}{b_5-b_3}\right) & \text{if } b_4<x<b_5\\ 0 & \text{otherwise}\end{cases} \tag{2}$$

Based on Castillo and Melin (2014), Figueroa-Garcia et al. (2012), TFS also can be described by using notion of footprint of uncertainty (FOU).

$$\begin{aligned}\text{FOU}\left(\tilde{B}\right)=&\left\{(x,u)\middle|b_1+u(b_3-b_1)\le x\le b_2+u(b_3-b_2),0\le u\le 1\right\}\\ &\text{U}\left\{(x,u)\middle|b_4-u(b_4-b_3)\le x\le b_5-u(b_5-b_3),0\le u\le 1\right\}\end{aligned} \tag{3}$$

It can be clearly seen that TFP would effectively handle parameters with TFS in decision problems while be incapable of dealing with dual uncertainty denoted as type-2 fuzzy interval (TFI) (Castillo and Melin, 2012). Moreover, the available amount of surface water and groundwater for agricultural irrigation in the future are varied under the integrated influences of multi-factors (e.g., precipitation, climate change, human activities) (Frappartab et al., 2018; Chen et al., 2020; Sadeghi et al., 2020a). Thus, it is of significance to analyze the variations in agricultural management by simulating various water supply structures. Based on above analysis, it is desired to integrate TFP, SA with IPP model into consideration for taking dual uncertainties (Miao et al., 2014; Zhang et al., 2014). Accordingly, the STFIP model could be formulated as follows:

$$\text{Max } \tilde{f} = C^{\pm} X^{\pm} \tag{4a}$$

subject to

$$A_1^{\pm} X^{\pm} \tilde{\preceq} \tilde{B}_1 \tag{4b}$$

$$A_2^{\pm} X^{\pm} \leq B_2^{\pm} \tag{4c}$$

$$X^{\pm} \geq 0 \tag{4d}$$

where $\tilde{B}_1 \in \left\{ \tilde{R} \right\}^{s\times1}$, $\tilde{R}$ represent the set of TFSs, $\tilde{\preceq}$ is the fuzzy partial order. The membership function and expression of TFS in STFIP model can be described by Formulas (2) and (3), respectively. Therefore, complex processes may be required for solving the model owing to the introduction of TFP method. The general solution processes of STFIP model are illustrated in Figure 1 and detailed solution algorithm can reference Maldonado et al. (2014), Wang et al. (2016).

Place Figure 1 here

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3. Case study

3.1 Overview of the study area

Henan Province, with an area of 167,000 km^2, is an important grain production base and a populous province in China. Its plains and basins account for about 55.7% of the total land area as shown in Figure 2, which makes it suitable for planting crops. In recent years, the improvement of living quality and development of socio-economic activities have led to a sharp decline of the available water resources for agricultural irrigation and a shortage of surface water, which could further result in the overexploitation of groundwater. Meanwhile, the contradiction between limited land and massive population increasingly stand out with climate change and other factors. Moreover, the increasing utilization of chemical fertilizers and pesticides has caused environmental non-point source pollution, restricting the sustainable development of agriculture.

Place Figure 2 here

3.2 STFIP-WEFN modeling formulation

This study introduces STFIP method to optimize crops planting structure and agricultural WEF resources allocation by formulating a STFIP-WEFN model. Figure 3 clearly presents the framework of the STFIP-WEFN model applied to the Henan Province, in which nine main food crops (i.e., rice, wheat, corn, beans, tubers, oil-bearing crops, cotton, vegetables, and fruits), two kinds of water sources, three kinds of pollution sources and other factors such as the total available land area are considered (SYHP). The detailed mathematical relationships of variables and parameters in objective function and multiple constraints are expressed as the following Formulas (5a) - (6l), respectively. Specifically, the maximum system benefit has been considered as the objective function, which comprehensively takes revenues of crop productions, costs for water, costs for energy, and costs of agricultural production conditions into account (Singh et al., 2012; Miao et al., 2014; Simić et al., 2017).

Place Figure 3 here

$$\text{Max } f^{\pm} = (1) - \left[(2)+(3)+(4)+(5)+(6)+(7)+(8)\right] \tag{5a}$$

(1) *Revenues of agricultural productions*

$$\sum_{t=1}^{6}\sum_{v=1}^{9} SAF_{t,v}^{\pm} \times OMFP_{t,v}^{\pm} \times OMP_{t,v}^{\pm} \tag{5b}$$

(2) *Costs for surface water*

$$\sum_{t=1}^{6}\left(\sum_{v=1}^{9} SAF_{t,v}^{\pm} \times AWQ_{t,v}^{\pm}\right) \times CSWS_{t} \times CSU_{t}^{\pm} \times \delta \tag{5c}$$

(3) *Costs for groundwater*

$$\sum_{t=1}^{6}\left(\sum_{v=1}^{9} SAF_{t,v}^{\pm} \times AWQ_{t,v}^{\pm}\right) \times CGWS_{t} \times CGU_{t}^{\pm} \times \gamma \tag{5d}$$

(4) *Costs of chemical fertilizers*

$$\sum_{t=1}^{6}\sum_{v=1}^{9}\left(SAF_{t,v}^{\pm} \times CCFA_{t,v}^{\pm}\right) \times CFP_{t}^{\pm} \times \alpha \tag{5e}$$

(5) *Costs of pesticides*

$$\sum_{t=1}^{6}\sum_{v=1}^{9}\left(SAF_{t,v}^{\pm} \times CCPA_{t,v}^{\pm}\right) \times CPP_{t}^{\pm} \times \vartheta \tag{5f}$$

(6) *Costs of agricultural films*

$$\sum_{t=1}^{6}\left(\sum_{v=1}^{9} SAF_{t,v}^{\pm}\right) \times PFAP_{t}^{\pm} \tag{5g}$$

(7) *Costs of energy consumption*

$$\sum_{t=1}^{6}\left(\sum_{v=1}^{9} SAF_{t,v}^{\pm}\right) \times UAM_{t}^{\pm} \times CEU_{t}^{\pm} \times \varphi \tag{5h}$$

(8) *Costs of seeds*

$$\sum_{t=1}^{6}\sum_{v=1}^{9} SAF_{t,v}^{\pm} \times SEDP_{t,v}^{\pm} \tag{5i}$$

The system benefit would be influenced and limited by the synthetic action of productive resources (e.g., water, energy, food and land). Thus, integrated management of above resources has been considered to avoid blindly pursuing net agricultural profit, which can form an internal self-regulating mechanism and optimize the WEF Nexus to some extent (Zhang and Vesselinov, 2017). Accordingly, the constraints mainly include energy demand-supply, water resources supply, food guarantee, arable area availability and restriction of production conditions (Li et al., 2019b; Tang et al., 2019; Yu et al., 2020). The detailed expressions are:

(1) *Electricity security of agricultural machinery constraint:*

$$\sum_{v=1}^{9} SAF_{t,v}^{\pm} \times UAM_t^{\pm} \times \varphi \le PAME_t^{\pm} \qquad (6a)$$

(2) *Fossil fuels demand and supply constraints:*

$$\sum_{v=1}^{9} CFF_{t,v}^{\pm} \le AFF_t^{\pm} \qquad (6b)$$

(3) *Surface water and groundwater provide constraints:*

$$\sum_{v=1}^{9} \left(SAF_{t,v}^{\pm} \times AWQ_{t,v}^{\pm} \right) \times CSWS_t \times \delta\, \mathrm{p}_{\%}\, \tilde{S}WA_t^{\pm} \qquad (6c)$$

$$\sum_{v=1}^{9} \left(SAF_{t,v}^{\pm} \times AWQ_{t,v}^{\pm} \right) \times CGWS_t \times \gamma \le GWA_t^{\pm} \qquad (6d)$$

(4) *Agricultural irrigation guarantee constraint:*

$$\sum_{v=1}^{9} SAF_{t,v}^{\pm} \times AWQ_{t,v}^{\pm} \le \left(WPSW_t^{\pm} + WPGW_t^{\pm} \right) \times \theta \qquad (6e)$$

(5) *Land use constraint:*

$$SAF_{t,v}^{\min} \le SAF_{t,v}^{\pm} \le SAF_{t,v}^{\max} \qquad (6f)$$

(6) *Total area of agricultural constraint*

$$\sum_{v=1}^{9} SAF_{t,v}^{\pm} \le TSAF_t^{\pm} \qquad (6g)$$

(7) *Agricultural production conditions consumption constraints, including chemical fertilizer environment constraint, pesticides restriction constraint and agricultural films environment constraint:*

$$\sum_{v=1}^{9}\left(SAF_{t,v}^{\pm}\times CCFA_{t,v}^{\pm}\right)\times\alpha\leq TEF_{t}^{\pm} \quad (6h)$$

$$\sum_{v=1}^{9}\left(SAF_{t,v}^{\pm}\times CCPA_{t,v}^{\pm}\right)\times\vartheta\leq TEC_{t}^{\pm} \quad (6i)$$

$$\sum_{v=1}^{9}SAF_{t,v}^{\pm}\times PFAP_{t}\leq TEAF_{t}^{\pm} \quad (6j)$$

(8) *Food guarantee constraint:*

$$SAF_{t,v}^{\pm}\times OMFP_{t,v}^{\pm}+PAJ_{t,v}^{\pm}\geq FD_{t,v}^{\pm} \quad (6k)$$

