

Article

Multi-Objective Crop Planting Structure Optimisation Based on Game Theory

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Abstract: To realise the ecological protection and high-quality development of the Yellow River Basin and transition from extensive utilisation to intensive conservation of agricultural water, a multi-objective crop planting structure optimisation model was established. The model enabled highly efficient crop planting in terms of net income with high yield and low consumption of water. Thereafter, the game algorithm was used to balance different requirements of each objective function under each constraint, both competitively and cooperatively, to obtain an optimal crop planting structure. Finally, the proposed model and analysis method were demonstrated and verified using the Xiaolangdi south bank irrigation area as an example. The results indicated that using the competitive game algorithm produced a superior crop planting structure in terms of high net income, high yield, and low water usage, suggesting that the relationships between game players and objective functions should be considered in designing the optimisation model. Thus, the proposed approach provides a theoretical basis for the sustainable development of the agricultural industry by realising the intensive utilisation of water resources in a particular irrigation area.

Keywords: intensive utilisation of water resources; game algorithm; crop planting structure; multi-objective optimisation



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1. Introduction

Water scarcity is a common global issue owing to rapid population growth and accelerating economic development. In particular, it is an urgent problem in agricultural countries. China is one among many countries with severe water shortage issues, and agriculture is a major water consumer. Notably, agriculture in the Yellow River basin guarantees national ecological security and regional food security.

The efficient, economic, and intensive utilisation of water resources in the Yellow River basin requires rational planning of population, urban, and industrial development. Such planning is necessary to develop water-saving industries and technologies, promote agricultural water conservation, and transform the utilisation of water resources from the extensive mode to the economical and intensive mode [1]. From 1956 to 2000, the average quantity of water resources in the Yellow River water supply area of Henan province was 19.198 billion m³; the per capita consumption of water was only 275 m³; and the average consumption of water by cultivated land was 4185 m³/hm², only 13.7% of the national average during this period. Therefore, the problem of insufficient water resources was prominent [2]. Within the Yellow River basin, agriculture is a large consumer of water resources, accounting for 55% of all water consumption. In particular, the 52 large and medium-sized irrigation areas fed by the Yellow River have not yet been modernised, the benefits of water resource irrigation have not been fully realised, and the water conservation

transformation has yet to be fully implemented [3]. To achieve high-quality development, conservation, and intensive utilisation of water resources in harmony with agricultural development in the Yellow River basin, it is necessary to consider factors such as social and economic development and ecological protection, optimisation of crop planting structure, development of a system for the reasonable allocation of limited water resources, and optimal allocation of limited water and soil resources among different crops to obtain the most comprehensive benefits.

Various technologies have been used to realise agricultural water conservation, including water-saving irrigation techniques [4], crop breeding [5], soil management [6], and crop planting structure optimisation (CPSO) [7]. Currently, CPSO methods are mostly multi-objective optimisation models, which are marked by their simultaneous consideration of economic, social, and ecological objectives and constraints to determine an optimal crop planting structure. Pearson and McRoberts [8] used linear programming to conduct a multi-objective optimisation of crop production in Germany based on trade balance maximisation, self-sufficiency, and virtual water footprint minimisation objectives. Qian [7] conducted a multi-objective fuzzy-robust programming method to obtain the optimal use of land and water resources in agriculture. However, major challenges remain when conducting the multi-objective planning of water resources in agricultural systems. In the CPSO of an irrigation area, the demand imposed by each objective on the crop planting area is different. For example, the water conservation objective imposes a higher demand for crops with smaller irrigation quotas, whereas meeting the economic objective requires more high-yield crops. Therefore, the process of meeting each target objective involves balancing various conflicting interests.

Generally, the multi-objective model is often transformed into a single objective model to find a solution. The transformation methods include the objective weight method, entropy weight coefficient method, and fuzzy optimisation method. However, selection of the weight coefficient or preference function of each objective is subjective and more empirical.

New multi-objective optimisation methods have been proposed to overcome this problem, including optimisation based on multi-objective particle swarm optimisation algorithm [9] and ant colony algorithm [10]. However, these methods must solve many number of Pareto non-inferior solutions with numerous calculations and slow convergence and the problem worsens with the increase of optimisation objectives and variables.

