Research on Crop Planting Optimization Strategy Based on Mixed Integer Programming

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Abstract. With the advancement of agricultural modernization, the optimization of crop planting structure is becoming more and more important, but in practice it faces great challenges due to factors such as empirical decision-making and multiple constraints. In order to maximize the income of growers, this study optimized the planting strategy of crops. According to different types of cultivated land, with the goal of maximizing the income of growers, the mixed linear programming models of crop planting were established respectively. Optimize when the total crop output exceeds the expected sales volume and the price is reduced. In order to make the model consistent with the real world, this study considered the requirements of continuous cropping, planting concentration and market richness. By reasonably distributing the planting area of crops on each plot, the results show that the largest planting area of carrots is 1382.12 mu from 2024 to 2030, and the largest sales profit of Chinese cabbage is 14 million yuan, and the total profit in seven years is 87 million yuan. By optimizing the planting area and variety of crops, growers can achieve greater economic benefits with limited land resources and promote the sustainable development of the industry.

Keywords: Mixed Linear Programming, Planting Strataegy, Nonlinear Regression Prediction, Continuous Cropping.

1. Introduction

In recent years, with the continuous advancement of China's agricultural modernization process, the optimization of crop planting structure has attracted increasing attention. Under the background of the overall promotion of rural revitalization strategy, the optimization of crop planting structure has become an important breakthrough to achieve high-quality agricultural development [1-3]. Reasonable planting structure is not only related to the increase of farmers' income, but also directly affects the sustainable development of agricultural production and the guarantee of food security [4-6].

However, the current crop planting structure optimization faces many challenges: on the one hand, traditional planting decisions often rely on farmers' experience accumulation and subjective judgment, and lack of scientific quantitative analysis methods, which leads to the disconnection between planting structure and market demand [7]. In addition to climate change, market demand analysis is also the basis of planting structure adjustment, but the traditional model is difficult to achieve accurate matching [8]. People's demand for safe, high-quality, nutritious and healthy high-quality agricultural products is more urgent [9]. On the other hand, there are significant differences in soil types, fertility levels and hydrological conditions of cultivated land resources. The research shows that the utilization efficiency of soil nutrients can be improved to the maximum extent by reasonably matching the rotation sequence and interval of different crops [10]. The comprehensive influence of these factors makes the decision-making of planting optimization extremely complicated.

This study takes a village in North China as the object: firstly, referring to the literature and combining with the rural reality, the problems that need to be solved are made clear, that is, two kinds of planting schemes under the sales situation are given for overproduced crops, the uncertainty and risk optimization scheme are comprehensively considered, and more realistic factors such as crop complementarity, the correlation between planting cost and sales volume are considered, and then the scheme is optimized again.

2. Data source and preprocessing

The data in this paper comes from www.mcm.edu.cn. The expected sales volume, planting cost, yield per mu and sales price of various crops in 2024~2030 are relatively stable in 2023, so the total output of various crops in 2023 can be used as the basis of the expected sales volume of crops in 2024~2030. On this basis, adding a fluctuation coefficient of ξ, there are:

$$D_{i,n} = \xi_n^{(k)} Z_i \ , \ k = 1, 2, 3 \tag{1}$$

Among them, $D_{i,n}$ is the expected sales volume of i crops in n years, and $\xi_n^{(k)}$ represents three types of crops (vegetables and edible fungi, beans and grain) in n years. It is assumed that the fluctuation coefficient of expected sales volume of various crops is consistent with their types. Combined with the sales data of various crops from 2015 to 2022, nonlinear regression prediction is made based on the least square method. Under the condition of minimizing the sum of squares of errors, the simplex method is used to make the convergence effect and convergence speed of the regression model ideal. Based on this prediction, the change rate of sales of various crops from 2024 to 2030, that is, fluctuation coefficient ξ, is obtained. See Table 1 for the specific results.

