Optimization of crop planting strategies in mountainous areas of North China based on mixed integer programming and Monte Carlo simulation

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Abstract. In this paper, a mixed integer programming model (MIP) and Monte Carlo simulation model were established to optimize the crop planting strategy of a village in the mountainous area of North China, considering the planting restrictions of different plots, crop growth laws and the uncertainty of external conditions. First, under stable market conditions, the MIP model can obtain the optimal planting plan for the next seven years by optimizing factors such as cultivated land area, land type restrictions, cropping constraints, legume crop planting requirements and field management. Secondly, the Monte Carlo simulation model considers the uncertainty of expected crop sales, per mu yield, planting cost and selling price, and obtains the optimal planting plan under uncertain conditions by simulating various market scenarios, effectively reducing risks and improving the robustness of returns. The results showed that the village should actively develop efficient cash crops, optimize planting structure, and adopt diversified planting strategies to cope with market risks and promote sustainable agricultural development.

Keywords: Mixed Integer Programming Model (MIP), Monte Carlo simulation, Crop Planting Strategy, Uncertainty Analysis, Sustainable Development.

1. Introduction

With the increasing demand for sustainable agricultural development, reasonable crop planting strategies are crucial to improve production efficiency, reduce planting risks and achieve efficient use of resources [1, 2]. However, crop cultivation faces many challenges, such as uncertainty in market demand, the impact of climate change, and fluctuations in growing costs. How to formulate scientific and reasonable planting strategies to cope with these challenges has become an urgent problem to be solved [3, 4].

In order to solve the problem of crop planting strategy optimization in a rural village in the mountainous area of North China, this paper established mixed integer programming model (MIP) and Monte Carlo simulation model for analysis, considering the planting restrictions of different plots, crop growth rules and the uncertainty of external conditions. First, under stable market conditions, the MIP model can obtain the optimal planting plan for the next seven years by optimizing factors such as cultivated land area, land type restrictions, cropping constraints, legume crop planting requirements and field management. Secondly, the Monte Carlo simulation model considers the uncertainty of expected crop sales, per mu yield, planting cost and selling price, and obtains the optimal planting plan under uncertain conditions by simulating various market scenarios, effectively reducing risks and improving the robustness of returns.

2. Data and methods

2.1. Data Introduction

The research data in this paper came from market research and open source website (www.mcm.edu.cn), and collected crop number, name, type, type of cultivated land suitable for planting, seasonal restrictions, yield per mu (jin/mu), unit planting cost (yuan/mu) and sales price range (yuan/jin) of each crop under different plot type and planting season. In order to better analyze and understand the known data, it is necessary to pre-process the data before formally analyzing and solving the problem. Tools such as Excel and Python were used to organize and observe the data from multiple angles and standards, so as to initially understand the basic situation of the overall data and provide support for the analysis and answer of subsequent questions.

2.1.1. Types of cultivated land and crop planting

Figure 1 (left) shows that irrigated land accounts for the highest proportion of 51.03% of the cultivated land in rural areas, which is mainly used to grow rice and two-season vegetables. This is followed by flat and dry land, accounting for 30.09%, which is mainly used for food crops. Terraces and hillsides account for 8.99% and 8.9%, respectively, suitable for one-season food crops. Ordinary greenhouses and smart greenhouses accounted for 0.79% and 0.2% respectively, although the area is small, it can improve the efficiency of land use and planting diversity.

Figure 1 (right) shows that in 2023, crop planting is mainly food, accounting for 58.82%, including wheat, corn, etc. Legume crops accounted for 28.95%, which is conducive to crop rotation and improving soil fertility. Vegetables accounted for 9.41%, mainly in irrigated fields and greenhouses. Edible fungi and legumes accounted for 2.08% and 0.74% respectively, although the proportion was small but the economic benefit was high.

On the whole, the rural cultivated land resources are diverse, the planting structure is balanced, mainly grain, while the combination of diversified and efficient cash crops, to ensure agricultural output and economic benefits.

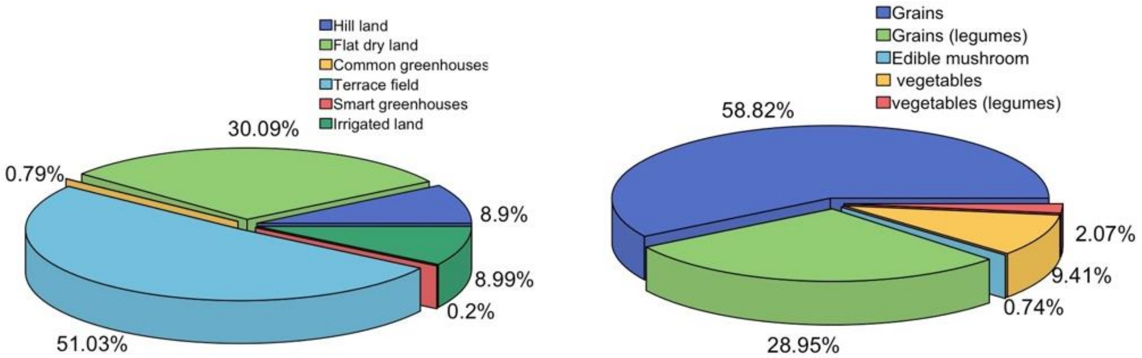

Figure 1. Existing arable land in rural areas (left) and crop planting in 2023 (right)

2.1.2. Relationship analysis of crop type, plot type and yield per mu

The highest yield of grain crops per mu was 38,738 jin, which occupied the dominant position. The legume crop yields 19,158 catty, about half of which helps maintain soil fertility. The output of vegetables per mu is second, and the output of beans and vegetables and edible fungi is less, respectively, 246.88 jin and 5.76 jin, but it has high economic value. On the whole, food crops are the main crops, supplemented by legumes, and vegetables and edible fungi have expansion potential.

