Research on Crop Planting Optimization Based on Linear Programming

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Abstract. In the face of challenges posed by population growth and climate change, modern agriculture urgently needs scientific optimization of cropping schemes to increase yields, reduce costs, and achieve efficient allocation of resources and stable economic benefits. This study proposes an optimized crop cultivation scheme for a rural village in North China in response to the challenges posed by population growth and climate change. By analyzing agricultural data for the year 2023 and considering a crop rotation system, this paper develops a model that maximizes profits while ensuring sustainable development. The optimization model contains 11 constraints and employs a weighted objective with 0.5 as the threshold value for the three objective groups. Under the stagnant sales scenario, the seven-year average profit increases by $1,631,900 compared to 2023, with an additional cost of $112,500. In the 50% price reduction scenario, profits increase by $1,376,100 and costs increase by $147,100. Using Monte Carlo simulation with 10,000 iterations to account for uncertainty in sales, acreage, costs, and prices, the most common scenario showed a seven-year average increase in profits of $1,240,900 and an increase in costs of $84,900. The proposed scenarios are highly adaptable and can be optimized according to the actual situation.

Keywords: Optimal planting strategy, multi-objective linear programming model, Monte Carlo simulation.

1. Introduction

With the continuous growth of the global population and the intensification of climate change, agricultural production is facing great challenges. How to increase crop yields and reduce production costs under limited land resources and environmental pressure has become one of the key issues in modern agricultural development. In order to meet this challenge, more and more research focuses on the efficient allocation of resources and maximization of output by optimizing planting schemes [1-4]. Traditional agricultural planting often relies on empirical decision-making and lacks scientific planning and data support, which not only easily leads to resource waste, but also may cause unstable economic benefits.

In recent years, with the continuous development of operations research and its related algorithms, linear programming, as an important mathematical optimization method [5-6], has gradually been widely used in the field of agriculture [7-8]. It mainly establishes mathematical models so as to help agricultural producers find the optimal crop planting combinations under certain constraints. In this study, linear programming is applied to crop planting optimization, and a model is constructed to guide the actual planting decisions in the countryside of North China, with a view to achieving the purpose of improving crop yields and agricultural economic benefits. At the same time, the planting ratio, area and crop rotation system of different crops were determined by model calculations considering factors such as soil type, climatic conditions, and crop growth cycle, in order to achieve profit-cost optimization [9-10]. In addition, Monte Carlo simulation was used to assess the robustness of the model [11], which predicts the range of fluctuations in crop yields and profits by simulating different production scenarios to forecast the expected returns and planting costs over the next seven years, and determines the optimal planting strategy accordingly.

2. Data Sources and Visualization

The data for this study were obtained from www.mcm.edu.cn, and in order to ensure the accuracy and reliability of the data, the data were subjected to a rigorous cleaning and pre-processing process, which included the removal of outliers, the filling of missing data, and the standardization of the data. First, the find function in MATLAB was used to find the missing values in the dataset, and no intuitively significant missing values were found. Since the data in the dataset may have different degrees of anomalies, and these outliers may adversely affect the subsequent analyses, a quasi-anomalous term set is used to pre-calculate the data corrections by borrowing the definition of box-and-line diagrams, and an algorithm for correcting the outliers similar to the nearest-neighbor interpolation algorithm is given to ensure the quality of outlier processing, and IQR is carried out on the attached data (interquartile range) outlier identification. The normal distribution interval is

$$[Q_1 - 1.5 \times IQR, Q_1 + 1.5 \times IQR] \tag{1}$$

After identification 10 outliers were found in mu yield and planting cost that were not applicable for normalization. Considering the statistical methods for outlier detection in multivariate data and the in-depth research in outlier analysis, and after reviewing the relevant yield and planting cost data, it was found that the outliers were reasonable in real life, so all the data were considered valid.

For the analysis of profits in 2023, it is assumed that the countryside is ideally planted with expectations that the total amount of output is approximately the same as the market demand, i.e., that the total production equals the total sales. Also the average selling unit price is taken as the selling unit price of the crop. After analyzing the data on unit price, cost, and sales volume, one can obtain the box line graph of unit price in Fig. 1. It is easy to see that for unit price, the unit price of edible mushrooms is the highest, while the unit price of grain is higher than the unit price of vegetables. For profit in 2023, crops such as grain, baby bok choy, cabbage, and elm mushrooms are highly profitable.