In recent years, game theory has been applied to solve multi-objective optimisation problems because it is similar to multi-objective optimisation design. B Zhang applied game theory to highlight the problem of water in the Heihe River basin [11]. Based on the game theory, Zhang introduced both external driving forces and internal equilibrium measures to explore a cooperation mechanism to mitigate the conflicts and encourage cooperation between upstream and downstream regions [12]. Currently, this method is mostly aimed at water resource management in water resource systems, and research on its application to CPSO is limited.

From this perspective, a multi-objective CPSO model of the Yellow River irrigation area was established in this study based on the intensive utilisation of water resources; the model was then solved using the game algorithm [13,14], considering cooperation or competition among the different demands of the target objectives, thereby obtaining an optimal strategy for crop planting in the irrigation area. To solve the model, each target is considered a game participant. The multi-objective model is standardised and multiplied to be solved as a cooperative game model. For a competitive game, the variable set is decomposed into the strategy set of each player. Each game player aims to maximise their benefit; thus, they combine the optimisation goals of the crop planting structure to find an optimum solution in their strategy set, form a round of game strategy combinations from all the optimisation results, and obtain the equilibrium solution through multiple rounds of games. Finally, the optimal strategy of the crop planting structure in the irrigation area is obtained by comparison.

2. CPSO Model Based on Intensive Utilisation of Water Resources

The concept of intensive utilisation of water resources represents an economic evaluation in which, by considering a relatively unchanged level of production technology, adjusting water resource use efficiency or reorganising factors to reduce the input cost, income can be increased relative to the utilised water resources [15]. Considering the water demand in and agricultural output of the irrigation area, the intensive use of water resources within the irrigation area can be reflected by three objectives: high efficiency, high output, and low consumption. A multi-objective optimisation model was accordingly established considering the net income generated by the crops grown in the irrigation area as the high-efficiency objective, the crop yield as the high output objective, and the irrigation water consumption as the low consumption objective. The crop planting area X_{Maj} was the decision variable.

2.1. Objective Functions

2.1.1. High-Efficiency Objective

The high-efficiency objective is defined to reflect the efficient use of agricultural water in the irrigation area and can be captured by the net income generated by the crops, which includes the degree of resource utilisation and production efficiency as follows:

$$\max f_1 = \sum_{j=1}^n X_{Maj} \times Y_j \times P_j, \quad (1)$$

where Y_j is the yield per hectare of crop j , P_j is the net income generated by crop j , and n is the total number of different crops.

2.1.2. High Output Objective

The high output objective is defined as the maximisation of the total crop output, which can be calculated as follows:

$$\max f_2 = \sum_{j=1}^n X_{Maj} \times Y_j, \quad (2)$$

2.1.3. Low Consumption Objective

The low consumption objective is defined as the minimisation of water consumed by crop irrigation and is expressed as follows:

$$\max f_3 = \sum_{j=1}^n X_{Maj} \times IQ_j, \quad (3)$$

where IQ_j is the irrigation quota for crop j .

2.2. Constraint Conditions

The planting industry is restricted by both natural and social conditions. Comprehensively considering the agricultural and water supply planning in the irrigation area, the crop planting constraints comprise the crop planting proportion, irrigation area, strictest restriction of the water resources management system, and non-negative constraints.

2.2.1. Crop Planting Proportion Constraint

The overall planting area is limited by regional land planning. The protection of cultivated land and basic farmland is determined by adhering to the strictest cultivated land protection system using the following constraint:

$$p_{j\max} \leq \sum_{j=1}^n X_{Maj} / X_{MA} \leq p_{j\min}, \quad (4)$$

where X_{MA} is the total area of cultivated land, $p_{j\min}$ is the planning-allowed minimum crop planting ratio, and $p_{j\max}$ is the planning-allowed maximum crop planting ratio.

2.2.2. Irrigation Area Constraint

The total planting area of crops shall not exceed the arable land; the constraint is as follows:

$$\frac{\sum_{j=1}^n X_{Maj}}{I_{mc}} \leq A_g, \quad (5)$$

where I_{mc} is the multiple cropping index in irrigation area, and A_g is the maximum available irrigation area.