Irrigated land has the highest yield per mu, reaching 495,000 jin, followed by terrace 325,015 jin, flat dry land 228,600 jin, and hilly land 104,640 jin. Although the greenhouses have a small area, the output of ordinary greenhouses is 82,020 catties and that of smart greenhouses is 25230 catties, showing its efficient agricultural potential (Figure 2).

Figure 2. Total production by crop type (left) and total production by plot type (right)

2.1.3. Sales volume of crops

This paper analyzes the sales volume of various crops in a village in 2023, and assumes that farmers have rich agricultural experience and can rationally anticipate market demand. As a result, crop yields are roughly in line with market demand. We quantified sales by multiplying the acreage of each crop by the yield per acre. The planting area combines four types of plots. According to the yield per mu of different crops in different plots, this study adds these areas and multiples the corresponding yield per mu, thus estimating the total output of each crop, and finally approximates the sales volume in 2023. The visualization of sales distribution of each crop is shown in Figure 3 below.

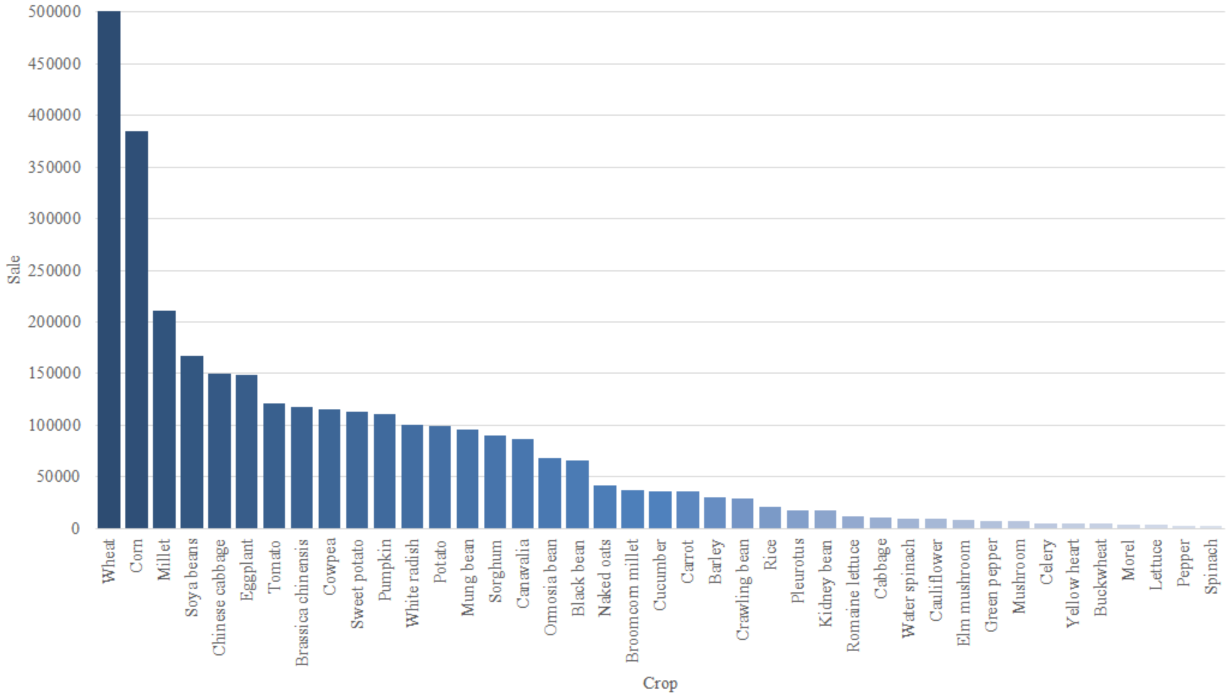

Figure 3. Distribution of sales volume by crop (in order of sales volume from largest to smallest)

This paper analyzes the sales volume of various crops in a village in 2023, and finds that the sales volume of grain crops such as wheat and corn is relatively high, while some vegetables and edible fungi are relatively low. The result accords with farmers' planting strategy and market demand, indicating that farmers have accurate expectations of market demand. Through these data, it can provide a reference for the reasonable planting area and sales volume of crops in the next few years to avoid excessive or insufficient yield. At the same time, by adjusting the planting area, we can maximize the use of limited resources, maximize economic benefits and promote sustainable agricultural development.

2.2. Research Methods

(1) Optimization of rural crop planting strategy in mountainous areas of North China under stable market conditions: It is assumed that the expected sales volume, planting cost, per mu yield and selling price of various crops in the future remain stable compared with 2023, and on this basis, the mixed integer programming model (MIP) is used to optimize the planting plan. The model takes the maximization of planting income in the next seven years as the objective function, and considers the two cases of slow sales and price reduction respectively for the part exceeding sales volume. The mixed integer programming model is established with the constraint conditions of cultivated land area, land type restriction, preventing repeat cropping, planting requirements of legume crops, and field management. Through optimization, the optimal planting plan under stable market conditions was obtained, which provided reference for the village to make scientific and reasonable planting strategy.