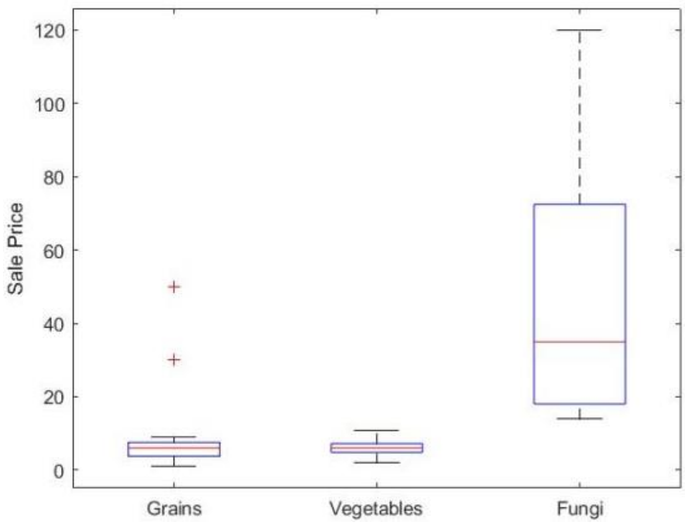

Figure 1. Unit sales price box plot

3. Optimal Planting Scheme Based on Linear Programming

3.1. General modeling

To facilitate the subsequent analysis, the plots were categorized by plot type and given numbers, as shown in Table 1.

Table 1. Terrain numbers

topographic	serial number
Flat drylands, terraces, hillsides	1,2,3...,26
wetland	27,28,...,34
greenhouse	35,36,...,50
intelligent greenhouse	51,...,54

It is assumed that the expected future sales volumes, planting costs, acreage, and sales prices for various crops will remain stable relative to 2023, i.e., using the data collected for 2023.

In order to explore the impact of various constraints on farmers' cultivation from multiple perspectives, two scenarios were set up in this study, where scenario 1 is the wastage of the stagnant portion and scenario 2 is the completion of the stagnant portion sold at half price.

The linear programming model used in this study is an important model in mathematical optimization, which is mainly used in the problems of optimal allocation of resources, minimization of costs and maximization of benefits. Thus, after data preprocessing, a linear programming model is established to synthesize two objective functions and constraints to solve the optimal planting scheme.

Selection of x_{ijtk} and z_{ijtk} as decision variables. where i Indicates parcel number, $i \in \{m,...,M\}$; j indicates crop number, $j \in \{n,...,N\}$; t indicates year of planting, $t \in \{0,1,...,7\}$ (2023~2030); k indicates the season of planting, imply

$$x_{ijtk} = \begin{cases} 1, & \text{If plot } i \text{ grows crop } j \text{ in season } k \text{ of year } t \\ & 0, \text{others} \end{cases} \tag{2}$$

Considering the optimal planting scheme, it is known through reviewing the literature that there are many objectives to formulate the optimal planting scheme, and should consider the market demand, planting cost, environmental protection, crop rotation system, planting mode, etc., and the objectives of maximizing profit and minimizing planting cost are selected here [5]. That is, the following objective function is derived.

$$MaximizeZ = \sum_{i=m}^{M}\sum_{j=n}^{N}\sum_{t=1}^{7}\sum_{k=1}^{T}(p_{ijtk}z_{ijtk}x_{ijtk}r_{ijtk} - c_{ijtk}z_{ijtk}x_{ijtk}) \tag{3}$$

$$MinimizeS = \sum_{i=m}^{M}\sum_{j=n}^{N}\sum_{t=1}^{7}\sum_{k=1}^{T}(c_{ijtk}z_{ijtk}x_{ijtk}r_{ijtk}) \tag{4}$$

Due to the large number of formula symbols in this study, they are first described here and are shown in Table 2.