(9) *Non-negative constraints*

$$SAF_{t,v}^{\pm}\geq 0 \quad (6l)$$

3.3 Data collection and scenario design

Nomenclatures for parameters and variables in STFIP-WEFN model have been clearly presented in Appendix A, and Appendix B explains the meaning of abbreviation in this paper. Moreover, the data were mainly extracted from "Statistical Yearbook" (SBHPNESD, 2017; SYHP, 2017), "Water Resources Bulletin" (HPWRB, 2017), "Government Report" (ABWQHP, 2014; FEDPHP, 2017; FPHPEEP, 2017), "Pertinent Literature" (Fan et al., 2015; Li et al., 2019b; Zeng et al., 2019; Yu et al., 2020). For instance, Table 1 shows the historical consumption amounts of agricultural production conditions (i.e. chemical fertilizer, electricity, pesticide and plastic film), which are the right-hand side of constraints (SYHP, 2017). The data of water resources in Henan Province from years of 2006-2017 are presented in Table 2 (HPWRB, 2017). Moreover, the cultivated area of crops in Henan Province were extracted from SYHP (2017). Considering the impacts of urbanization, industrialization, prevailing cropping practices, and region planning (FPHPEEP, 2017), fraction to which the existing area of each crop can be increased in various planning periods could be obtained with empirical analysis (Singh and Panda, 2012). Then, the maximum planting area of each crops was determined by multiplying existing area with limited fraction and were expressed as interval numbers, as shown in Table 3 (Tong, 1994; Daher et al., 2019). Besides, the crop-related parameters (e.g., unit cost of crops, seeds, pesticides and chemical fertilizers) were obtained from pertinent literatures published by Li et al. (2019a), Zeng et al. (2019), Yu et al. (2020). Other energy and economic data were acquired from the statistical yearbooks and the 13th Five-year Plans of Henan Province (FEDPHP, 2017; FPHPEEP, 2017; SYHP, 2017). Then, the STFIP-WEFN model was solved by the software of *Lingo versions 10*, which can accurately obtain global optimal solution with simplex algorithm in tackling linear programming problems (Dantzig, 1955; Cottle and Dantzig, 1970).

Place Tables 1-3 here

According to FPHPRAD (2017), the Strictest Water Resources Management System (SWRMS) has been applied in Henan Province for achieving sustainable agricultural development and efficient utilization of water resources. There is an important point that has been emphasized, the exploitation of water resources should attach great importance to the protection of groundwater system and gradually return the over-exploited groundwater. Thus, the supply ratios of surface water (x) and groundwater (y) in agriculture should be dynamic and variable. Four scenarios are simulated with the combined consideration of surface water and groundwater endowment, current situation of agricultural irrigation and future policy orientation for water resource management (HPWRB, 2017). The selected four scenarios mean that surface water and groundwater supply ratios $\left(x, y\right)$ in agricultural irrigation are (0.60, 0.40), (0.55, 0.45), (0.50, 0.50) and (0.45, 0.55) which are defined as scenario 1 to scenario 4 (abbreviated as S1, S2, S3 and S4), respectively. The specific parameters of above supply ratios are $CSWS$ and $CGWS$, which have been illustrated in Formulas (6c) and (6d).

4. Results and discussion

4.1 Optimized solution of crops planting structure and agricultural system benefits

As a major populous and agricultural province, Henan produces more than one tenth of grains and a quarter of wheats with six percent of the country's arable land, which makes outstanding contributions to the country's food security. Figure 4 presents the planting areas of different crops under various scenarios and planning periods which has been obtained by solving STFIP-WEFN model under the limitation of maximum planting area shown in Table 3. The total planting area of crops would change from [129.3, 133.6] × 10^3 km^2 to [132.0, 135.6] × 10^3 km^2 over the entire planning horizon, which could be attributed to the optimization of planting structure with STFIP method. In detail, as shown in Figure 4, the cultivated area of rice would raise from [5707, 6050] km^2 (S1) to [5904, 6954] km^2 (S3) in period 1, while remained unchanged in period 6 among different scenarios. This is mainly because the planting area of rice in period 1 was mainly affected by irrigation water amount (especially for surface water), while in period 6 the supplying water would be amply because of technical upgrading or other factors. And the consumption of electricity and fertilizer would then take place of available surface water amount to be the determinant factors of planting structure. On the contrary, the area of cotton would reduce [183, 194] km^2 (S1) and [189, 200] km^2 (S4) over the planning horizon, respectively. Results indicated that planting cotton would obtain less benefits compared to other crops under the same consumption of agricultural production conditions. In conclusion, for the sake of obtaining maximum economic benefits, the planting structure should be adjusted toward more high-profit crops (e.g., rice, wheat, vegetables and fruits). Besides, results obtained by STFIP-WEFN model were validated by historical trend, actual situation and developing plans of study area. As shown in Figure 4, area of wheat would raise from [48.7, 50.0] × 10^3 km^2 to [54.4, 57.7] × 10^3 km^2 for meeting the increasing demand of yield; while cotton would be consistent with the historical trend and keep on decreasing during the whole planning periods.

Place Figure 4 here

Figure 5 presents the lower bound, mean value (i.e. solution results with linear programming) and upper bound of system benefits (abbreviated as LBB, MV and UBB, respectively) under various periods and scenarios. In detail, the system benefits would range from [0.408, 0.485] ×

10^{12} RMB ¥ (S3) to [0.421, 0.491] × 10^{12} RMB ¥ (S4) in period 1; while they would range from [0.570, 0.679] × 10^{12} RMB ¥ (S3) to ¥ [0.588, 0.684] × 10^{12} RMB ¥ (S4) in period 6. Results indicated that the system benefits would increase significantly during the entire planning horizon, while increase slightly when groundwater ratio raises from 50 % to 55 %. Mean value of system benefits would be 0.591 × 10^{12} RMB ¥ (S3) and 0.610 × 10^{12} RMB ¥ (S4) in period 6. Results also implied that the shortage of water would result in a slight decline of agricultural system benefits but could lead to a huge increase when adequate water supply was available. Besides, the annual system benefit would increase by [6.67, 6.83] % under STFIP-WEFN model, which can authentically satisfy the requirement of FPHPRAD (2017). Relatively, the UBB indicates larger contribution to the growth of national economy at the cost of more consumption of water resources and neglecting of environmental protection; while system benefit obtained with LB model would helpful for alleviating overexploitation of groundwater and easing pressure on energy supply. Thus, optimized solutions of crops planting structure can provide support and alternatives for agricultural managers adjusting crop patterns towards a reasonable way, which would coordinate the conflictions among irrigation benefit, resources supply security and environmental pollution.

Place Figure 5 here

4.2 Optimized solution of WEF resources

Figure 6 presents the average allocated water resources of lower and upper bound under different scenarios and planning periods. In this figure, left, middle and right column mean average water consumption (i.e., surface water and groundwater), allocated amount for various periods and crops respectively, and ribbons shows connected relation and its intensity among water sources, periods and crops. For instance, the average allocated groundwater over the planning horizon would be 21.56 × 10^9 m^3 (S1) and 35.45 × 10^9 m^3 (S4); while the average allocated surface water would be 32.34 × 10^9 m^3 (S1) and 29.01 × 10^9 m^3 (S4), respectively. Besides, the total allocated water resources would be different under different scenarios. For example, the total allocated water would be 8.85 × 10^9 m^3 (S1), 9.67 × 10^9 m^3 (S2), 10.53 × 10^9 m^3 (S3) and 10.48 × 10^9 m^3 (S4) in period 1, respectively. Results indicated that the water shortage would no longer limit the production of crops but the fertilizer and pesticide consumptions with the increment of groundwater supply-ratio. In summary, surface water should be given priority to manage the agricultural development in order to gain maximum system benefits and avoid over-exploiting groundwater resources. In this way, the allocated water resources would be effectively limited for relieving the contradiction between increasing resources demand and limited supplying capacity.

Place Figure 6 here

Figure 7 shows the electricity consumption for agricultural machines during the entire planning horizon, in which four scenarios also were analyzed. The electricity consumption of wheat would be higher than other crops owing to its high planting area and yield. Besides, the proportion of wheat's electricity consumption would go ascend with the increment of groundwater supply ratio.

In detail, the proportion of wheat's electricity consumption would be [37.58, 38.28] % (S1), [38.71, 39.06] % (S2), [38.70, 39.07] % (S3) and [38.92, 39.15] % (S4), respectively. Comparably, the electricity consumption proportion for beans would change from [2.70, 2.82] % (S2) to [2.89, 2.93] % (S4). Results indicated that when groundwater became the main water resource, beans would replace other crops as high benefits and advantageous crops owing to its low energy equivalent (Sadeghi et al., 2020b). Therefore, effective electricity distributing in accordance to water resources' supplying structure should be encouraged for pursuing maximum agricultural benefits and cutting energy waste.