(2) Optimization of rural crop planting strategy in mountainous areas of North China under uncertain market conditions: the uncertainties of expected crop sales, per mu yield, planting cost and selling price were considered, and Monte Carlo simulation model was introduced to optimize crop planting planning. By simulating multiple market scenarios, the model analyzes the performance of each crop under different market conditions and generates a robust planting plan based on these yield results. This method can effectively help the model to find the scheme to maximize the income under uncertain conditions, avoid the market risk, and provide a theoretical basis for the village to develop a scientific and reasonable planting strategy.

3. Model establishment and solution

3.1. Optimization of rural crop planting strategies in mountainous areas of North China based on stable market conditions

3.1.1. Establishment of optimal crop planting scheme model

Based on the characteristics of the existing farmland and the economic benefits of crops, a planting strategy model was established for the village. The model should take into account the expected sales volume, planting cost, per mu yield and selling price of crops to remain stable relative to 2023, and give the optimal planting plan for crops from 2024 to 2030. The model should be based on the planting requirements of the crops, combined with the type and distribution of cultivated land, to ensure that the crops will not be unsalable due to exceeding the expected sales volume in each season, or adopt the strategy of selling the unsalable part at a lower price, and analyze the two scenarios of waste caused by slow sales and sales at a 50% lower price. The following is a table of parameters used to build the model (Table 1).

Table 1. Parameter table

Type	parameter	Specific meaning
Decision variable	$x_{i,j,k}$	The area of plot i growing j crops in year k
	$p_{i,j,k}$	A binary variable that indicates whether the i type of crop is planted in the j season of the k year, with 1 indicating planting and 0 indicating no planting
parameter	$P_{j,k}$	Denotes the sales price of the j crop in the k year (yuan/jin)
	$Y_{j,k}$	Represents the unit yield of the j crop in the k year (jin/mu)
	$C_{j,k}$	Represents the cost of planting the j crop in year k
	A_i	Available planting area of Plot i
	$S_{j,k}$	The expected sales of crop i in year k

(1) Determination of objective function

The model of this problem belongs to Mixed-Integer Programming (MIP), which is an effective tool for solving complex optimization problems and is widely used in resource allocation, supply chain management and production planning [5-8]. The establishment of mixed integer programming model is based on the limitation of rural cultivated land resources, the diversity of crop cultivation and the need of maximizing economic benefits [9]. The MIP model is characterized by both continuous variables (such as actual values such as acreage) and binary variables (indicating whether a particular crop is planted), and these variables are limited by a series of linear constraints[10]. In this context, the model fully considers the multi-dimensional factors involved in the planting plan, including the expected sales volume of different crops, planting cost, per mu yield and selling price, and maximizes the annual total planting income in the next seven years under the premise of meeting various restrictions.

The objective function of the model is in linear form, defined as the maximization of total plantation returns over the next seven years. This objective function not only takes into account the crop income from normal sales, but also deals with the case of excess partial sales according to the actual market demand. In the application of the model, we will consider the following two cases:

In case one, the surplus is unsalable, and the unsalable crop is considered a waste and does not generate any income. The mathematical expression in this case is:

$$maxZ_k = \sum_{i=1}^{54} \sum_{j=1}^{40} min(x_{i,j,k} \cdot Y_{j,k} \cdot S_{j,k}) \times P_{j,k} - C_{j,k} \cdot x_{i,j,k} \tag{1}$$

In case two, the excess part is sold at a 50% discount, that is, when the total production exceeds the market demand, the excess part is sold at 50% of the original price. The mathematical expression in this case is:

$$maxZ_k = \sum_{i=1}^{54} \sum_{j=1}^{40} (S_{j,k} \times P_{j,k} + \frac{max(0,x_{i,j,k} \cdot Y_{i,k} - S_{j,k})}{2} \times P_{j,k}) - C_{j,k} \cdot x_{i,j,k} \tag{2}$$

(2) Determination of constraint conditions

1) Restriction of cultivated land area

The total planted area of each plot cannot exceed its actual area, i.e.:

$$\sum_j x_{i,j,k} \le A_i, \ \forall i, k \tag{3}$$

2) Land type constraints

Different land types are suitable for planting different crops, such as flat dry land, terraced land, hillside land suitable for growing food crops, irrigated land suitable for growing rice or vegetable crops. Its mathematical expression is as follows:

$$p_{i,j} \le M_{i,j}, \ \forall i, j \tag{4}$$

Where, M_(i,j) is a 0-1 matrix that represents whether the i plot is suitable for growing the j crop

3) Restriction of continuous planting

Each crop can not be continuously planted in the same plot (including greenhouses), to ensure that the same plot must be rotated between successive planting seasons, in order to prevent the loss of production caused by repeated cropping:

$$p_{i,j,k} + p_{i,j,k-1} \le 1, \ \forall i, j, k \tag{5}$$

4) Legumes must be planted once in three years

Because the rhizobium of legumes is conducive to improving the soil structure and promoting the growth of other crops, every field (including greenhouses) must be planted with legumes at least once within three years to improve soil fertility and optimize the growth conditions of subsequent crops. This requirement can be expressed by the following constraints:

$$\sum_k^{k+3} p_{i,j,k} \ge 1, \forall j \in {}_{Bean\ crops,}\ k \in \{2023,2024,2025,2026,2027\} \tag{6}$$