Table 1. Fluctuation coefficient of crop sales from 2024 to 2030

Age	Vegetables and edible fungi	Beans	Food
2024	2.209%	0.000%	-1.103%
2025	-1.055%	4.730%	-1.784%
2026	-3.200%	5.806%	-2.194%
2027	2.466%	-3.049%	2.669%
2028	5.274%	3.774%	8.742%
2029	6.518%	12.727%	2.426%
2030	-1.616%	-1.920%	-5.030%

According to the predicted change rate of sales volume from 2024 to 2030 and the total output of crops in 2023, the expected sales volume of some crops in 2024 to 2030 is calculated, as shown in Table.2.:

Table 2. Expected sales of some crops from 2023 to 2030

	2024	2025	2026	2027	2028	2029	2030
soybean	58725	61502.53	62134.84	56934.6	60941.04	66199.09	57597.41
black soya bean	21850	22883.45	23118.71	21183.84	22674.53	24630.91	21430.45
red bean shrub	22400	23459.46	23700.65	21717.07	23245.28	25250.91	21969.89

For soybeans, the highest sales volume is expected to appear in 2029 and the lowest sales volume will appear in 2027.

3. Basic Model Construction and Solution for Crop Planting Planning

Under the basic premise that the expected sales volume, planting cost, yield per mu and selling price of various crops in the future remain stable relative to 2023, and the crops planted every season are sold in the current season, there may be two situations in the quarterly production of a crop: exceeding part of the unsalable or selling at 50% of the selling price in 2023.

The crop planting situation of different types of cultivated land is different. The cultivated land in flat dry land, sloping land and terraced fields can only meet the crop harvest in one season and can only grow food crops. The greenhouse and irrigated land can meet the planting of crops twice a year, and the planting types include rice, vegetables and edible fungi. Therefore, according to different types of cultivated land, different constraints and objective functions are set to determine the optimal planting strategy.

3.1. Flat dry land, terraced fields and hillside fields

3.1.1. Decision variables:

Let $B_{i,j,n}$ represent whether the crops numbered i are planted in j plot in n years, then there are:

$$B_{i,j,n}=\begin{cases}0, & \textit{The crops numbered } i \textit{ are planted in plot } j \textit{ in thenth year}\\ 1, & \textit{The crops numbered } i \textit{ will not be planted in the } i \textit{ ploti } n \textit{ thenth year}\end{cases} \tag{2}$$

Among them, $i=1,2,...,15; j=1,2,...,26; n=1,2,...,8$, $n=1$ represents 2023, and so on, and $X_{i,j,n}$ represents the planting area of the i crop in the j plot in the n year.

3.1.2. Objective function:

P_i is the unit selling price of crop i, $X_{i,j,n}$ represents the planting area of crop i in plot j over n years, $Y_{i,u}$ is the yield per mu of crop i in plot u (here referring to three types of plots: flat and dry land, terraced fields and sloping land, $u=1,2,3$), and W_i indicates the unit area planting cost of crop i. On the one hand, in order to facilitate farming and field management, it is necessary to ensure that the planting plots of each crop are not too scattered when formulating planting strategies. By restricting the minimum number of planting plots and ensuring the maximum area of planting plots, the crop planting dispersion is defined:

$$\min \frac{\sum B_{i,j,n}}{\sum B_{i,j,n} \cdot X_{i,j,n}} \tag{3}$$

On the other hand, to ensure the maximum profit, the objective function expression is:

$$max \sum_{i=1}^{15} \sum_{j=1}^{26} \sum_{n=2}^{8} \left[P_i \cdot min \left\{ \sum_{j=1}^{26} (B_{i,j,n} \cdot X_{i,j,n}) \cdot Y_{i,u}, D_{i,n} \right\} - \sum_{j=1}^{26} (B_{i,j,n} \cdot X_{i,j,n} \cdot W_i) \right] \tag{4}$$

Among them, $P_{i,n}$ refers to the income of i crop in n years, $X_{i,j,n}$ refers to the planting area of i crop in j plots in n years, $Y_{i,u}$ refers to the yield per mu of i crop in u plots (here refers to three types of plots of flat dry land, terraced fields and hillside fields, $u=1,2,3$), and W_i refers to the planting cost of i crop.