Place Figure 7 here

In this study, crops' production has been considered as constraint for ensuring regional food security and supporting social development, which can reasonably quantify the relationship between food supply and demand (Amjath-Babu et al., 2019; Ji et al., 2020). Figure 8 presents the average crops' production of LB and UB under different periods and scenarios. For instance, the production of rice in S1 would be 4.53×10^9 kg in period 2, 4.83×10^9 kg in period 4 and 5.03×10^9 kg in period 6, respectively. Results indicated that the rice's production in S1 would change a lot in comparison with other scenarios (i.e. S2, S3 and S4) due to its sensitivity to the water-supply pattern. When surface water became the main water resource, rice's area would definitely squeeze the area of other crops but except fruits as the supply surface water raised. However, fruits' production would remain almost unchanged on the basis of high system benefits with low consumption of production factors (e.g., water, seed). Results implied that some crops' production (e.g., oil-bearing crops and vegetables) would be affected prominently by the interaction of multiple constraints. It would be not desirable to maximize crop yields simply by increasing the amount of supplying water resources, which might be limited by available cultivated area or limited use of pesticides and fertilizers. Besides, crops differ greatly in their calorific values or nutritive values, which can better reflects interactions between resources consumption and crop yield (Al-Thani et al., 2020; Sadeghi et al., 2020b). Unfortunately, limited by data availability, it is difficult to quantify water and energy consumption of unit calorific or nutritive values of various crops, which makes establish corresponding constraints in STFIP-WEFN model into a dilemma.

Place Figure 8 here

4.3 Optimized solution of fertilizer and pesticides

Fertilizer not only protects the crop production but also damages the environment (e.g., the emission of nitrogen, phosphorus). Figure 9 shows the allocated proportion of total fertilizer consumption during the entire planning horizon. It could be clearly seen that wheat took up the primary position of fertilizer consumption. The ratio of fertilizers using for wheat would be [35.07, 35.76] % under S1 while it would increase to [36.45, 36.67] % under S4. Results implied that planting wheat would not take advantages under the restriction of environmental pollution when available water amount was sufficient. Under the same environmental capacity limitation, wheat would gain less benefits compared to others crops such as rice and beans; while the status would be improved as the groundwater supply ratio raised. In comparison, the ratios of fertilizer using for oil-bearing crops would account for [5.62, 5.78] % (S1) and [5.42, 5.46] % (S4), respectively. Results revealed that the priority of cultivated crops would be changed by the environmental objectives. Therefore, decision makers should be apt to reduce the area of crops (e.g., cotton) with decreasing trend of consumption ratio. Although the vegetables had small cultivated areas, their fertilizer utilization would account for [21.59, 21.77] % (S1), [21.22, 21.96] % (S2), [21.38, 21.50] % (S3) and [21.31, 21.97] % (S4), respectively. Thus, efforts should be made to reduce the fertilizer consumption of vegetables, such as using farm manure and improving technical level.

Place Figure 9 here

Figure 10 shows the average amounts of pesticides consumption under different periods and scenarios. For example, the amount of pesticides using for oil-bearing crops in period 1 would be 1.55×10^6 kg under S1 and 1.74×10^6 kg under S3, and the corresponding values would respectively be 1.67×10^6 kg under S1 and 1.64×10^6 kg under S3 in period 2. Results implied that the pesticide consumption for oil-bearing crops might be sensitive to the variations of supplying water (i.e. surface water or groundwater) whatever they would raise or reduce. Comparably, the amount of pesticides using for fruits would change a little even under different scenarios owing to its high economic and ecological benefits.

Place Figure 10 here

4.4 Comparing among optimization methods and scenarios

Figure 11 presents the compared results of diverse water allocations (i.e. surface water and groundwater) and system benefits among linear programming (LP), interval parameter programming (IPP), interval-fuzzy linear programming (IFLP) and scenario-based type-2 fuzzy interval programming (STFIP) under scenario 2. In detail, during the entire planning horizon, the system benefits of LP, IPP, IFLP, STFIP would be 2.968×10^{12} RMB ¥, $[2.851, 3.337] \times 10^{12}$ RMB ¥, $[2.879, 3.435] \times 10^{12}$ RMB ¥ and $[2.861, 3.372] \times 10^{12}$ RMB ¥, respectively. Results showed that values obtained in STFIP are slightly more than that obtained in IPP, while less than IFLP. It is because IPP could merely handle the uncertainties existed in parameters with LB and UB, while incapable of reflecting the ambiguity of surface water availability, which would result in a defensive attitude towards its available amount. As shown in Figure 11b, the allocated surface water would be $[28.15, 36.28] \times 10^9$ m^3 (IPP), $[28.52, 37.48] \times 10^9$ m^3 (IFCP), $[28.29, 36.84] \times 10^9$ m^3 (STFIP) under scenario 2. IFLP can properly deal with its ambiguity, while it neglects to coordinate the contradictions resulted by multi-aspects and multi-constraints in WEFN system. The degree of satisfaction (λ) has been proposed in STFIP method which could measure the possibility to satisfy the objective and constraints. when the groundwater supply ratio reaches 45%, the lower and upper bound values of λ obtained from STFIP are 0.562 and 0.581, respectively, which means STFIP can not only effectively handle the vagueness of supply amount of surface water, but also coordinate the development of Henan Province among water, energy, and food as well as environment (Wang et al., 2016). Therefore, the STFIP method is superior to LP, IPP and IFLP methods, which can overcome limitations of above methods and effectively handle the uncertainties and complexities existed in real-word agricultural management system.

Place Figure 11 here

In this study, four scenarios were conducted to investigate the relationships among crops planting structure, system benefits and water supply structure. For instance, the total planting area of crops would raise from [0.789, 0.813] × 10^6 km^2 (S1) to [0.821, 0.863] × 10^6 km^2 (S4) under the entire planning horizon. Meanwhile, as shown in Figure10, the system benefits would be [2.846, 3.262] × 10^{12} RMB ¥ (S1) and [3.015, 3.499] × 10^{12} RMB ¥ (S4), respectively. Results implied that planting area of crops and system benefits would definitely raise with the increment of available water resources. In detail, as shown in Figure 7, the total allocated water resources would increase from 53.9 × 10^9 m^3 (S1) to 64.64 × 10^9 m^3 (S4) when the groundwater ratio changes from 40 % to 55 %. However, the allocated water resources in S4 would increase merely 0.63% compared with S3, because other factors (i.e., the allowable consumption of electricity, pesticide, fertilizer and available arable area) has limited the development of WEFN system. It could be concluded that high supply ratios of groundwater (i.e. more than 50 %) would result in higher benefit at the cost of environmental pollution and waste of water resources. Thus, it is advisable that surface water are considered as main source of agricultural irrigation in study area and groundwater having high quality should be used to guarantee human lives for the purpose of obtaining the greater overall socioeconomic benefits. Meanwhile, decision makers also should attached great importance to transform water supply network and improve water-saving irrigation technologies.

5. Conclusions

In this study, a STFIP method has been developed to optimize agricultural WEF and crop area allocation with the formulation of STFIP-WEFN model for Henan Province, China. Multiple strategies have been obtained for crops planting structure, fertilizer consumption, pesticides consumption, water resources allocation, electricity distribution, crops production and system benefit under consideration ofvarious scenarios and multiple uncertainties, which can provide useful suggestions to decision makers. Results of optimal land allocation showed a reduction in corn, beans, cotton while an increase in wheat, tubers and fruits due to the differences consumption quotas of productive resources among various crops. Under the optimal land and WEF resources allocation, the contradiction among limited supply capacity and increased resource demands as well as agricultural non-point source pollution can be alleviated, which in turn relieve the overexploitation of groundwater and support the development of " Green Agriculture". Besides, uncertainty analysis of model parameters indicates that variation of water supply structure, market price fluctuations of crop production and changes of resources' availability would generate prominent impacts on agricultural system benefits. Agricultural managers and policy makers are advised to take control measures for maintaining the stability of agricultural product market, establishing high-efficiency resource allocation system and gradually giving dominant status to surface water in agricultural irrigation. However, the high degree uncertainty of available amount for surface water would increase the risk of water shortage for agriculture and food shortage for other sectors. Thus, in order to realize the continuous supply of surface water for agriculture, scientists would strengthen the planning for control and scheduling projects which can adjust the surface water from both spatial and temporal dimension. In addition, the STFIP-WEFN model merely considers one single-level or one target (i.e. maximizing the system benefit), and it neglects the conflicts among different objectives or different decision hierarchies, leading to the difficulties in achieving the feedback and coordination among different decision makers. Thus, the multi-objective programming (MOP) or multi-level programming (MLP) approaches shall be considered in further studies. Moreover, different calorific values or nutritive values of crops would result in great differences of resource consumption, thus calories and energy equivalent should be considered to further improve the practicality of STFIP-WEFN model.