2.2.3. Strictest Restriction of the Water Resources Management System

The water available for irrigation in the irrigation area must be less than the planned water supply from each water source in the irrigation area as follows:

$$\sum_{i=1}^n X_{Maj} \times IQ_j \leq Q_A, \quad (6)$$

where Q_A is the total planned water supply for irrigation.

2.3. Multi-Objective Optimisation Solution Based on the Game Algorithm

Game theory represents a process of balancing multiple objectives to obtain an optimal solution through a game-based strategy and has considerable advantages in multi-objective and standard optimisation decision-making processes [14]. Because the high efficiency, high output, and low consumption objectives are contradictory in the multi-objective CPSO model developed in this study, the game algorithm is well-suited to obtaining an optimal balance among them. There are three elements in the game algorithm: the decision maker, strategy set, and benefit function. For transformation of the multi-objective model into a game model $G = \{P, S, F\}$, the decision maker is $i \in P$, $P = (1, 2, 3)$, the policy set for each decision maker is $S = (s_1, s_2, s_3)$, and the profit function of the decision maker is $F = (f_1, f_2, f_3)$. When solving for the desired goal, cooperative and competitive games are used to solve the problem. The key to transforming the multi-objective model into a game is to divide the variable set into the strategy set owned by the game player, and the process is as follows:

1. According to the multi-objective CPSO model, a single objective optimisation of each of three objectives is conducted, and the optimisation values $f_1(X_1^*)$, $f_2(X_2^*)$, $f_3(X_3^*)$ are obtained for each single objective function.
2. The single objective functions of the CPSO model are divided into game parties, each of which strives to optimise its objective through competition. Considering the different objective targets, each objective function is processed into a dimensionless function as follows:

$$u_i = \frac{f_i(x) - f_i(x^*)}{f_i^+(x) - f_i^-(x^*)} \quad (7a)$$

$$u_i = \frac{f_i(x^*) - f_i(x)}{f_i^+(x) - f_i^-(x^*)} \quad (7b)$$

3. If the decision maker considers the decision as a cooperative game, the multi-objective model is transformed into the income function for a cooperative game by

$$F(x) = \prod_{i=1}^k u_i \quad (8)$$

where k is the number of objects.

If the decision maker assumes the decision as a comparative game, the priority of each player is determined, and then the initial policy set is obtained according to the objective function.

- For any design variable x_k , the definition domain is divided into n segments according to the step length Δx_k . The influence factor Δ_{ji} of the variable x_k on game $f_i(x)$ can be expressed as

$$\Delta_{ji} = \frac{\sum_{t=1}^T |f_i(x_{1x}^*, \dots, x_{ji}(t), \dots, x_{ni}^*) - f_i(x_{1x}^*, \dots, x_{ji}(t-1), \dots, x_{ni}^*)|}{T\Delta x_j} \tag{9}$$

- Defining $\Delta_j = (\Delta_{j1}, \Delta_{j1}, \dots, \Delta_{jk})$ as the set of influence factors of the j th variable on the k th objective function, the degree of similarity between influence factors can be determined according to the Euclidean distance as follows:

$$d_{pq} = \sqrt{\sum_{i=1}^k |\Delta_{pi} - \Delta_{qi}|^2}, \tag{10}$$

where p and q define the solution points between which the distances are measured, as in $1, 2, \dots, n$. Thereafter, similarity matrix D is established based on Equation (10) as follows:

$$D = \begin{pmatrix} d_{11} & d_{11} & \cdots & d_{1n} \\ d_{21} & d_{22} & \cdots & d_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ d_{n1} & d_{n2} & \cdots & d_{nn} \end{pmatrix} \tag{11}$$