Table 2. Description of symbols

symbols	Description
i	Parcel i, i ∈ {m, ..., M}
j	Crop j, j ∈ {n, ..., N}
t	Planted in year t, t ∈ {0, 1, ..., 7}
k	Planted in the k th season, k ∈ {0, 1}
α	Objective function coefficient weights
Xijtk	Plot i grows crop crop j in season k of year t,Xijtk ∈ {0, 1}
pijtk	Selling price of crop j in the kth season of the tth year of the i-th plot
zijtk	Area under crop j in season k of year t in plot i
rijtk	Unit yield of crop j in the kth season of the tth year in the i-th plot
cijtk	Unit cost of crop j in the kth season of the tth year of the i-th plot
Aj	Yield of crop j in 2023
Aij	Yield of crop j on plot i in 2023
Mjt	Yield of crop j in year t

By analyzing function 4, the following coefficient values were selected.

$$MaxF = \alpha Z - (1-\alpha)S, \alpha \in \{0.1, 0.2, ..., 0.9\} \quad (5)$$

α of 0.3 is biased towards the goal of minimizing planting costs and is suitable for farmers who wish to have a low-risk planting program;

α of 0.5 is a centered target and is suitable for the average farmer's cropping program;

α of 0.7 is biased towards the profit maximization objective and is suitable for farmers who want a more profitable planting scheme;

Next, determine the constraints .

Crop rotation system constraints were imposed to ensure that all land in each plot (including barns) was required to be planted with a legume crop at least once in three years from 2023 onwards. Extracting whether plots were planted with legumes or not in 2023, 19 out of 54 plots had been planted with legumes. Calculate every three years from 2023 onwards to determine whether or not legumes have been planted, up to a = 5, i.e., the year up to 2028.

$$\sum_{t=a}^{a+2} x_{ijtk} \geq 1, a \in \{0, ..., 5\} \quad (6)$$

Planting area constraints, the area of each crop planted in a single plot (including greenhouses) should not be too small, and observing the planting program in 2023, co-cropping exists only in the greenhouses. By reviewing the literature, it is analyzed that the profitability of multiple crop co-growing can be enhanced. Here it is assumed that on plot i, the planted area should be more than 10%.

$$\frac{z_{ijtk}}{A_i} \geq 10\% * x_{ijtk} \quad (7)$$

The total area constraint, which requires the plot to be full of crops in each season of the year, is discussed here in terms of crops due to the different types of plots and seasons in which crops are suitable for planting, i.e., the sum of the areas of crops that can be planted on the corresponding plots in each season of the year is equal to the area of the plot.

$$\sum_{j=n}^{N} (z_{ijtk} x_{ijtk}) = A_i \quad (8)$$

Concentration constraints, where each crop cannot be spread too thinly each season, due to the different types of plots and seasons in which crops are suitable for planting, discussed here in terms of terrain, i.e., the same crop planted in the same terrain cannot be spread out over two plots in the same terrain.

$$\sum_{i=m}^{M} x_{ijtk} \leq 1, j \in \{n...N\} \quad (9)$$

Planting pattern constraints, according to the growth pattern of crops, each crop in the same plot (including greenhouses) can not be continuously re-cropped planting, extracted the plot planting crops in 2023, starting from 2023 to calculate every two years to determine whether there is planting the same to a = 6, that is, the year to 2029.

$$\sum_{t=a}^{a+1} \sum_{k=1}^{T} x_{ijtk} \leq 1, a \in \{0...6\} \quad (10)$$

Flat dry land, terraces, and hillside constraints, the first three terrains (numbered 1-26) were analyzed to grow only crops 1-15 and in a single season. That is, m=1, M=26; n=1, N=15; k=1;

$$i \in \{1...25\}, j \in \{1...15\}, k = 1 \quad (11)$$

Watered land constraints, according to the annex description of watered land (numbered 27-34) can be planted with one crop numbered 16 rice or with two crops, and the first crop is numbered 17-34 and the second crop is numbered 35-37. That is, m=27, M=34; n=N=16, k=1; n=17, N=34, k=1; n=35, N=37, k=2;

$$i \in \{27...34\}, j = 16, k = 1 \tag{12}$$

$$i \in \{27...34\}, j \in \{17...34\}, k = 1 \tag{13}$$

$$i \in \{27...34\}, j \in \{35...37\}, k = 2 \tag{14}$$

Show that crops 35-37 can only be planted individually on a plot and cannot be combined. Then the following constraints are satisfied.

$$z_{ijtk} * x_{ijtk} = A_i, i \in \{27...34\}, j \in \{35,36,37\}, k = 2 \tag{15}$$

