Crop Planting Optimization Scheme Based on Linear Programming and Monte Carlo Algorithm

Yunqi Li #, Xuanyi Xiang #, Xinyue Zhang, Di Liu *

Pittsburgh Institute, Sichuan University, Chengdu, China, 610044

* Corresponding Author Email: di.liu@scupi.cn

#These authors contributed equally.

Abstract. Crop planting optimization is an important part of current agricultural development, as it directly influences the productivity and economic viability for farmers. Based on linear programming and the Monte Carlo algorithm, an optimized crop planting strategy is presented to address the problem of uncertain factors such as expected sales volume, planting costs, yield per acre, and fluctuating sales prices. The proposed stochastic simulation model incorporates these uncertainties, using Monte Carlo simulation to generate a wide range of potential market scenarios, reflecting the diverse conditions that farmers may encounter and then applying linear programming to optimize the planting strategy. The results show that in the face of uncertainty, the planting plan should be more diversified, with dynamic adjustments of crop types and planting proportions based on different scenarios, effectively reducing market risks and improving overall returns. This research is significant for the sustainable development of rural economies, as it helps to improve production efficiency and develop organic farming industries.

Keywords: Crop Planting Optimization, Linear Programming, Monte Carlo Algorithm, Uncertainty Factors.

1. Introduction

In a rural area located in the mountainous region of North China, where the average temperature is consistently low throughout the year, most arable land can only support the cultivation of crops for one season. The area consists of six types of arable land: dryland (6 plots), terraced fields (14 plots), sloping land (6 plots), irrigated land (8 plots), regular greenhouses (16 plots), and smart greenhouses (4 plots), totaling 54 plots. There are 41 crop varieties, including soybeans, corn, and wheat. Grain crops, except for rice, can be grown on dryland, terraced fields, and sloping land. Rice can only be cultivated on irrigated land for one season per year. If rice is not planted on irrigated land, two seasons of vegetables can be grown instead. The first season, from March to June, includes a variety of vegetables such as Chinese cabbage, radishes, and carrots. The second season, from July to October, only allows for the cultivation of one type of vegetable from the three options. Regular greenhouses can be used to grow a variety of vegetables from May to September (first season) and edible mushrooms from September to April of the following year (second season). Smart greenhouses can be used to grow multiple seasons of various vegetables, excluding Chinese cabbage, radishes, and carrots.

It is important to note that leguminous plants can fix nitrogen through a symbiotic relationship with rhizobia, making them excellent soil fertilizers [1]. However, continuous cultivation of the same crop may deplete soil nutrients, reduce soil fertility, and deteriorate soil physical properties, which is not conducive to sustainable cultivation [2]. To ensure consistent yields, it is necessary to avoid continuous cultivation of the same crop on a single plot and to plant leguminous crops at least once every three years. Additionally, it is desirable to minimize the fragmentation of planting areas for each crop to facilitate agricultural operations and field management. Each crop should occupy a reasonably sized plot to ensure efficient land use, improve crop yields and quality, and promote the sustainable development of agriculture [3].

With the constant progress of agricultural technology and changes in market demand in recent years, crop planting optimization has become a popular research topic. Wang conducted a study on the adoption of intercropping planting model in agricultural production, which emphasizes its advantages in improving land profitability, crop yields and soil quality, points out the troubles of the model and proposes relevant optimization strategies [4]. Fu and Wang deeply analyzed the influence of agricultural planting factors on planting structure, pointing out that planting factors such as crop varieties, planting density, and fertilizer application will have a significant impact on planting structure [5]. This study provides an important theoretical basis for subsequent planting optimization. Many scholars have made relevant studies on the application of linear programming in the field of agricultural cultivation. Li et al. specifically optimized the layout of grape planting, thus improving the yield and quality of grapes by constructing a linear programming layout model [6]. Hang et al. carried out linear planning and other methods, comprehensively considered multiple factors such as soil carbon storage, crop yield, and economic benefits, and proposed a reasonable optimization scheme for the scale of planting and raising [7]. Zhang et al. constructed a multi-objective linear planning model for the planting structure adjustment problem in Hebei and realized the coordinated development of economic, social, and ecological benefits by optimizing the crop planting structure and layout [8]. In addition, ROB W. BROOKER et al. pointed out that by increasing plant diversity and adopting ecologically intensive planting methods, crop yields and quality can be improved while reducing the impact on the environment [9].