- The similarity matrix D is fuzzy clustered to obtain the classification results of Δ . Because $\Delta = (\Delta_1, \Delta_2, \dots, \Delta_l)$ and the policy set $S = \{x_1, x_2, \dots, x_l\}$ correspond to each other, the clustering results of Δ are the same as those of S . The design variable strategy set S_1, S_2, \dots, S_k is obtained according to the clustering results and can be selected by each player according to the sum of their respective objectives and influencing factors.
- If the policy set S_i^* is the optimal policy set of the i th crop planting structure optimisation objective, take this strategy is taken as the initial strategy $S^{(0)}$ to find the optimal strategy of other objectives. The new strategy combination is expressed as $S^{(1)} = \{S_1^*, S_2^*, S_3^*\}$. It is then verified if the distance between two adjacent policy combinations $S^{(0)}$ and $S^{(1)}$ satisfies the inequality $\|S^{(1)} - S^{(0)}\| \leq \epsilon$, where ϵ is the game convergence criterion. If it meets the inequality criterion, the competitive game ends. Otherwise, it continues on the basis of $S^{(1)}$ until the optimal strategies of all the players are stable and satisfied, and the game equilibrium solution is obtained, that is, the optimal strategy of the competitive game for the optimisation problem.
- Comparing the optimal strategy of the cooperative game with that of the competitive game, the most suitable strategy is selected as the optimal strategy of the model.

3. Example Application

3.1. Introduction to the Evaluated Irrigation Area

The Xiaolangdi south bank irrigation area is located in the North Mangling of Luoyang city and represents an important commercial grain production base in Henan Province, adjacent to the Yellow River to the north and the Luohe River to the south. Limited by natural conditions, the Xiaolangdi south bank irrigation area experiences severe droughts and water shortages; annual precipitation is scarce, and the available surface water in the irrigation area is limited. The industrial, agricultural, and domestic water supply depends on the exploitation of groundwater and the Xiaolangdi Reservoir on the Yellow River. Therefore, intensive utilisation of water resources and maximum social and economic benefits must be urgently realised in this area.

According to [16], agriculture in the Xiaolangdi south bank irrigation area is devoted to grain production, followed by cash crops, and then the forestry and fruit industries. Grain crops include cereals (wheat, corn), beans, and sweet potatoes (autumn miscellaneous);

cash crops include oil (peanut, rape, sesame), cotton, vegetables, melons, tobacco leaves, medicinal materials, flowers, etc. As the planting area of each of such crops is relatively small, they are collectively referred to as cash crops in this study. In 2018, the total economic output of Xiaolangdi south bank irrigation area was 65.84 billion yuan; the controlled cultivated land area was 50,647 hm²; the designed irrigation area was 35,787 hm²; the multiple cropping index was 1.8; the total water supply of the irrigation area was 82.63 million m³; and the net water supply of surface water, groundwater, and Yellow River water were 9.16 million m³, 25.65 million m³, and 47.82 million m³, respectively.

3.2. Model Parameters

The four main crop types—wheat (x_1), corn (x_2), autumn miscellaneous (x_3), and cash crops (x_4)—were considered as the decision variables in this study; the total planned irrigation water volume included surface water, groundwater, and Yellow River water. A multi-objective CPSO model was established using these parameters and optimised using the procedure provided in Section 2. The economic benefit is expressed by the income per unit area, and the social benefit is expressed by the output per unit area. The income per unit area and yield per unit area of wheat and maize are obtained from the Henan Statistical Yearbook and Henan Survey Yearbook. The income per unit area and yield per unit area of autumn miscellaneous and cash crops are weighted according to the planned planting area of the irrigation areas and calculated in combination with the Henan Statistical Yearbook and Henan Survey Yearbook. According to the irrigation area planning, the irrigation assurance rate is 50%. The irrigation quota of wheat and maize is obtained by selecting the irrigation quota of each crop in western Henan according to the local standard of Henan Province,—the 2020 agricultural and rural domestic water quota, and combining the autumn miscellaneous and cash crops with the proportion of crops in the irrigation area planning (Table 1).

Table 1. Parameters of the model.