3.1.3. Constraints:

Avoid continuous cropping.

Reasonable rotation can improve the nutritional structure of cultivated land and increase the economic benefits of growers [1], so it is required that the same crop cannot be continuously cultivated on the same plot, otherwise it will easily lead to the simplification of soil nutrition and the breeding of microbial germs, resulting in the decline of soil fertility and land yield:

$$B_{i,j,n} + B_{i,j,n+1} \leqslant 1 \tag{5}$$

Plant beans at least once in three years.

The metabolic process of rhizobia at the root of leguminous crops will fix nitrogen in the soil, increase fertilizer for the soil, which is beneficial to the increase of crop yield. It is required to plant leguminous plants at least once every three years to improve the utilization rate of nitrogen fertilizer, and at the same time, it is beneficial to improve soil fertility and reduce crop pests and diseases, namely:

$$B_{i,j,n} + B_{i,j,n+1} + B_{i,j,n+2} \geqslant 1 \tag{6}$$

Meet the market product richness.

In order to ensure that the richness of agricultural products can meet the market demand and ensure the residents' requirements for food quality, it is stipulated that all crops should be planted at least once in 2024~2030. Therefore:

$$\sum_{j=1}^{26} B_{i,j,n} \geqslant 1 \tag{7}$$

Planting concentration.

On the one hand, the small planting area of a single plot is not conducive to the unified management of the same crop, and at the same time, the decentralized harvesting workflow greatly increases the management cost, so it is required that the planting area of each crop in each plot should not be too small. When the first crop is planted in a plot, it is stipulated that its planting area should not be less than 60% of the minimum planting area or 30% of the average planting area of this crop in 2023, so there are:

$$B_{i,j,n} \cdot X_{i,j,n} \geqslant \min\left\{0.6S_{i\min}, 0.3\overline{S}_i\right\}, B_{i,j,n} = 1 \tag{8}$$

Among them, $S_{i\min}$ is the minimum planting area of the i crop in 2023, and $\overline{S}_i$ is the average planting area of the i crops in 2023.

Planting area constraints.

The planting area of combined crops in a certain plot cannot exceed the area of the plot itself, so:

$$\sum_{i=1}^{15} X_{i,j,n} \cdot B_{i,j,n} \leqslant A_j \tag{9}$$

Where A_j is the area of each plot.

Combining the above constraints, the objective function is established:

$$max \sum_{i=1}^{15} \sum_{j=1}^{26} \sum_{n=2}^{8} \left[P_i \times min\left\{ \sum_{j=1}^{26} (B_{i,j,n} \times X_{i,j,n}) \times Y_{i,u}, D_{i,n} \right\} - \sum_{j=1}^{26} (B_{i,j,n} \times X_{i,j,n} \times W_{i,j}) \right] \tag{10}$$

$$\min \frac{\sum B_{i,j,n}}{\sum B_{i,j,n} \cdot X_{i,j,n}} \tag{11}$$

Meet the constraints:

$$s.t. \begin{cases} B_{i,j,n} + B_{i,j,n+1} \leqslant 1 \\ B_{i,j,n} + B_{i,j,n+1} + B_{i,j,n+2} \geqslant 1 \\ \sum_{j=1}^{26} B_{i,j,n} \geqslant 1 \\ B_{i,j,n} \cdot A_j \geqslant \min\left\{0.6S_{i\min}, 0.3\overline{S}_i\right\}, B_{i,j,n} = 1 \\ \sum_{i=1}^{15} X_{i,j,n} \cdot B_{i,j,n} \leqslant A_j \end{cases} \tag{12}$$

3.2. Irrigated land and greenhouses

3.2.1. Decision variables:

Similarly, if $B_{i,j,n,t}$ represents whether the crops numbered i are planted in the j plot in the t quarter of n years, and $t=0$ represents single-season planting, there are:

$$B_{i,j,n,t}=\begin{cases}0, & The\ crop\ numbered\ i\ is\ planted\ in\ the\ j\ plot\ in\ the\ t\ season\ of\ the\ n\ year\\1, & The\ crop\ numbered\ i\ is\ not\ planted\ in\ the\ j\ plot\ in\ the\ t\ season\ of\ the\ n\ year\end{cases} \tag{13}$$

Among them, $i=16,17,...,41; j=27,28,...,54; n=1,2,...,8; t=0,1,2$, $n=1$ stands for 2023, and so on.