5) Restrictions on planting area

Under the premise of hypothesis 5),

$$\sum_{j=1}^{40} p_{i,j,k} \le 2, \ \forall i, k \tag{7}$$

$$x_{i,j,k} = \frac{Ai}{\sum_{j=1}^{40} p_{i,j,k}}, \ \forall i,j,k \tag{8}$$

(3) Optimization model summary

The following formula is the optimization model of crop planting scheme, and the final summary is as follows:

$$maxZ_k = \sum_{i=1}^{54} \sum_{j=1}^{40} min(x_{i,j,k} \cdot Y_{j,k} \cdot S_{j,k}) \times P_{j,k} - C_{j,k} \cdot x_{i,j,k} \tag{9}$$

$$maxZ_k = \sum_{i=1}^{54} \sum_{j=1}^{40} (S_{j,k} \times P_{j,k} + \frac{max(0, x_{i,j,k} \cdot Y_{i,k} - S_{j,k})}{2} \times P_{j,k}) - C_{j,k} \cdot x_{i,j,k} \tag{10}$$

$$s.t. \begin{cases} \sum_j x_{i,j,k} \le A_i, \ \forall i,k \\ p_{i,j} \le M_{i,j}, \ \forall i,j \\ p_{i,j,k} + p_{i,j,k-1} \le 1, \ \forall i,j,k \\ \sum_{k=1}^{k+3} p_{i,j,k} \ge 1, \ \forall j \in \text{Bean crops}, k \in \{2023,2024,2025,2026,2027\} \\ \sum_{j=1}^{40} p_{i,j,k} \le 2, \ \forall i,k. \\ \\ x_{i,j,k} = \frac{A_t}{\sum_{j=1}^{40} P_{i,j,k}}, \ \forall i,j,k \end{cases} \tag{11}$$

3.1.2. Model solution

Based on 0-1 programming model, binary decision variables are used to describe the crop planting choice of each field. In this paper, the model is solved by MATLAB optimize function, and the crop planting plan for the next seven years is optimized.

The planting data of 2023 is initialized. During the annual iteration, the model will update the yield information of the plots, calculate the actual planted crops and area of each plot, and obtain the total annual income. The optimal planting schemes for crops under scenario 1 and scenario 2 from 2024 to 2030 are shown in Table 2 below.

Table 2. Result1-1 Partial results of the first quarter

Plot name	Soya beans	Black bean	Ormosia bean	Mung bean	Crawling bean	Wheat	corn	millet
A1	0	0	0	0	0	0	80	0
A2	0	0	0	0	0	0	0	0
A3	0	0	0	0	0	0	0	0
A4	0	0	0	0	0	0	0	72
A5	0	0	0	0	0	68	0	0
A6	0	0	0	0	0	0	55	0
B1	0	0	60	0	0	0	0	0
B2	0	0	0	46	0	0	0	0
B3	0	0	0	0	0	40	0	0
B4	0	0	0	0	0	28	0	0
B5	0	0	0	0	0	0	0	0
B6	0	0	0	0	0	86	0	0
B7	55	0	0	0	0	0	0	0
B8	44	0	0	0	0	0	0	0
B9	0	0	0	50	0	0	0	0
B10	0	0	0	0	25	0	0	0
B11	0	0	0	0	0	0	0	60
B12	0	45	0	0	0	0	0	0
B13	0	0	0	0	0	0	0	35
B14	0	0	0	0	0	0	0	0

The result visualization of Result1-1 is shown in Figure 4 below.