Parameters	Wheat	Corn	Autumn Miscellaneous	Cash Crops
Net income (Yuan/hm ²)	18,158	16,004	10,200	16,628
Yield per hectare (kg/hm ²)	6053	5519	2250	3326
Irrigation quota (m ³ /hm ²)	1650	975	750	1425

As wheat and corn are the major commercial grains in the Xiaolangdi south bank irrigation area, the irrigation area development plan states that the planting proportions of wheat, corn, autumn miscellaneous, and cash crops in the irrigation area shall not be less than 0.7, 0.4, 0.2, and 0.05, respectively, and shall not be greater than 0.9, 0.7, 0.4, and 0.2, respectively. Therefore, the design planting ratio for these crops was set as 0.8, 0.6, 0.3, and 0.1, respectively. Meanwhile, the total irrigation area of crops in the irrigation area was set to 35,787 hm², and the irrigation water was limited to 82.63 million m³.

3.3. Model Solution

According to the multi-objective model and constraints established in Section 2 and defined in Section 3.2, the game algorithm was applied to first calculate the single-objective optimisation values and their corresponding strategies. For the solution of the game model, the strategy set is initially “fuzzy clustered”; that is, from the perspective of cluster analysis, $f_1(x)$ is entirely determined by (x_1, x_4) , $f_2(x)$ is determined by (x_1, x_2) , and $f_3(x)$ is determined by (x_2, x_3) . The income function of the game model can be defined according to the results of the strategy set division. Because the objective functions $f_1(x)$ and $f_2(x)$ are the maximisation objectives while $f_3(x)$ is the minimisation objective, Equation (7a) was

selected to evaluate $f_1(x)$ and $f_2(x)$, while Equation (7b) was selected to evaluate $f_3(x)$. Thus, the income function was defined for the cooperative game model as follows:

$$\max F(x) = \frac{f_1^+(x^*) - f_1(x)}{f_1^+(x) - f_1^-(x)} \cdot \frac{f_2^+(x^*) - f_2(x)}{f_2^+(x) - f_2^-(x)} \cdot \frac{f_3(x) - f_3^-(x^*)}{f_3^+(x) - f_3^-(x)}, \tag{12}$$

where $f_i^+(x)$ and $f_i^-(x)$ are the maximum and minimum values of the single objective targets, respectively, as defined in Table 2. The planting area of each crop in the single-objective optimisation strategy is shown in Figure 1. The minimum value of the objective function provided by Equation (12) was obtained by the game algorithm, and the result represents the optimal crop planting structure under the cooperative game, as shown in Table 3.

Table 2. Single objective optimisation value of CPSO model.

Objective Function	High Efficiency	High Output	Low Consumption
$f_1(x)(10^4 \text{ Yuan})$	105,280	105,872	100,177
$f_2(x)(10^4 \text{ kg})$	32,774	34,929	32,207
$f_3(x)(10^4 \text{ m}^3)$	8575	8294	7649

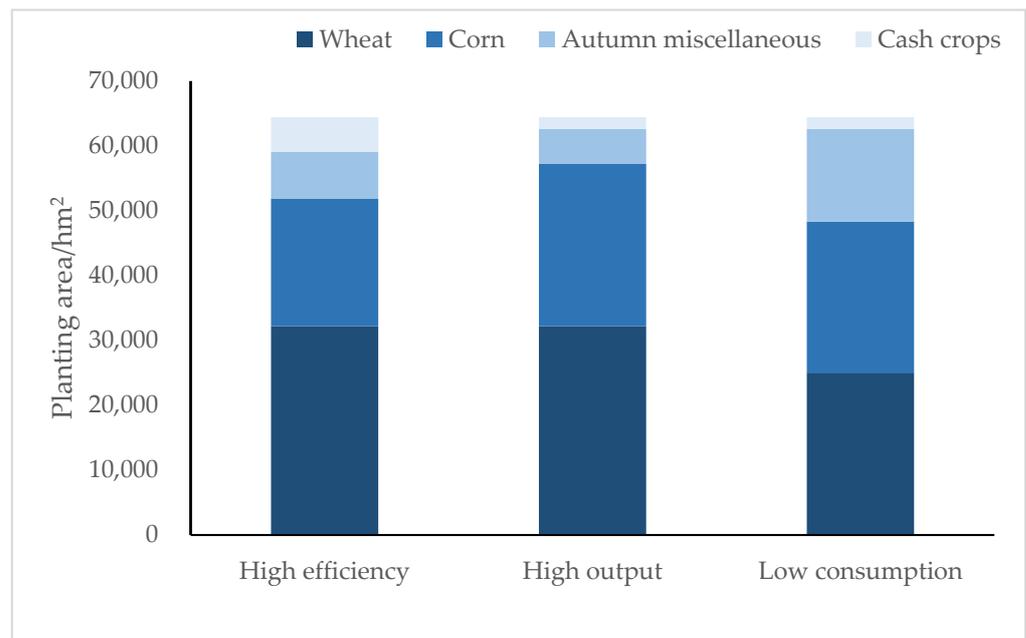


Figure 1. Individual optimal crop planting strategy according to each objective function.