Ordinary greenhouses (numbered 35-50) were able to grow crops 17-34 in the first season, i.e., m=35, M=50; n=17, N=34; k=1;

$$i \in \{35...50\}, j \in \{17...34\}, k = 1 \tag{16}$$

General greenhouses (numbered 35-50) were able to grow specific crops 38-41 edible mushroom crops in the second season i.e. m=35, M=50; n=38, N=41; k=2;

$$i \in \{35...50\}, j \in \{38...41\}, k = 2 \tag{17}$$

Smart greenhouses (numbered 51-54) can grow two seasons and both crops are numbered 17-34, i.e., m=51, M=54; n=17, N=34;

$$i \in \{51...54\}, j \in \{17...34\} \tag{18}$$

3.2. Model optimization based on stagnant waste

That is, consider that for the next seven years, unsold crops will no longer earn a profit.

3.2.1. Planting programs on flat drylands, terraces and hillsides

In the following three terrains (numbered 1-26) only crops 1-15 can be grown in a single season. According to Annexure 2, it can be observed that terrain only affects the unit yield, the rest of the cost, selling price are same. See Table 3 for the differences in unit yields as follows.

Table 3. Differences in unit production (partial)

Crop number	Crop name	Flat drylands	Terraces	Hillsides
1	soya bean	400	380	360
2	Black soybean	500	475	450
3	azuki bean	400	380	360
4	mung bean	350	330	315

The objective function can be optimized as

$$Maximize Z = \sum_{t=1}^{7} \sum_{j=1}^{15} p_j \min(\sum_{i=1}^{26} z_{ijt} x_{ijt} r_{ij}, A_j) - \sum_{t=1}^{7} \sum_{j=1}^{15} \sum_{i=1}^{26} c_j z_{ijt} x_{ijt} \tag{19}$$

$$Minimize S = \sum_{t=1}^{7} \sum_{j=1}^{15} \sum_{i=1}^{26} (c_j z_{ijt} x_{ijt} r_{ij}) \tag{20}$$

3.2.2. Planting program for wetland

Wetland (Nos. 27-34) can be planted with crops 16-37, see wetland Constraints. Since this terrain crops are also grown in other terrains, the total crop yield of this terrain is considered to be used as the desired sales volume.

The objective function can be optimized as

$$MaximizeZ = \sum_{t=1}^{7}\sum_{j=16}^{37} p_j \min(\sum_{i=27}^{34} z_{ijt}x_{ijt}r_{ij}, \sum_{i=27}^{34} A_{ij}) - \sum_{t=1}^{7}\sum_{j=16}^{37}\sum_{i=27}^{34} c_j z_{ijt}x_{ijt} \tag{21}$$

$$MinimizeS = \sum_{t=1}^{7}\sum_{k=1}^{2}\sum_{j=16}^{37}\sum_{i=27}^{37}(c_j z_{ijt}x_{ijt}r_j) \tag{22}$$

3.2.3. Planting program for the first season of the greenhouse

Greenhouse (numbers 35-50) can grow crops 17-34 in the first season, see Greenhouse first season constraints. As crops from this terrain are also grown in other terrains, the treatment is consistent with the above.

The objective function can be optimized as

$$MaximizeZ = \sum_{t=1}^{7}\sum_{j=17}^{34} p_j \min(\sum_{i=35}^{50} z_{ijt}x_{ijt}r_{ij}, \sum_{i=35}^{50} A_{ij}) - \sum_{t=1}^{7}\sum_{j=17}^{34}\sum_{i=35}^{50} c_j z_{ijt}x_{ijt} \tag{23}$$

$$MinimizeS = \sum_{t=1}^{7}\sum_{j=17}^{34}\sum_{i=35}^{50}(c_j z_{ijt}x_{ijt}r_j) \tag{24}$$

3.2.4. Planting program for the second season of the greenhouse

Greenhouses (numbers 35-50) can grow crops 38-41 in the second season, see Greenhouse Second Season Constraints.