3.2.2. Objective function:

The minimum dispersion of irrigated land and cultivated land in greenhouse is expressed as:

$$\min\frac{\sum B_{i,j,n,t}}{\sum B_{i,j,n,t}\cdot X_{i,j,n,t}} \tag{14}$$

Among them, $X_{i,j,n,t}$ represents the planting area of the crop i in plot j in the t quarter of n years.

Taking the maximum profit and minimum dispersion as the objective functions, a linear integer programming model is established, and the expression of the objective function is:

$$max\sum_{i=16}^{41}\sum_{j=27}^{54}\sum_{n=2}^{8}\left[P_{i,j,t}\cdot min\left\{\sum_{j=16}^{41}(B_{i,j,n,t}\cdot X_{i,j,n,t})\cdot Y_{i,u,t},D_{i,n}\right\}-\sum_{j=27}^{54}(B_{i,j,n,t}\cdot X_{i,j,n,t}\cdot W_{i,j,t})\right] \tag{15}$$

Among them, $P_{i,n,t}$ is the sales unit price of i crop in the t quarter of n years, $Y_{i,u,t}$ is the yield per mu of i crop in the t quarter in plot u (here refers to irrigated land, common greenhouse and smart greenhouse, $u=1,2,3$), and $W_{i,j,t}$ refers to the unit planting cost of i crop in plot j in the t quarter.

3.2.3. Constraints:

According to the data, the crop planting seasons in smart greenhouses are distributed in different years, so it is necessary to avoid the double cropping of crop planting. Therefore:

$$\begin{cases}B_{i,j,n,1}+B_{i,j,n,2}\leqslant 1\\B_{i,j,n,2}+B_{i,j,n+1,1}\leqslant 1\end{cases} \tag{16}$$

Irrigated land can choose to plant one season of rice or two seasons of vegetables every year, but the topic limits that only carrots, white radishes and Chinese cabbage can be planted in the second season of irrigated land, and other vegetable crops except carrots, white radishes and Chinese cabbage can be planted in the first season, without the constraint of continuous cropping, so only one season of rice can be planted every year, and there are:

$$B_{i,j,n,0}+B_{i,j,n+1,0}\leqslant 1,\quad i=16 \tag{17}$$

Plant beans at least once in three years.

$$\sum_{t=0}^{2}B_{i,j,n,t}+\sum_{t=0}^{2}B_{i,j,n+1,t}+\sum_{t=0}^{2}B_{i,j,n+2,t}\geqslant 1,\quad i=1,...,5,17,18,19 \tag{18}$$

Single and double cropping.

Among the three types of cultivated land, namely irrigated land, common greenhouse and smart greenhouse, only irrigated land is planted in a single season, and crops are not planted in a greenhouse. Therefore:

$$B_{i,j,n,0}=0, j=35,\dots,54 \tag{19}$$

Each irrigated land plot can only choose single-season planting or double-season planting, and there are:

$$B_{i,j,n.0}+\frac{B_{i,j,n,1}+B_{i,j,n,2}}{2}=1, j=27,\dots,34 \tag{20}$$

Meet the market product richness:

$$\sum_{j=27}^{54} B_{i,j,n,t}\geqslant 1 \tag{21}$$

Planting concentration:

$$B_{i,j,n,t}\cdot X_{i,j,n,t}\geqslant \min\left\{0.6S_{i\min}, 0.3\overline{S}_i\right\}, B_{i,j,n,t}=1 \tag{22}$$

Planting area constraints:

$$\sum_{i=16}^{47}\sum_{j=27}^{54} B_{i,j,n,t}\cdot X_{i,j,n,t}\leqslant A_j \tag{23}$$