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Table 1. Consumption of agricultural production conditions

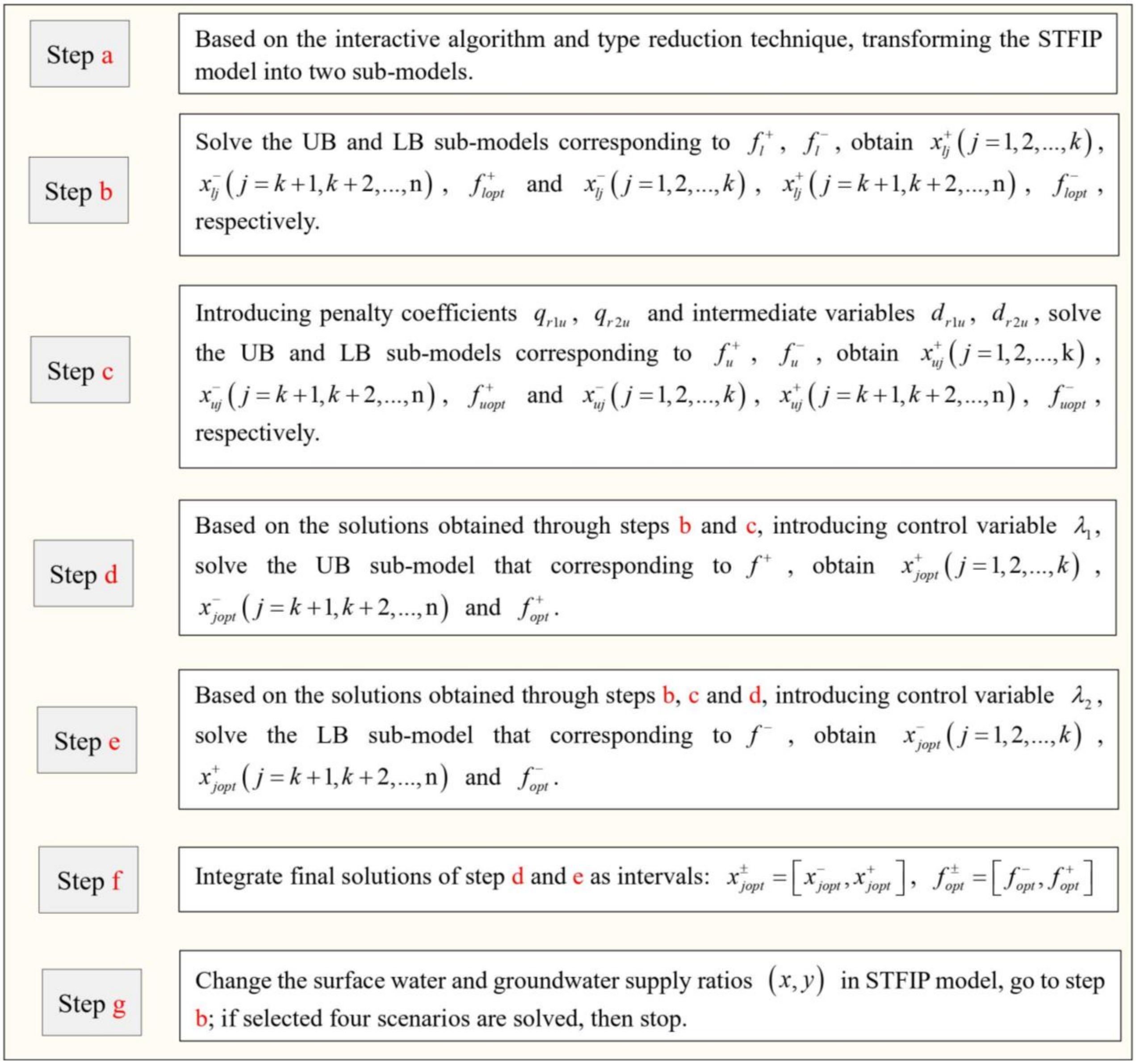
	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Consumption of chemical fertilizer by 100％ effective component (10^9 kg)	5.40	5.70	6.02	6.29	6.55	6.74	6.84	6.96	7.06	7.16	7.15	7.07
Electricity consumption in rural areas (10^9 kWh)	18.88	22.34	23.74	25.78	26.94	28.18	29.00	30.54	31.32	32.10	31.72	32.88
Consumption of pesticides (10^6 kg)	111.6	118	119.1	121.4	124.9	128.7	128.3	130.1	129.9	128.7	127.1	120.7
Plastic film used for agriculture (10^6 kg)	118.4	126.6	130.7	141.4	147.0	151.6	155.2	167.8	163.5	162.0	163.1	157.3

Table 2. Historical data of water resources (10^9 m^3)

	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Total supply amount of surface water	9.01	8.34	9.27	9.43	8.86	9.69	10.05	10.11	8.86	10.06	10.50	11.31
Total supply amount of groundwater	13.65	12.55	13.44	13.90	13.51	13.13	13.72	13.88	11.94	12.07	11.98	11.55
Total water consumption	22.70	20.93	22.75	23.37	22.46	22.91	23.86	24.06	20.93	22.28	22.76	23.38
Irrigated water supply	14.02	12.01	13.35	13.81	12.56	12.46	13.55	14.16	11.76	12.59	12.56	12.28

Table 3. Maximum planting area of crops during planning periods (10^3 km^2)

Crops	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
Rice	[6.56, 6.95]	[6.36, 6.74]	[6.31, 6.69]	[6.25, 6.62]	[6.19,6.56]	[6.14, 6.51]
Wheat	[54.26, 57.51]	[54.30, 57.56]	[54.32, 57.58]	[54.35, 57.61]	[54.37, 57.64]	[54.41, 57.67]
Corn	[33.44, 35.44]	[33.11, 35.10]	[32.92, 34.89]	[32.73, 34.69]	[32.48, 34.43]	[32.31, 34.24]
Beans	[4.14, 4.38]	[4.12, 4.37]	[4.08, 4.32]	[4.04, 4.28]	[4.00, 4.24]	[3.96, 4.19]
Tubers	[3.54, 3.76]	[3.51, 3.72]	[3.45, 3.65]	[3.42, 3.62]	[3.40, 3.60]	[3.34, 3.54]
Oil-bearing	[16.01, 16.97]	[16.04, 17.01]	[16.10, 17.06]	[16.13, 17.10]	[16.15, 17.13]	[16.17, 17.15]
Cotton	[1.20, 1.27]	[1.15, 1.22]	[1.11, 1.18]	[1.08, 1.15]	[1.04, 1.11]	[0.99, 1.05]
Vegetables	[17.52, 18.57]	[17.61, 18.67]	[17.71, 18.77]	[17.79, 18.85]	[17.80, 18.87]	[17.83, 18.89]
Fruits	[3.45, 3.65]	[3.50, 3.71]	[3.53, 3.74]	[3.58, 3.79]	[3.60, 3.81]	[3.60, 3.82]



Step a

Based on the interactive algorithm and type reduction technique, transforming the STFIP model into two sub-models.

Step b

Solve the UB and LB sub-models corresponding to f_l^+, f_l^-, obtain $x_{lj}^+\left(j=1,2,...,k\right)$, $x_{lj}^-\left(j=k+1,k+2,...,\mathrm{n}\right)$, f_{lopt}^+ and $x_{lj}^-\left(j=1,2,...,k\right)$, $x_{lj}^+\left(j=k+1,k+2,...,\mathrm{n}\right)$, f_{lopt}^-, respectively.

Step c

Introducing penalty coefficients q_{r1u}, q_{r2u} and intermediate variables d_{r1u}, d_{r2u}, solve the UB and LB sub-models corresponding to f_u^+, f_u^-, obtain $x_{uj}^+\left(j=1,2,...,\mathrm{k}\right)$, $x_{uj}^-\left(j=k+1,k+2,...,\mathrm{n}\right)$, f_{uopt}^+ and $x_{uj}^-\left(j=1,2,...,k\right)$, $x_{uj}^+\left(j=k+1,k+2,...,\mathrm{n}\right)$, f_{uopt}^-, respectively.

Step d

Based on the solutions obtained through steps b and c, introducing control variable λ_1, solve the UB sub-model that corresponding to f^+, obtain $x_{jopt}^+\left(j=1,2,...,k\right)$, $x_{jopt}^-\left(j=k+1,k+2,...,\mathrm{n}\right)$ and f_{opt}^+.

Step e

Based on the solutions obtained through steps b, c and d, introducing control variable λ_2, solve the LB sub-model that corresponding to f^-, obtain $x_{jopt}^-\left(j=1,2,...,k\right)$, $x_{jopt}^+\left(j=k+1,k+2,...,\mathrm{n}\right)$ and f_{opt}^-.

Step f

Integrate final solutions of step d and e as intervals: $x_{jopt}^\pm=\left[x_{jopt}^-,x_{jopt}^+\right]$, $f_{opt}^\pm=\left[f_{opt}^-,f_{opt}^+\right]$

Step g

Change the surface water and groundwater supply ratios $\left(x,y\right)$ in STFIP model, go to step b; if selected four scenarios are solved, then stop.