The objective function can be optimized as

$$MaximizeZ = \sum_{t=1}^{7}\sum_{j=38}^{41} p_j \min(\sum_{i=35}^{50} z_{ijt}x_{ijt}r_{ij}, \sum_{i=35}^{50} A_{ij}) - \sum_{t=1}^{7}\sum_{j=38}^{41}\sum_{i=35}^{50} c_j z_{ijt}x_{ijt} \tag{25}$$

$$MinimizeS = \sum_{t=1}^{7}\sum_{j=38}^{41}\sum_{i=35}^{50}(c_j z_{ijt}x_{ijt}r_j) \tag{26}$$

3.2.5. Planting program in intelligent greenhouses

Intelligent greenhouses (numbers 51-54) can grow crops 17-34, see Smart Sheds Constraints. Since the crops in this terrain are also grown in other terrains, the unit cost, unit yield, and selling price of the same crop are different in different seasons, and the unit yield in the second season is smaller than that in the first season, and the unit cost and selling price are higher than that in the first season.

The objective function can be optimized as

$$MaximizeZ = \sum_{t=1}^{7}\sum_{k=1}^{2}\sum_{j=17}^{34} p_{jk} \min(\sum_{i=51}^{54} z_{ijtk}x_{ijtk}r_{ijk}, \sum_{i=51}^{54} A_{ijk}) - \sum_{t=1}^{7}\sum_{k=1}^{2}\sum_{j=17}^{34}\sum_{i=51}^{54} c_{jk} z_{ijtk}x_{ijtk} \tag{27}$$

$$MinimizeS = \sum_{t=1}^{7}\sum_{k=1}^{2}\sum_{j=17}^{34}\sum_{i=51}^{54}(c_{jk} z_{ijtk}x_{ijtk}r_{ijk}) \tag{28}$$

The optimal solution was found for all the above plot planting scenarios and the results of the scenarios were combined to arrive at an average profit of 7,274,000 for seven years for the optimized planting scenario under the stagnant sales scenario, which is an increase of 1,631,900 as compared to the profit of 5,638,500 for the year 2023.The seven-year average cost of 915,700 is 112,500 more compared to the 2023 cost of 803,200.

3.3. Model optimization based on price reduction

The constraints section is the same as in scenario 1, where only the profit objective function is optimized.

3.3.1. Planting programs on flat drylands, terraces and hillsides

The objective function can be optimized as

$$MaximizeZ = \sum_{t=1}^{7}\sum_{j=1}^{15} p_j \min(\sum_{i=1}^{26} z_{ijt}x_{ijt}r_{ij}, A_j) - \sum_{t=1}^{7}\sum_{j=1}^{15}\sum_{i=1}^{26} c_j z_{ijt}x_{ijt} + 0.5*\sum_{t=1}^{7}\sum_{j=1}^{15} p_j \max((\sum_{i=1}^{26} z_{ijt}x_{ijt}r_{ij} - A_j),0) \quad (29)$$

3.3.2. Planting program for wetland

The objective function can be optimized as

$$MaximizeZ = \sum_{t=1}^{7}\sum_{j=16}^{37} p_j \min(\sum_{i=27}^{34} z_{ijt}x_{ijt}r_{ij}, \sum_{i=27}^{34} A_{ij}) - \sum_{t=1}^{7}\sum_{j=16}^{37}\sum_{i=27}^{34} c_j z_{ijt}x_{ijt} + 0.5*\sum_{t=1}^{7}\sum_{j=16}^{37} p_j \max((\sum_{i=27}^{34} z_{ijt}x_{ijt}r_{ij} - \sum_{i=27}^{34} A_{ij}),0) \quad (30)$$

3.3.3. Planting program for the first season of the greenhouse

The objective function can be optimized as

$$MaximizeZ = \sum_{t=1}^{7}\sum_{j=17}^{34} p_j \min(\sum_{i=35}^{50} z_{ijt}x_{ijt}r_{ij}, \sum_{i=35}^{50} A_{ij}) - \sum_{t=1}^{7}\sum_{j=17}^{34}\sum_{i=35}^{50} c_j z_{ijt}x_{ijt} + 0.5*\sum_{t=1}^{7}\sum_{j=17}^{34} p_j \max((\sum_{i=35}^{50} z_{ijt}x_{ijt}r_{ij} - \sum_{i=35}^{50} A_{ij}),0) \quad (31)$$