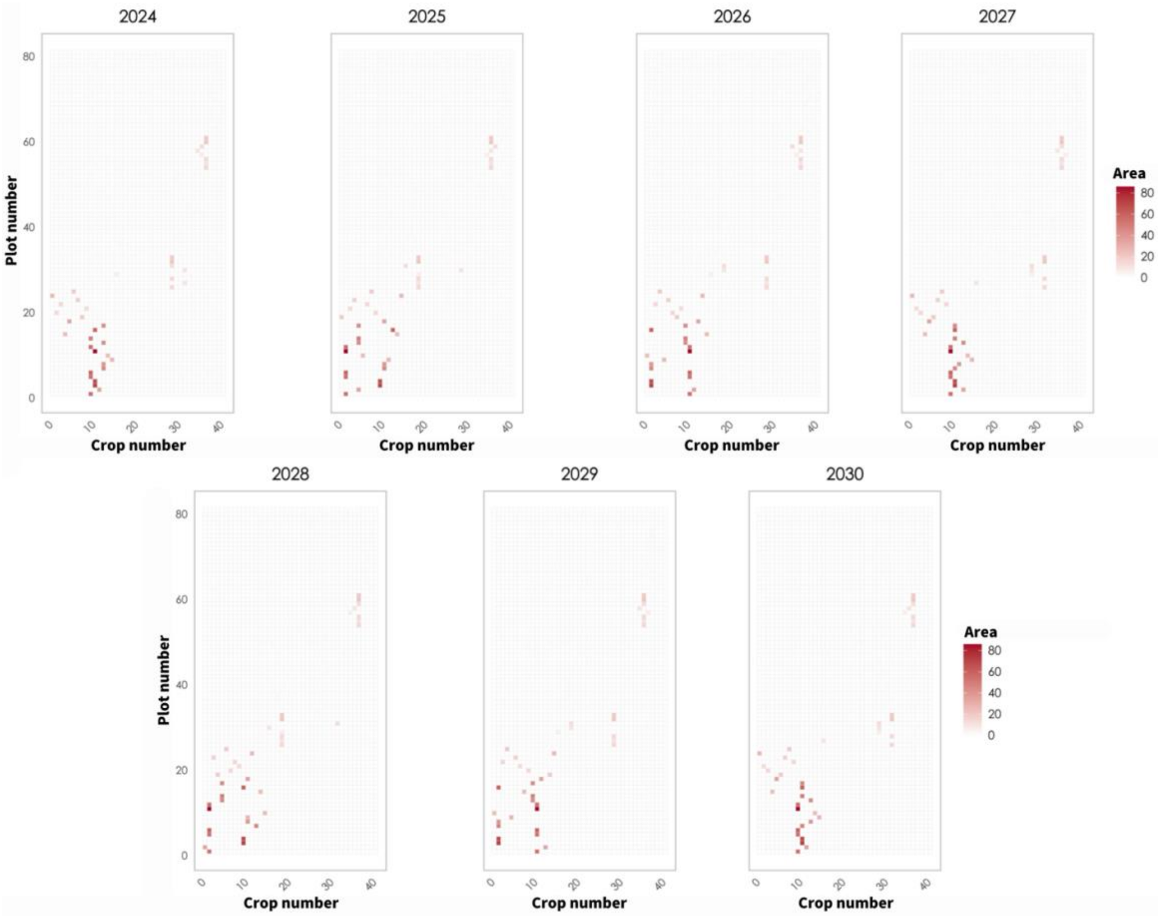

Figure 4. Result1-1 Visual heat map

Table 3. Result1-2 Partial results of the first quarter

Plot name	Mung bean	Crawling bean	millet	Broomcorn millet	buckwheat	Pumpkin	Sweet potato	Naked oats
A1	0	0	0	0	80	0	0	0
A2	0	0	0	55	0	0	0	0
A3	0	0	0	0	0	35	0	0
A4	0	0	0	0	72	0	0	0
A5	0	0	0	0	68	0	0	0
A6	0	0	0	55	0	0	0	0
B1	0	0	0	60	0	0	0	0
B2	0	0	0	0	0	0	46	0
B3	0	0	0	0	0	0	40	0
B4	0	0	0	0	0	0	0	0
B5	0	0	0	0	0	0	0	25
B6	0	0	0	0	86	0	0	0
B7	0	0	0	55	0	0	0	0
B8	0	0	0	0	0	0	44	0
B9	0	0	0	50	0	0	0	0
B10	25	0	0	0	0	0	0	0
B11	0	0	0	0	60	0	0	0
B12	0	0	0	0	0	0	45	0
B13	0	35	0	0	0	0	0	0
B14	0	0	20	0	0	0	0	0

The result visualization of Result1-2 is shown in Figure 5 below.