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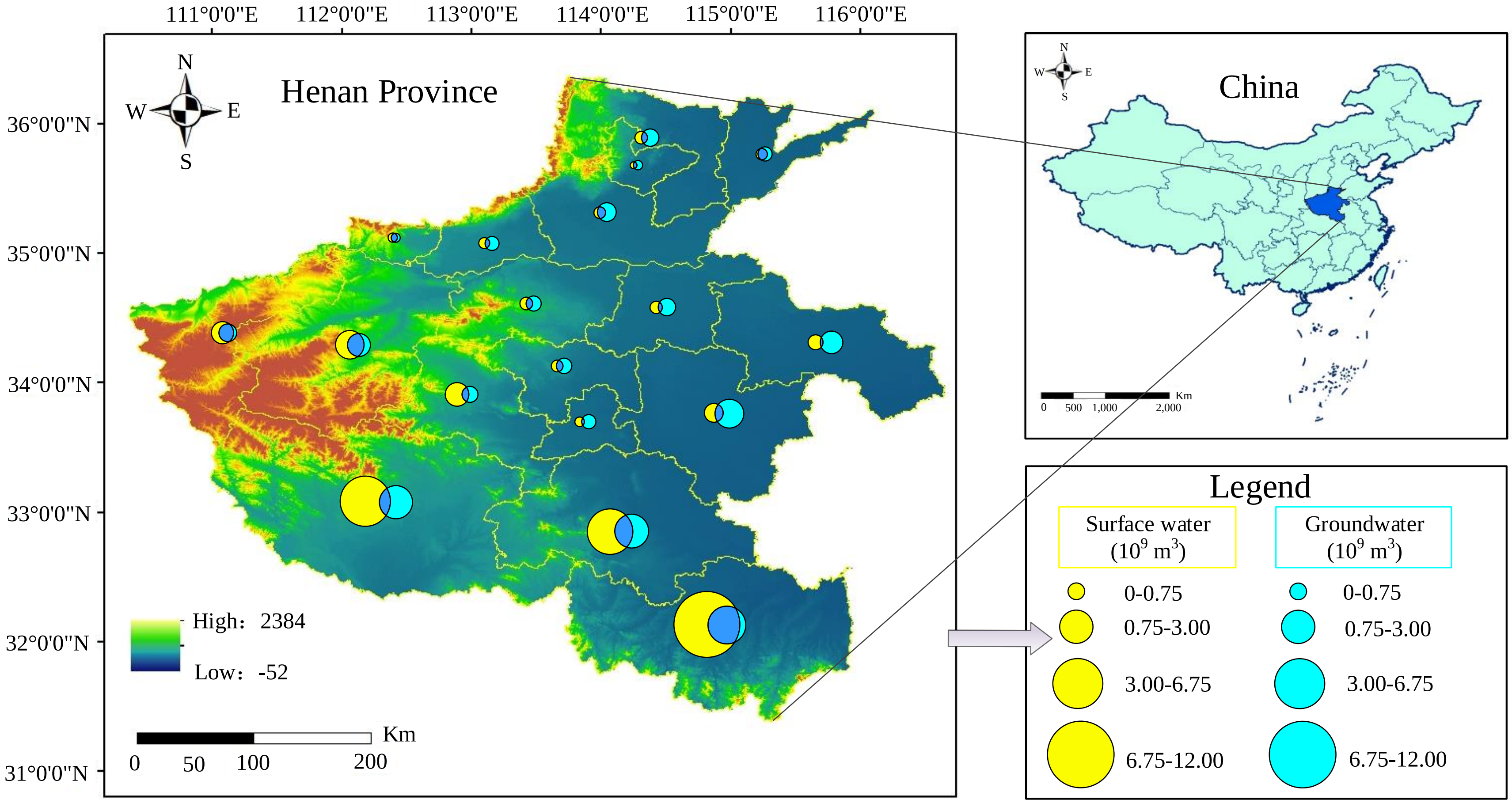

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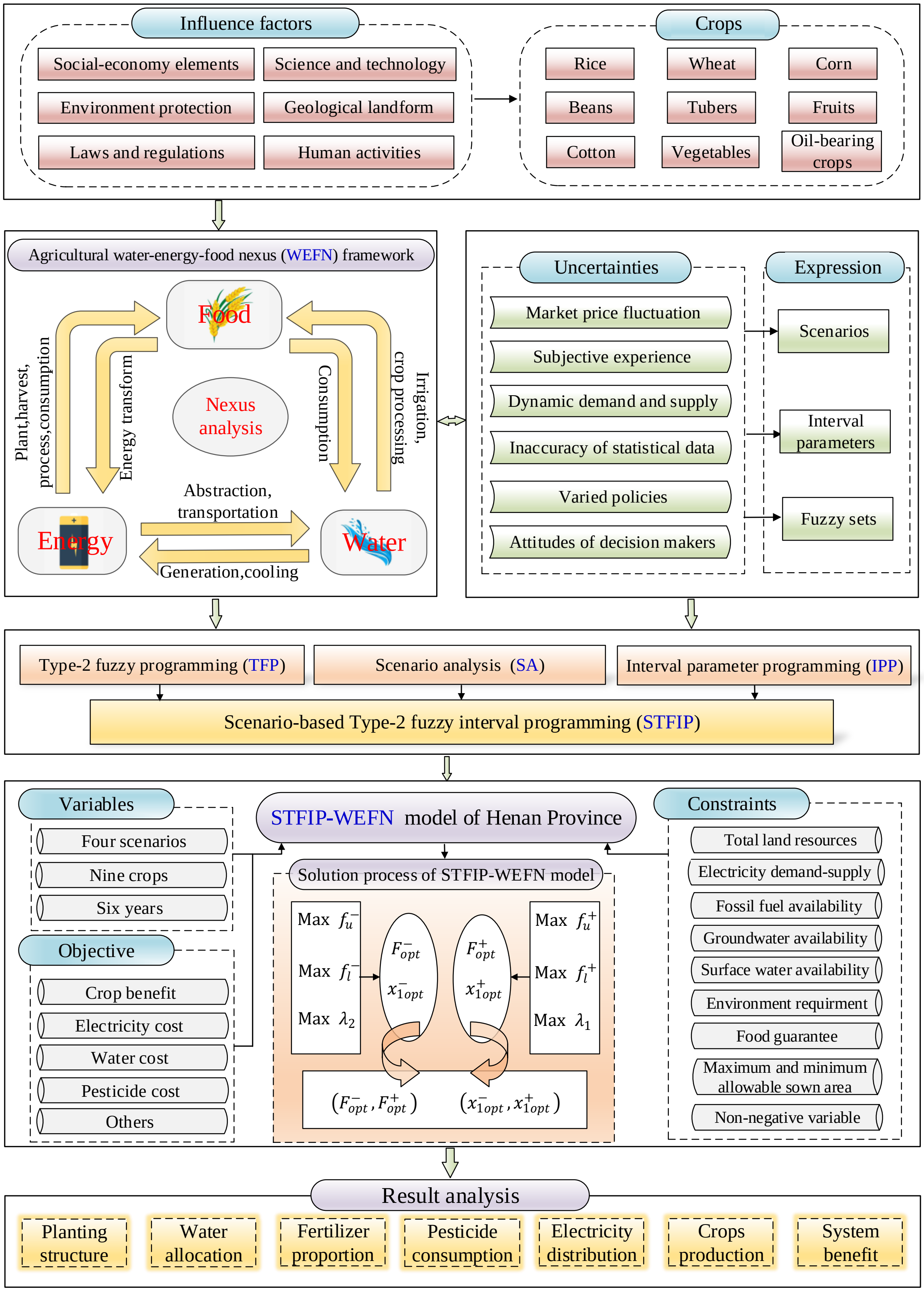