3.3.4. Planting program for the second season of the greenhouse

The objective function can be optimized as

$$MaximizeZ = \sum_{t=1}^{7}\sum_{j=38}^{41} p_j \min(\sum_{i=35}^{50} z_{ijt}x_{ijt}r_{ij}, \sum_{i=35}^{50} A_{ij}) - \sum_{t=1}^{7}\sum_{j=38}^{41}\sum_{i=35}^{50} c_j z_{ijt}x_{ijt} + 0.5*\sum_{t=1}^{7}\sum_{j=38}^{41} p_j \max((\sum_{i=35}^{50} z_{ijt}x_{ijt}r_{ij} - \sum_{i=35}^{50} A_{ij}),0) \quad (32)$$

3.2.5. Planting program in intelligent greenhouses

The objective function can be optimized as

$$MaximizeZ = \sum_{t=1}^{7}\sum_{k=1}^{2}\sum_{j=17}^{34} p_{jk} \min(\sum_{i=51}^{54} z_{ijtk}x_{ijtk}r_{ijk}, \sum_{i=51}^{54} A_{ijk}) - \sum_{t=1}^{7}\sum_{k=1}^{2}\sum_{j=17}^{34}\sum_{i=51}^{54} c_{jk} z_{ijtk}x_{ijtk} + 0.5*\sum_{t=1}^{7}\sum_{k=1}^{2}\sum_{j=17}^{34} p_{jk} \max((\sum_{i=51}^{54} z_{ijtk}x_{ijtk}r_{ijk} - \sum_{i=51}^{54} A_{ijk}),0) \quad (33)$$

The optimal solution was found for all of the above plot planting scenarios, and the results of the scenarios were combined to yield a seven-year average profit of 70,146,000 for the optimized planting scenario with a 50% reduction in the price of the stalled portion of the planting, an increase of 1,376,100 in comparison to the profit in 2023. The average cost for seven years is 950,300 which is 147,100 more compared to the cost in 2023.

3.4. Monte Carlo simulation

Monte Carlo simulation is a statistical method for modeling random variables and estimating the probability distribution of outcomes by constructing a large number of potential scenarios. In this study, Monte Carlo simulation was used to predict the expected returns and planting costs for the next seven years in the case of stagnant wastage and to determine the optimal planting strategy accordingly.

Uncertainty is introduced: the data is transformed into a rate of change, where positive values are increases and negative values are decreases.

Table 4. Uncertainties and their rates of change

factor	fluctuation range
Annual rate of change in wheat and corn sales	5%…10%
Annual rate of change in sales of crops other than wheat and corn	-5%…5%(Based on 2023)
Rate of change in acreage	-10%…10%
Rate of change in planting costs	5%
Rate of change in vegetable sales prices	5%
Rate of change in sales price of morel mushrooms	-5%
Rate of change in sales prices of edible mushrooms other than morel mushrooms	-5%…-1%

The number of simulation experiments is set to be 10,000. During each simulation, the random variables described above will be generated and the expected benefits and planting costs of the various scenarios will be calculated. At the same time, the scenario with the highest frequency of occurrence is recorded. This scheme is the optimal planting scheme, which is the one that maintains stability under a wide range of possible changing conditions. Under the uncertainty of the expected sales volume, acreage, planting cost and sales price of various crops and potential risks, as shown in Figure 2, the average profit of the optimal planting scheme for seven years is 6,879,400 , which is an increase of 1,240,900 compared to the profit in 2023. The average cost for seven years is 882,700, which is 84,900 more compared to the cost in 2023.