To solve the competitive game, the optimisation value of $f_3(x_3)$ is considered as the known quantity, the single objective optimisation of $f_1(x)$ in the variable set $\{x_1, x_2, x_4\}$ is conducted, and the result represents the optimal scheme for the three variables except $\{x_3\}$. Similarly, only $\{x_1\}$ is used to optimise $f_1(x)$ and $f_2(x)$, and the result is the optimal decision-making scheme for $\{x_3\}$. The union of these two schemes represents the optimal decision scheme for all objective functions; the results are shown in Table 3, Figures 2 and 3.

Table 3. Optimisation results of crop planting obtained using different game mechanisms.

Game Mechanism	Crop Planting Area (hm ²)				Objective Function (hm ²)		
	Wheat	Corn	Autumn Miscellaneous	Cash Crops	High Efficiency (10 ⁴ Yuan)	High Output (10 ⁴ kg)	Low Consumption (10 ⁴ m ³)
Design value	28,629	21,472	10,736	3579	103,248	32,783	8133
Strategic value of cooperative game	25,051	17,893	14,315	7157	100,623	30,637	7971
Strategic value of competitive game	25,051	28,361	9215	1789	103,248	33,481	7845

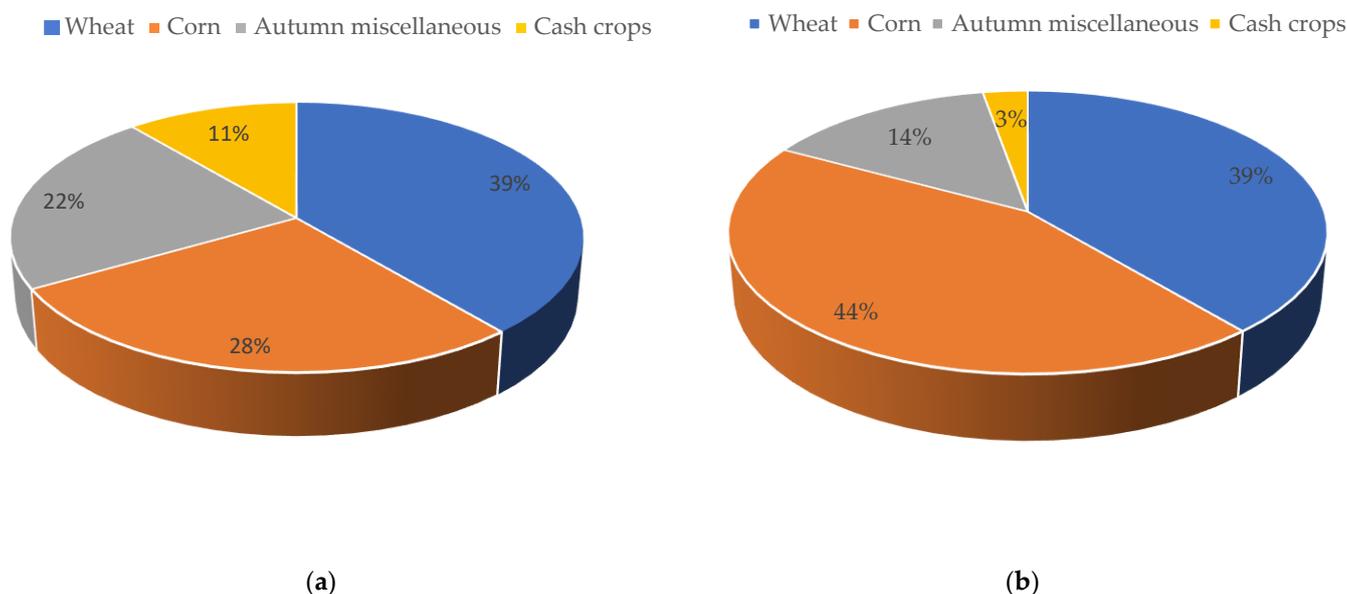


Figure 2. Comparison of optimised planting structures obtained under (a) cooperative and (b) competitive game mechanisms.