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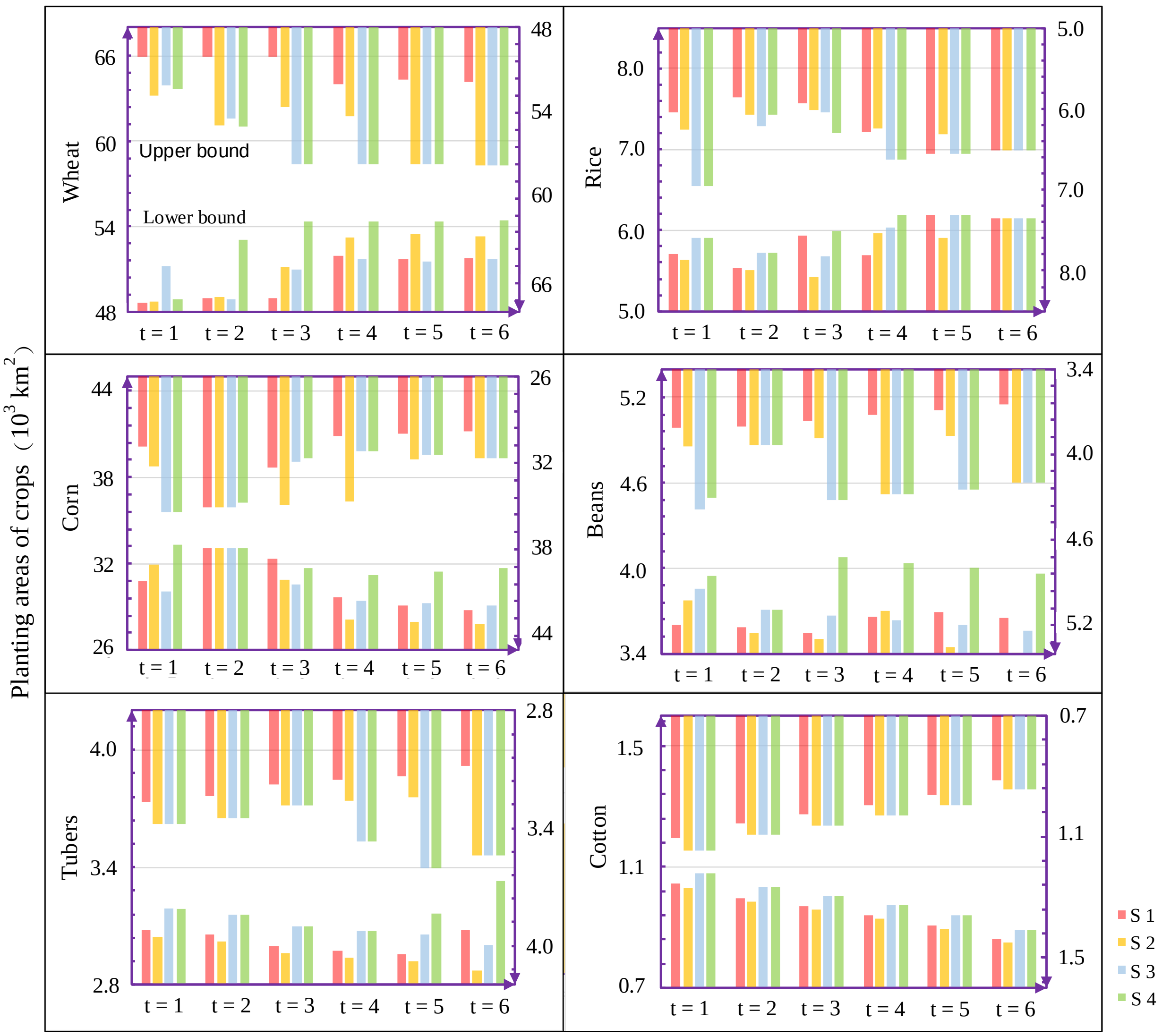

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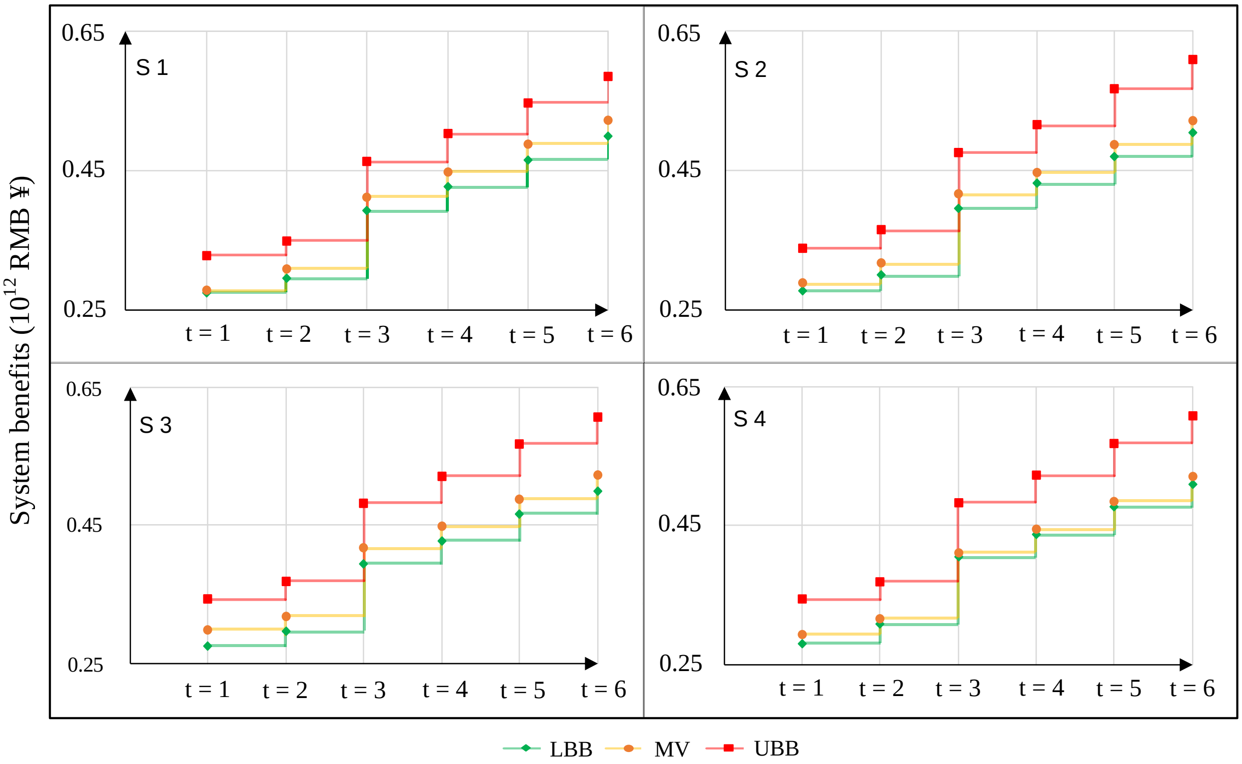

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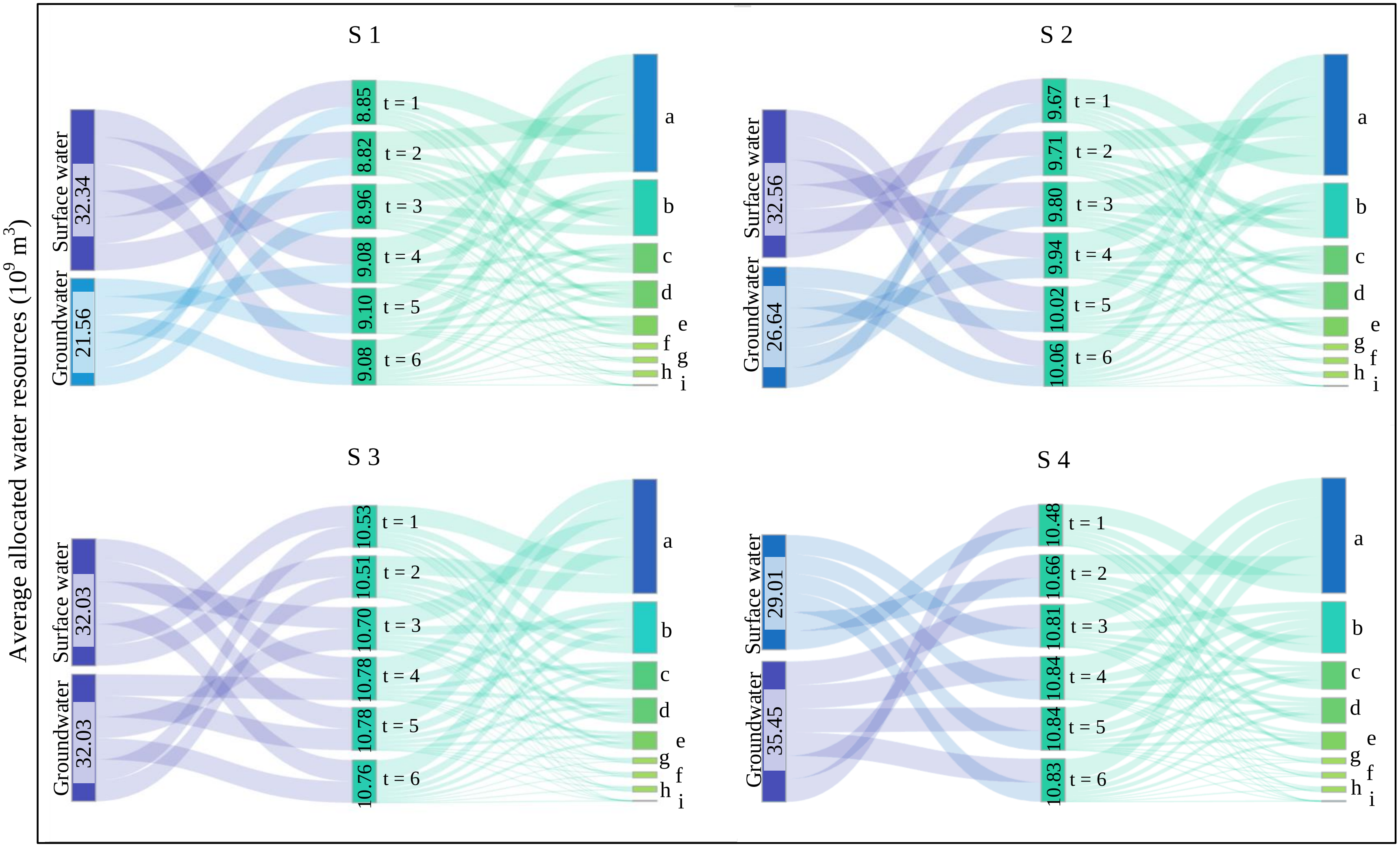