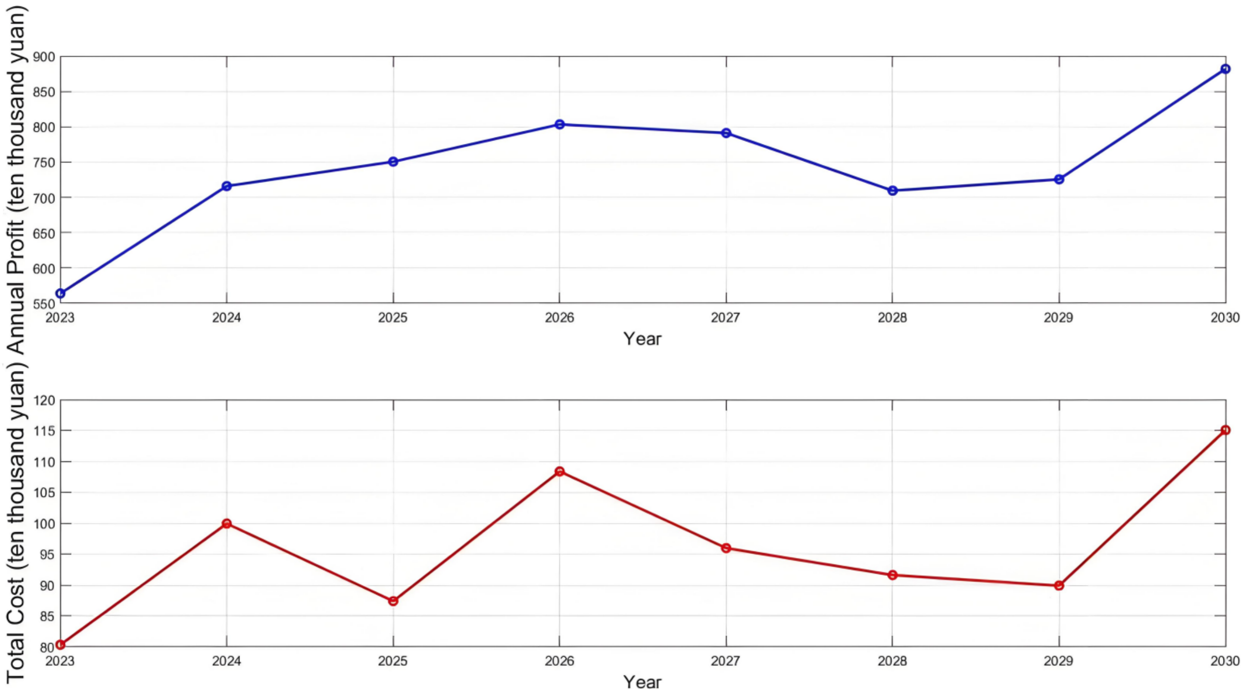

Figure 2. Change in Cost Profit

As can be observed from the chart, the annual distribution of profit costs shows a clear imbalance. This phenomenon is mainly based on in-depth consideration and fine planning of crop cultivation patterns. Specifically, on the same piece of land, none of the crops can be planted continuously with heavy crops, which is to avoid soil nutrient imbalance and accumulation of pests and diseases. In addition, in order to maintain soil fertility and ecological balance, legume crops must also be planted on the land every three years. However, these legume crops are relatively less profitable, leading to a significant decline in profit levels in some years. In addition to this, the planting plan is formulated with due consideration to the stability of costs and selling prices, in an effort to ensure that profits and costs are optimally balanced in a changing market environment, thereby achieving long-term sustainable development.

4. Conclusion

This paper investigates the crop planting optimization problem based on linear programming, aiming to increase yield, reduce cost, and achieve efficient allocation of resources and stable economic benefits. Taking a rural village in North China as an example, the study formulated a crop planting scheme by constructing a multi-objective linear programming model, taking into account crop substitutability and complementarity, as well as constraints such as crop rotation system and planting pattern. The results of the study showed that by optimizing the planting area and crop rotation system, the developed planting scheme increased the seven-year average profit by 1,631,900 and 1,376,100, and the cost by 112,500 and 147,100 more, respectively, in the case of stagnation and price reduction by 50%, relative to the data in 2023. In addition, the study introduced Monte Carlo simulation to assess the robustness of the model by simulating different production scenarios, predicting the range of fluctuations in crop yields and profits, and identifying the optimal planting strategy. Ultimately, the planting scenarios derived from the study are highly adaptable and flexible, and can be adjusted and optimized according to the actual situation.

This paper is relatively simple in terms of data processing and analysis, and in the future, more sophisticated data analysis methods, such as machine learning algorithms, can be introduced to improve the accuracy of prediction. Secondly, the article lacks an in-depth comparison and critical analysis of related studies in the discussion section, and in the future, a detailed discussion of the existing literature can be added to better position the research contribution of this paper. The experimental design is relatively basic, and more innovative experiments can also be designed in the future to verify the hypotheses and improve the innovation and persuasiveness of the study.

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