Combining the above constraints, the objective function is established:

$$max\sum_{i=16}^{41}\sum_{j=27}^{54}\sum_{n=2}^{8}\left[P_{i,j,t}\cdot min\left\{\sum_{j=16}^{41}(B_{i,j,n,t}\cdot X_{i,j,n,t})\cdot Y_{i,u,t}, D_{i,n}\right\}-\sum_{j=27}^{54}(B_{i,j,n,t}\cdot X_{i,j,n,t}\cdot W_{i,j,t})\right] \tag{24}$$

Solution of Crop Planting Planning Model Based on Case 3.1

Considering that the description and analysis of all crop species is too large and unrepresentative, 14 crops, such as wheat and buckwheat, are selected for specific analysis in order to describe the planting characteristics of various crops in North China in the next seven years and the potential factors to maximize profits.

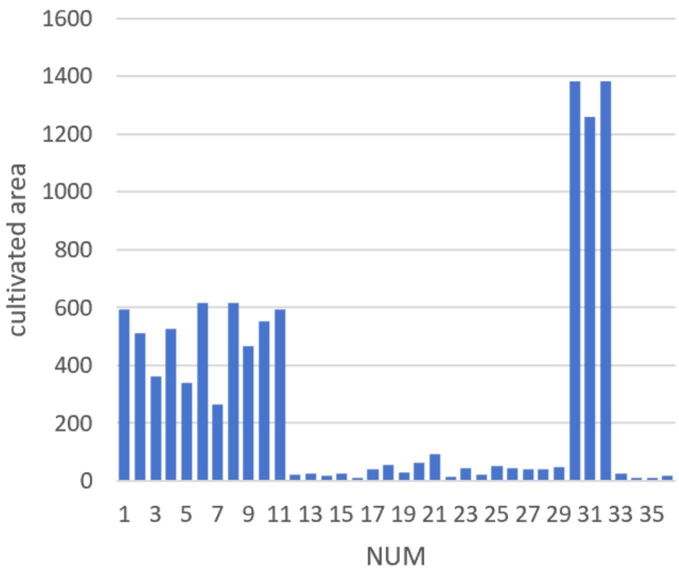

Figure 1. Select the yield of crops

As shown in Figure 1, in terms of crop yield, Chinese cabbage, white radish and red radish have the largest planting area and the highest output, which might be attributed to the fact that North China is a major production area for these crops and thus has abundant yields. From the perspective of profit, morel, as a rare and precious edible fungus, despite having a relatively small planting area and low yield per mu, still achieves a high profit due to its high selling price of 100 yuan per unit. In contrast, white button mushroom, with the lowest selling price among edible fungi, is favored by consumers for its good quality and low price. It has a high sales volume and a wide planting area, and ultimately achieves a relatively high profit level.

4. Crop Planting Planning Model Considering Price Reduction for Excess Products

4.1. Model establishment

On the basis of the waste of crops exceeding the expected sales volume in the previous section, the agricultural products exceeding the expected sales volume are set to be sold at 50% price, and other constraints remain unchanged, then the crop planting planning model for sloping fields, terraces and flat drylands is established as follows:

$$\begin{cases} max\sum_{i=1}^{15}\sum_{j=1}^{26}\sum_{n=2}^{8}\left[P_i\cdot D_{i,n}+\frac{P_i}{2}\left(B_{i,j,n}Y_{i,u}-D_{i,n}\right)-\sum_{j=1}^{26}\left(B_{i,j,n}\cdot X_{i,j,n}\cdot W_n\right)\right], B_{i,j,n}Y_{i,u}>D_{i,n} \\ max\sum_{i=1}^{15}\sum_{j=1}^{26}\sum_{n=2}^{8}\left[P_i\cdot B_{i,j,n}\cdot Y_{i,u}-\sum_{j=1}^{26}\left(B_{i,j,n}\cdot X_{i,j,n}\cdot W_n\right)\right], B_{i,j,n}Y_{i,u}<D_{i,n} \end{cases} \tag{25}$$