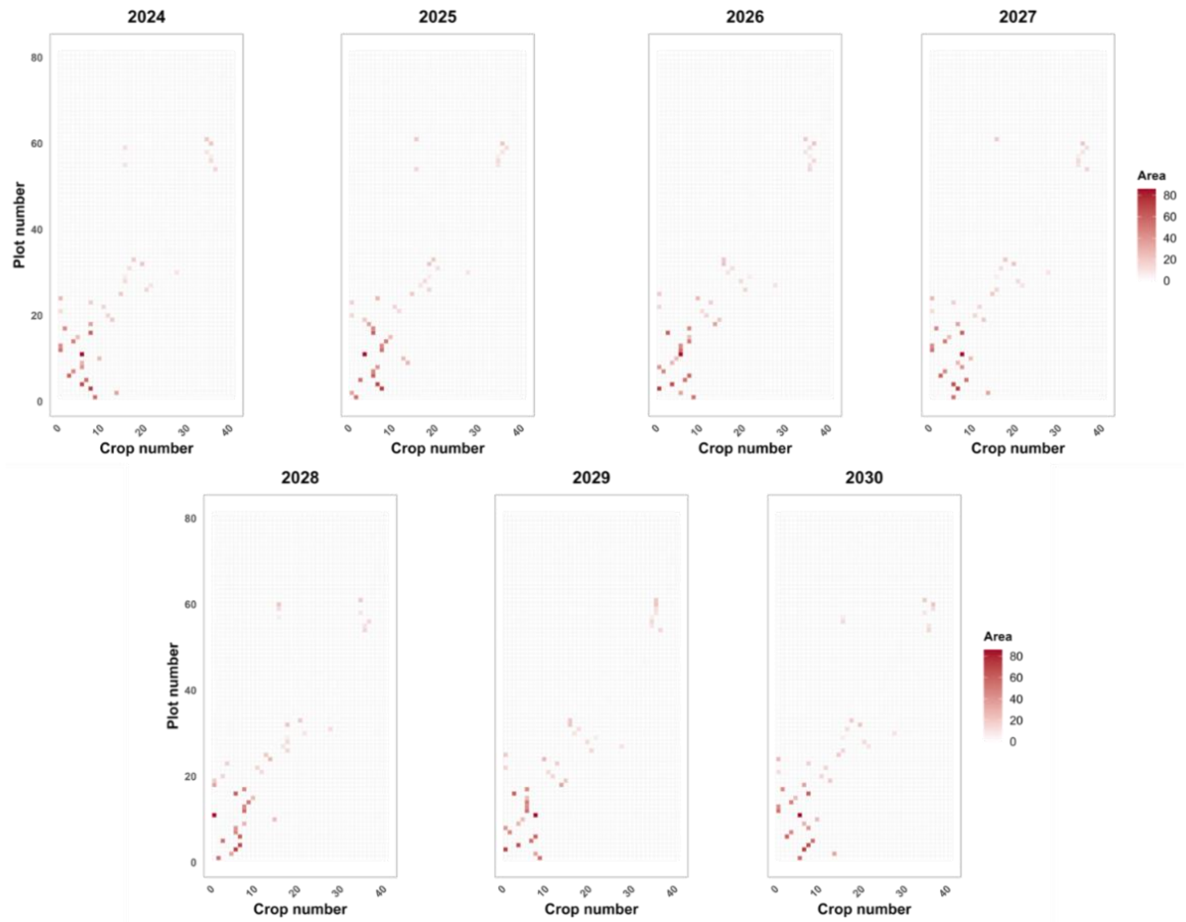

Figure 5. Result1-2 Visual heat map

During the whole planting cycle, the planting strategy of each year gradually evolved from the initial conservative strategy to the intensive production model, showing significant changes and optimization trends:

I. Conservative initial planting strategy: In 2024, the planting strategy is more conservative, focusing on a few high-efficiency crops, and mainly distributed in the first 20 plots. This strategy is designed to ensure stable initial returns and reduce reliance on market and ecological uncertainties. This reflects the model's preventive measures and coping strategies in the face of initial risks.

II. Medium-term expansion and equilibrium: From 2025 to 2026, the planting strategy will gradually expand, the crop variety will increase, the planting scope will expand to more plots, and the utilization rate of all plots will increase significantly, especially in 2026, the utilization of plots will be more balanced, spreading risks and maximizing economic benefits. The model showed an effective balance between crop selection and plot allocation.

III. Fine adjustment and crop rotation: From 2027 to 2028, the planting strategy will enter the stage of fine adjustment. By adjusting planting density, reducing the planting area of some crops and implementing crop rotation, the efficiency of land resource utilization has been effectively improved, and the accumulation of diseases and pests has been prevented, demonstrating the concern for sustainable development.

IV. Intensive production in the later stage: in 2029 and 2030, the planting strategy will be further intensified, with the dominant crops being high-yield varieties and the inefficient crops being phased out. Through crop selection and planting area optimization, the model realizes the double maximization of land utilization and economic benefit. At this stage, the strategy tends to be stable, showing effective control of multiple variables and long-term optimization effect.

The next step is to make a visual return chart for the optimized planting plan from 2024 to 2030. The new planting plan makes the return rate show a steady growth trend during the 6-year period. The return under the first and second cases is shown in Figure 6.

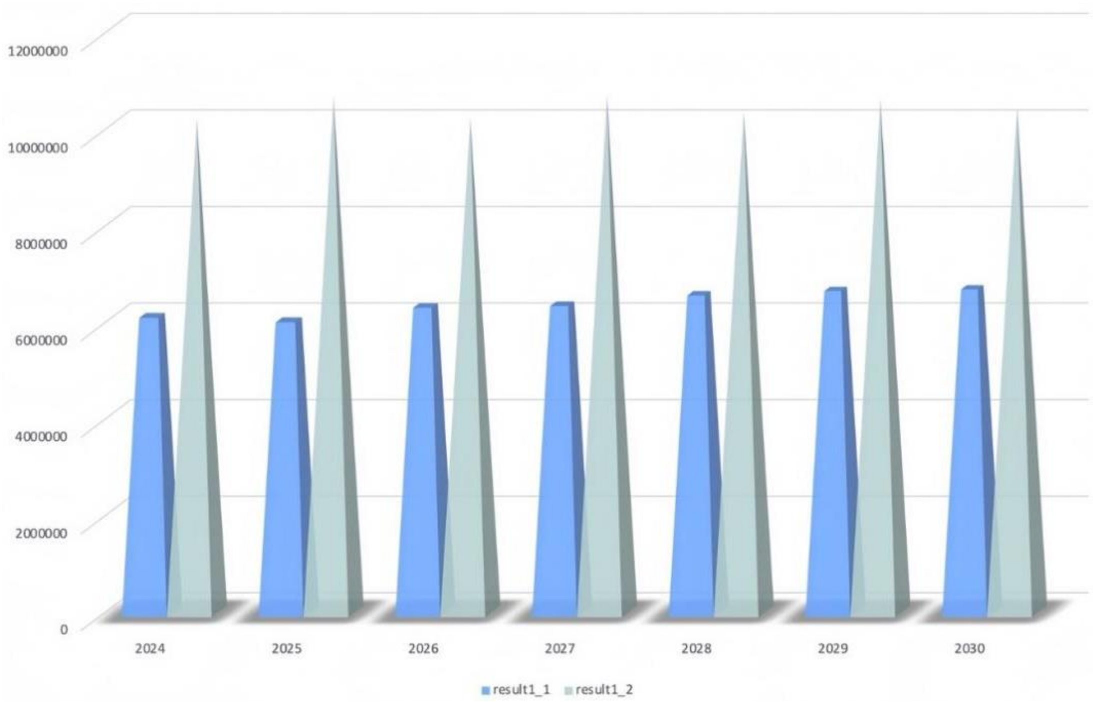

Figure 6. Annual revenue trend chart for optimal planting programs from 2024 to 2030

3.2. Optimization of rural crop planting strategies in mountainous areas of North China based on uncertain market conditions

Consider the uncertainty of the expected sales volume, yield per acre, planting cost and selling price of the crop, and build a model based on these changes. Based on the historical data of crops and the expectations of future market conditions, reasonable crop planting strategies are selected to cope with the influence of external factors such as climate and market price fluctuations. The model should ensure that crop yields are maximized under uncertainties, and the planting plan should be optimized to the optimal state, and the results should be applied to the crop planting plan for 2024 to 2030. To develop an optimal planting plan for 2024-2030, taking into account uncertainties in expected crop sales, yield per acre, planting costs and selling prices, as well as potential planting risks.