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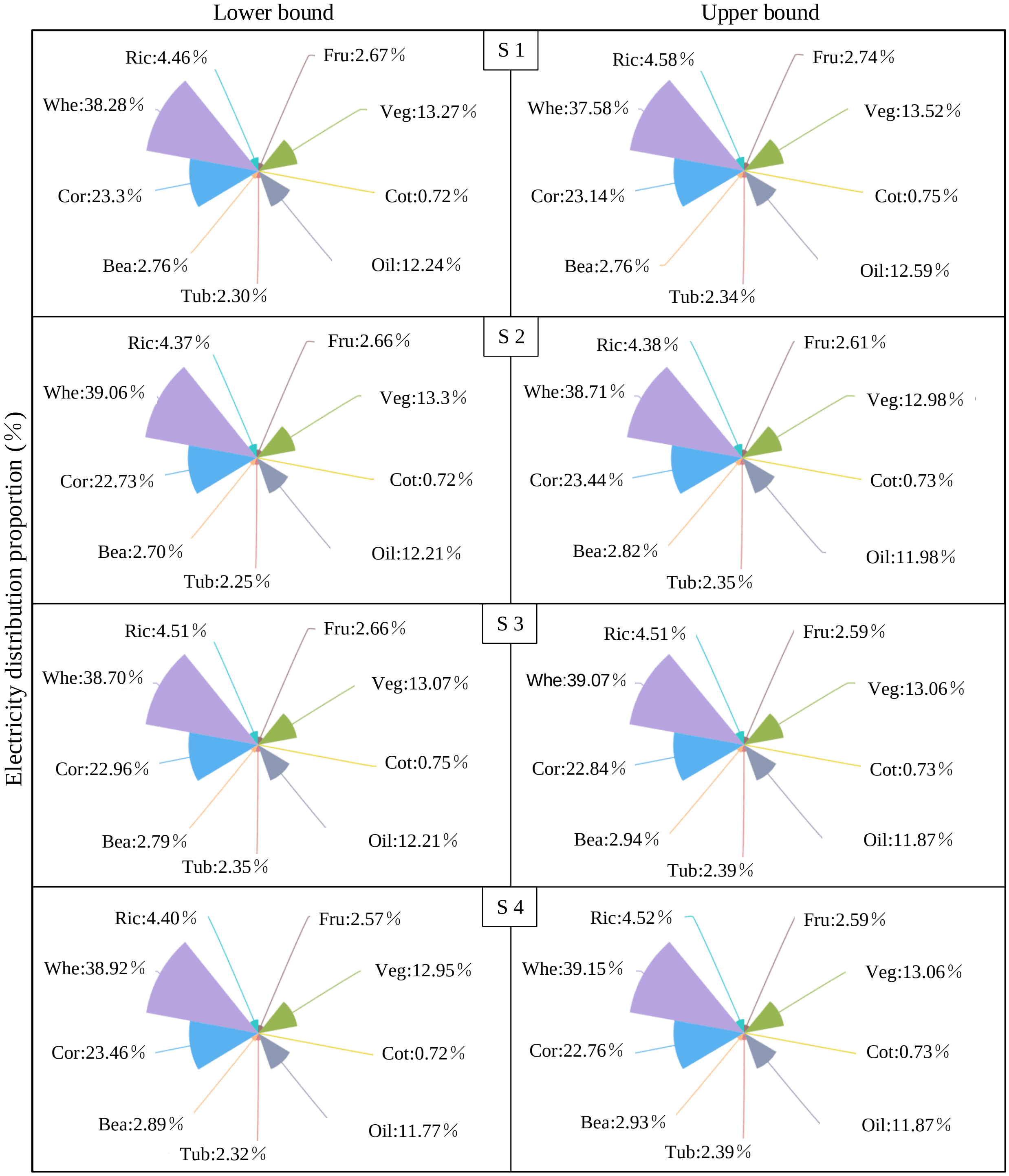

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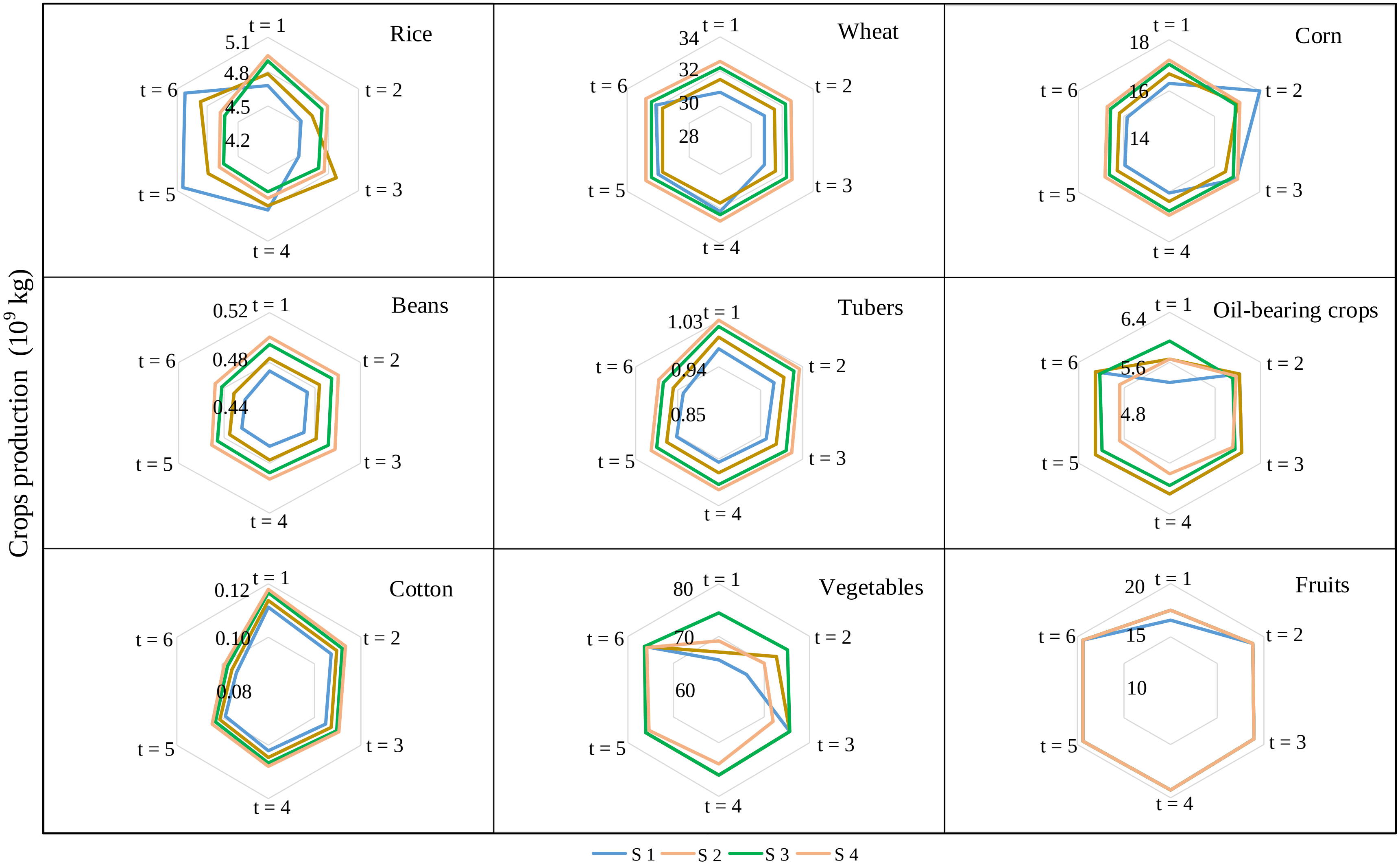