The objective function should maximize total crop profit, requiring output to exceed annual expected sales volumes. In the maximum profit objective function, income from sales exceeding projections (at 50% discount) is included. Since discounted sales generate significantly lower profits than full-price sales, maximum planting area should be achieved while ensuring crop yields don't exceed expected demand.

$$s.t.\begin{cases} B_{i,j,n}+B_{i,j,n+1}\leqslant 1 \\ B_{i,j,n}+B_{i,j,n+1}+B_{i,j,n+2}\geqslant 1 \\ \sum_{j=1}^{26}B_{i,j,n}\geqslant 1 \\ B_{i,j,n}\cdot X_{i,j,n}\geqslant \min\left\{0.6S_{i\min},0.3\overline{S}_i\right\}, B_{i,j,n}=1 \\ \min\frac{\sum B_{i,j,n}}{\sum B_{i,j,n}\cdot X_{i,j,n}} \end{cases} \tag{26}$$

The first four constraints are consistent with the above modeling. In order to facilitate the subsequent calculation and solution, the objective function of minimizing crop planting dispersion in the above objective function is defined as a constraint.

4.2. Solution results

Using the model (26) with known data for flat dry land, terraced fields, and hillside fields, we obtained the 2024-2030 crop planting strategy through Lingo software. The same approach was used for irrigated land and greenhouse crops. Table 3 presents planting strategies for single/first season crops in 2024 under slow sales conditions. In 2024, plot A1 grew only mung beans (80 mu); plot A2 had black beans (5.812 mu), mung beans (4.735 mu), and wheat (25.61 mu); plot A3 contained mung beans (10.53 mu) and sorghum (4.911 mu); plot A4 grew black beans (23.52 mu) and red beans (23.53

mu). Throughout 2024-2030, white radish had both the largest planting area (1749.30 mu) and highest profit (1.6 million yuan). The seven-year total profit across all crops exceeded 87 million yuan.

Table 3. Crop Planting Strategy in Single Season or First Season in 2024 (Partial)

Massif	Soybean	Black soya bean	Red bean shrub	Mung bean	Climb beans	Wheat	Corn	Millet	Kaoliang
A1	0.0	0.0	0.0	80	0.0	0.0	0.0	0.0	0.0
A2	0.0	5.8	0.0	4.7	0.0	25.61	0.0	0.0	0.0
A3	0.0	0.0	0.0	10.5	0.0	0.0	0.0	0.0	4.9
A4	0.0	23.5	23.5	0.0	0.0	0.0	0.0	0.0	0.0
A5	0.0	0.0	6.6	0.0	2.2	0.0	0.0	11.89	0.0
A6	17.3	0.0	0.0	0.0	10.2	0.0	27.48	0.0	0.0

5. Conclusion

Firstly, by classifying cultivated land and establishing a mixed linear programming model, the optimal planting strategies of the two types of cultivated land are obtained by using LINGO with the goal of maximizing income and combining planting constraints (such as continuous cropping restriction, bean rotation, etc.) under the situation of slow sales or price reduction. On this basis, the realistic factors such as climate and market are further introduced, and the uncertainty (such as yield fluctuation and cost change) is quantified by stochastic programming model, and the profit maximization model is optimized, and finally the optimal planting strategy adapted to the dynamic environment is obtained. Then, through the correlation of crop substitutability, complementarity and expected sales-yield per mu-unit price, the crop correlation index is integrated into the model, and combined with genetic algorithm optimization, the results show that growers are more inclined to choose crops with higher unit profit.

Agricultural production involves unpredictable factors like technological upgrades, yield improvements, and price increases from high-quality varieties. This study makes predictions based only on 2023 statistics; future model improvements should incorporate multi-year actual data. This research provides a conceptual framework for agricultural economics, policy-making, and sustainable development. The combination of multi-factor dynamic optimization with data-driven decision-making demonstrates both feasibility and practical value. These methods not only provide a scientific basis for agricultural planning but can also be applied to industrial production layout optimization.

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