3.2.1. Monte Carlo simulation to establish an uncertainty model

Factors such as expected sales volume, yield per mu, planting cost and selling price of crops are uncertain, which have a great impact on planting decision. To cope with these uncertainties, Monte Carlo simulations are used to optimize crop planting planning. Monte Carlo simulation generates multiple uncertain scenarios through repeated random sampling to help analyze the performance of different decisions and find the optimal planting scheme in multiple scenarios.

(1) Uncertainty simulation

According to hypothesis (n), the fluctuations of these variables conform to a uniform distribution. Through random sampling to generate a number of different scenarios, corresponding to different uncertain conditions, each variable can be represented by random variables. The following uncertainties are introduced:

1) Expected sales: The annual growth rate of wheat and corn is assumed to be 5%-10%, and other crops fluctuate between ±5% per year, with random variables as follows:

$$S_j(t+2023) = S_j(2023) \times \prod_{k=1}^{t} (1+g_i(k)),\ g_i(k) = \begin{cases} U(0.05, 0.1), & \text{"Wheat and corn."} \\ U(-0.05, 0.05), & \text{"Other crops."} \end{cases} \quad (12)$$

2) Yield per mu: Crop yield per acre fluctuates ±10% per year, depending on the climate.

$$Y_j(t+2023) = Y_j(2023) \times \prod_{k=1}^{t} (1+f_j(k)), f_j(k) = U(-0.1, 0.1) \quad (13)$$

3) Planting cost:

Average annual growth of 5% based on market conditions:

$$C_j(t+2023) = C_j(2023) \times (1.05)^t \tag{14}$$

4) Sales price:

The price change trend of different crops is different (for example, the price of vegetables increases by 5% per year, and the price of edible fungi decreases by 1% to 5% per year), which is expressed as follows:

$$P_j(t+2023) = P_j(2023) \times \prod_{k=1}^{t} (1 + P_j(k)), \tag{15}$$

$$P_j(k) = \begin{cases} 0.05, & \textit{Vegetable crops} \\ U(-0.05, -0.01), & \textit{Edible mushroom crops} \\ -0.05, & \textit{Morels} \end{cases} \tag{16}$$

$$T:\ t \in \{1,2,3,4,5,6,7\} \tag{17}$$

(2) Determine the objective function

The goal is to maximize the expected benefits under uncertain conditions for the period 2024-2030. The difference is that the parameters of the revenue function (sales, yield per acre, cost, price) are now random variables in the Monte Carlo simulation. Assuming that all of the surplus is unsalable, the unsalable crop is considered a waste, that is, the waste coefficient is 1.

In this paper, the objective function is expressed as the average return under multiple scenarios, and its mathematical expression is as follows:

$$max\ E[\sum_{i=1}^{54} \sum_{j=1}^{40} (min(x_{i,j,n} \cdot Y_j(n), S_i(n)) \times P_j(n) - X_{i,j,n} \cdot C_j(n)] \tag{18}$$

- $E[\cdot]$represents the expected value for all random scenarios.
- *n=t+2023*
- Variable is set to random variable here.

(3) Optimization model summary

There is no need to add additional constraints to each scenario, as Monte Carlo simulations already dynamically adjust crop sales, yields per acre, planting costs, and so on across different scenarios. The optimization model is summarized as follows:

$$max\ E[\sum_{i=1}^{54} \sum_{j=1}^{40} (min(x_{i,j,n} \cdot Y_j(n), S_i(n)) \times P_j(n) - X_{i,j,n} \cdot C_j(n)] \tag{19}$$

$$s.t. \begin{cases} \sum_j x_{i,j,k} \le A_i, & \forall\, i, n \\ p_{i,j} \le M_{i,j}, & \forall\, i, j \\ p_{i,j,n} + p_{i,j,n-1} \le 1, & \forall\, i, j, n \\ \sum_{k=1}^{3} p_{i,j,n} \ge 1, & \forall\, j \in \textit{Bean crops} \\ \sum_{j=1}^{40} p_{i,j,n} \le 2, & \forall\, i, n \\ x_{i,j,n} = \frac{A_i}{\sum_{j=1}^{40} p_{i,j,n}}, & \forall\, i, j, n \end{cases} \tag{20}$$

3.2.2. Model solution

Figure 6 and 7 show the annual returns from an optimized planting strategy based on result_2 for the period 2024 to 2030. The main reasons for fluctuations in earnings include changes in market demand, crop prices and yields. With the gradual increase in the market demand for wheat, corn and other food crops, as well as the rise in the price of vegetable crops, the annual income has shown an overall increasing trend. At the same time, earnings growth slowed slightly in some years due to factors such as rising planting costs and falling prices of edible fungi crops. Overall, thanks to optimized planting strategies, annual returns have maintained a relatively stable upward trend in the coming years despite uncertainties.