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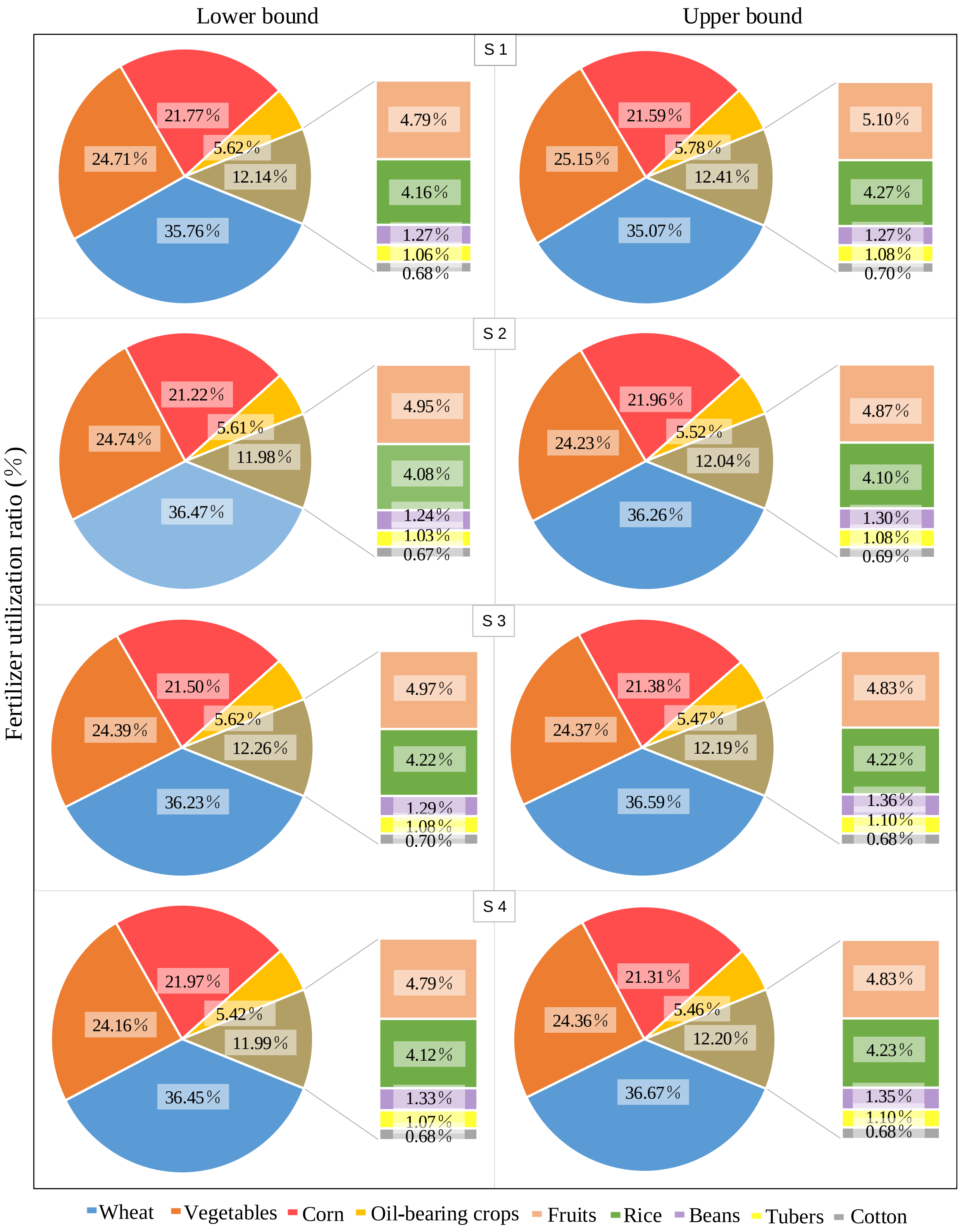
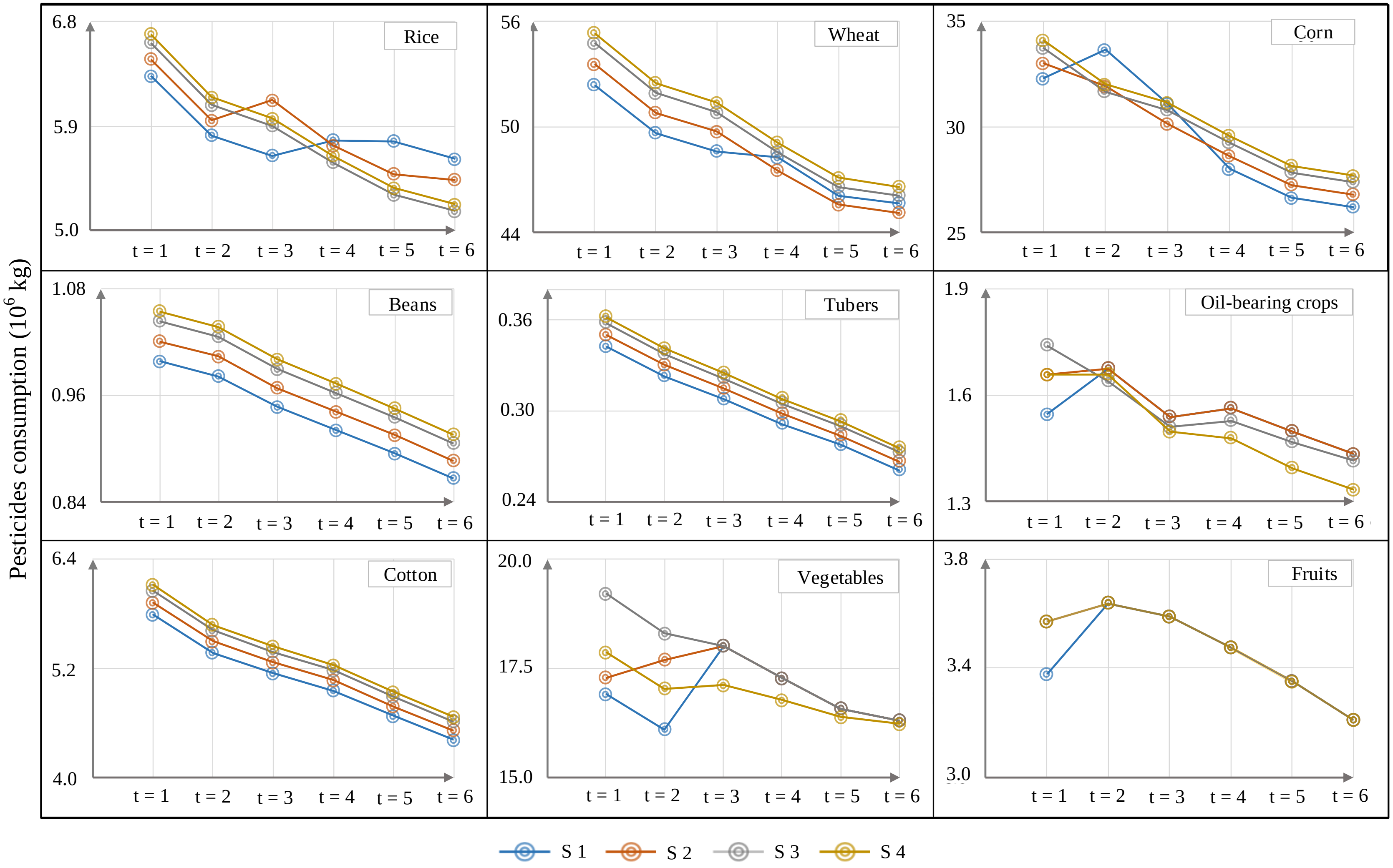


Figure 9. Fertilizer utilization ratio of nine crops throughout the planning periods under various scenarios in Henan Province



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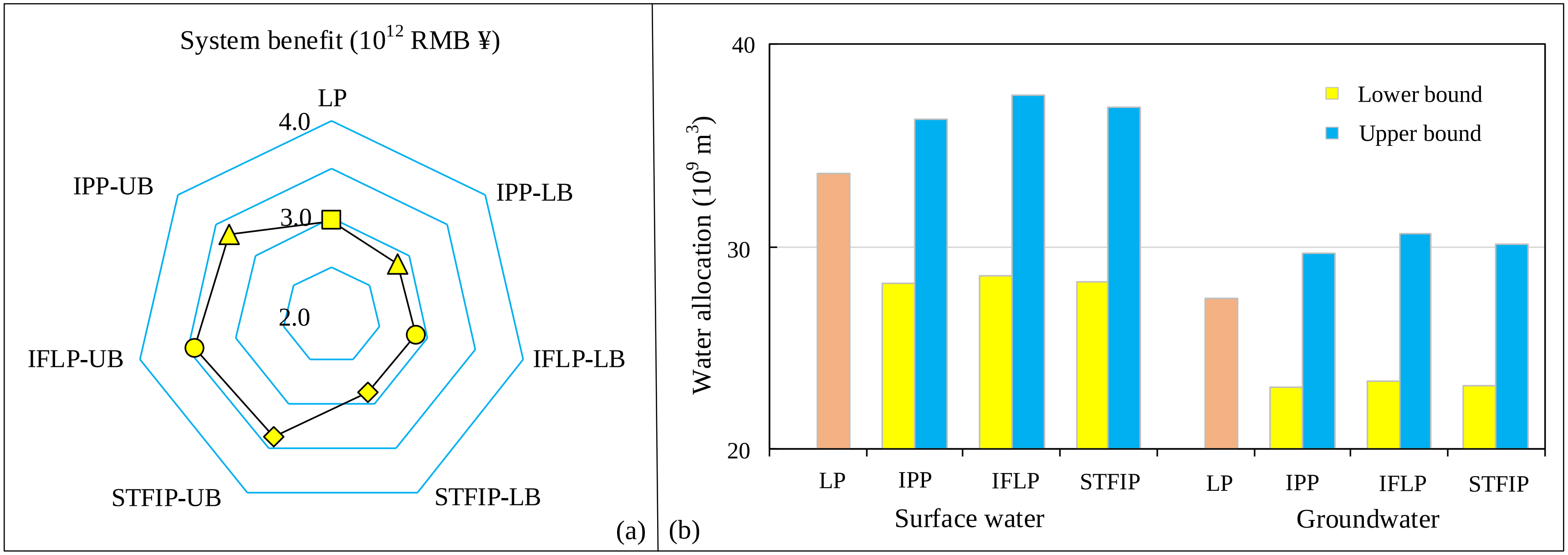

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