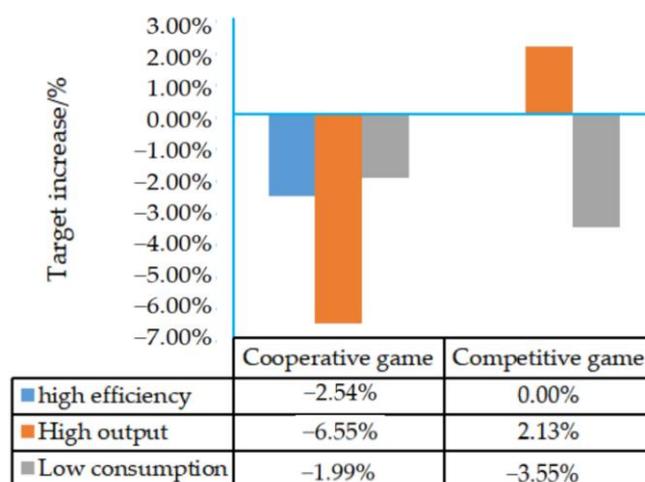


Figure 3. Target increase (%) obtained under cooperative and competitive game mechanisms according to the multi-objective optimisation.

The comparison between the cooperative and competitive game optimisation strategies in Table 3 and Figure 3 shows that, under the cooperative game optimisation strategy,

the planting areas of wheat and corn are reduced while the planting areas of autumn miscellaneous and cash crops are increased. Compared with the design planting ratio conditions, although the low consumption objective value was improved by reducing the irrigation water usage by 1.99%, the other two objective values were not: the net income generated by grain in the irrigation area decreased by 2.54%, and the total crop yield decreased by 6.55%. However, under the competitive game optimisation strategy, the planting areas of wheat, autumn miscellaneous, and cash crops were reduced, whereas that of corn was increased. The net income generated by grain remained unchanged, the total grain output increased by 2.13%, and the total irrigation water usage decreased by 3.55%. Thus, the obtained CPSO scheme provides increased income and output while reducing consumption, conforming with the principle of intensive utilisation of water resources in the irrigation area.

It can be observed from these results that the optimisation scheme obtained using a cooperative game mechanism differs from that obtained using a competitive game mechanism. In the process of solving multi-objective optimization, the objective functions restrict each other, and it is difficult to achieve all the target values in the optimal state. In the cooperative game, the object value increases at least one side for the whole value of the irrigation area to increase. However, in a competitive game, all player's actions are regarded as individual actions. To obtain the Nash equilibrium of planting structure, the priority of decision makers is considered. Thus, measuring how the players negotiate their decisions according to the objective function relationship during the modelling process is necessary to determine the appropriate game mechanism for CPSO planning.

4. Conclusions

The process of CPSO is complex because it should reflect the constraints of land and water resources as well as the characteristics of crop water demand law, market demand, and market positioning. Therefore, to realise intensive utilisation of water resources in an irrigation area, a multi-objective CPSO model was established considering high net income, high yield, and low water consumption as the objective functions, with the cultivated land area, most stringent water supply target of the water resources management system, and minimum planned planting area as the constraints. To account for the conflict between each objective when approaching its optimum value, the game algorithm was employed to determine the optimal crop planting model. Using the cooperative and competitive game mechanisms, the multi-objective optimisation problem was transformed into a strategy set to solve the game problem to obtain an optimal crop planting structure in an irrigation area. An example for the application of the proposed CPSO model demonstrated that, during the solution process, the strategy set obtained by the competitive game mechanism provided superior results to that obtained by the cooperative game mechanism, resulting in a more suitable model for the intensive utilisation of water resources by achieving high net income, high yield, and low water consumption of crops the irrigation area.

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