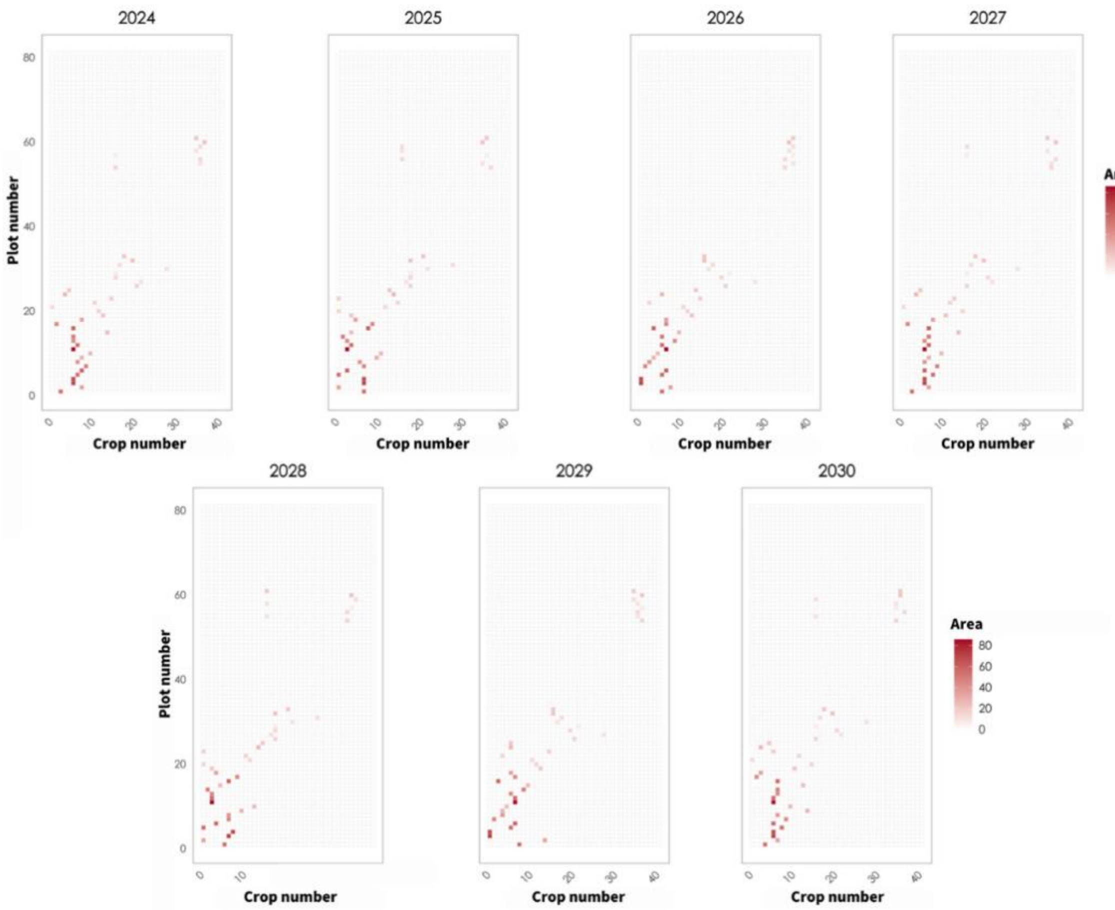

Figure 7. Result visual heat map 2

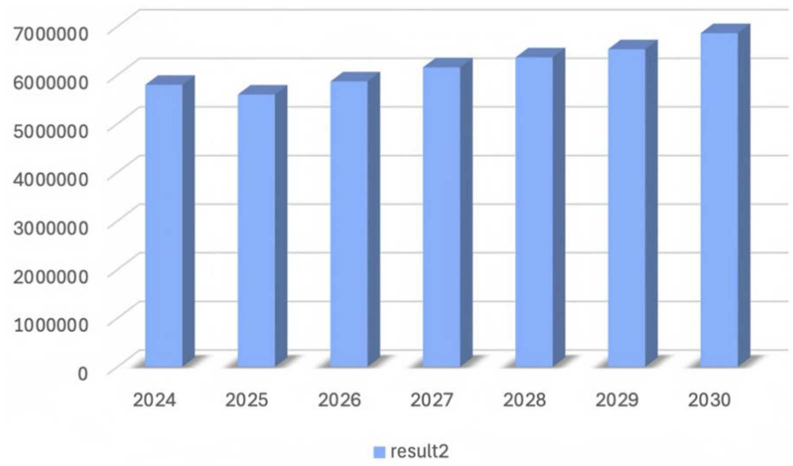

Figure 8. Annual gains from optimizing planting strategies

4. Conclusion

This research, concentrating on optimizing crop planting strategies in a mountainous village within North China, employs a comprehensive approach integrating a mixed integer programming (MIP) model and Monte Carlo simulation. In stable market scenarios, the MIP model factors in various elements such as cultivated land area, land type, cropping constraints, and legume crop requirements to devise an optimal planting plan spanning the next seven years. Meanwhile, the Monte Carlo simulation tackles the uncertainties in expected crop sales, per mu yield, planting cost, and selling price, generating robust planting plans through simulating diverse market conditions.

The outcomes affirm that the optimized planting strategies not only maximize returns under both stable and uncertain market conditions but also notably curtail risks and enhance the robustness of returns. This research thus furnishes a robust theoretical underpinning for the village to formulate scientific and reasonable crop planting strategies, playing a pivotal role in propelling sustainable agricultural development. Future investigations could potentially delve into further refining these models, expanding their application scopes, and optimizing associated parameters to better adapt to dynamic agricultural landscapes.

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