Though these articles explored the relevant factors of crop cultivation from different perspectives, they did not provide specific optimization methods or models, which lacked practical operability, or only provided theoretical guidance and specific optimization models and empirical analysis, which had a limited role in optimizing the actual cultivation strategy. The optimized crop planting strategy based on linear programming and the Monte Carlo algorithm proposed in this paper integrally considers a more specific model and carries out detailed analysis, which comprehensively considers a variety of uncertainties, helping to realize the sustainable development of agricultural production.

2. Model Established

2.1. The structure of linear programming

Linear programming is a mathematical method for optimizing (maximizing or minimizing) a linear objective function given linear constraints. It is one of the oldest and most widely used tools in operations research and is widely used in resource allocation, production planning, transportation problems, and other fields [10].

To obtain the maximum earnings, the objective function is:

$$Max\ Z_t = R_t - C_t = \sum_{j\in J}[(S_{t,j}R_{t,j} - C_{t,j})\sum_{i\in I}\sum_{k\in K} x_{i,j,k,t}], \forall t \in T \tag{1}$$

In addition, this paper gives two different ways of dealing with slow sales, subdividing the objective function into more than expected slow sales and 50% price reduction, can optimize the objective function to:

The first way is to get rid of the unsalable parts:

$$Max\ Z_t = R_t - C_t = \sum_{j\in J}[(S_{t,j}R_{t,j} - C_{t,j})\sum_{i\in I}\sum_{k\in K} Q_{i,j,k,t}], \forall t \in T \tag{2}$$

The second way is that the products more than expected sales are sold at 50% discount:

$$Max\ Z_t = R_t - C_t = \sum_{j\in J}[(S_{t,j}R_{t,j} - C_{t,j})\sum_{i\in I}\sum_{k\in K}(0.5 \cdot x_{i,j,k,t} + 0.5 \cdot Q_{i,j,k,t})], \forall t \in T \tag{3}$$

Where $Q_{i,j,k,t}$ is the expected sales volume of the j crop planted on the i plot in the k quarter of the t year, and is also the expected sales volume for the next 7 years, and the above part is sold in excess of expectations.

Considering the different crops corresponding to different cultivated land types, constraints are set to ensure that the planting area does not exceed the cultivated land area, no continuous planting, the planting area should not be too small and there are legumes within three years. The following constraints can be listed.

According to the cultivated land area limit, the planting area of each plot cannot exceed the cultivated land area of the plot, and should meet the following requirements:

$$\sum_{j\in J} x_{i,j,k,t} \leq A_i\,, \forall i \in I, k \in K, t \in T \tag{4}$$

According to each crop in the same plot (including greenhouses) cannot be continuous repeat planting, in the same plot of the same crop in different seasons do not repeat planting, the number of acres of two crops at least one is 0, should satisfy that:

$$x_{i,j,1} \cdot x_{i,j,2} = 0, \forall i \in I, j \in J \tag{5}$$

According to the minimum planting area should not be too small, the minimum planting area can be set as 10% of the total area of each farming plot as the minimum planting area, that is, the number of acres per planting should not be less than 10% of the plot area, should follow that:

$$x_{i,j,k,t} \geq 10\% A_i, \forall i \in I, j \in J, t \in T \tag{6}$$

According to the requirement that beans be planted at least once within three years, the following should be met:

$$\sum_{t=1}^{6} x_{i,j=beans,k,t-1} + x_{i,j=beans,k,t} + x_{i,j=beans,k,t+1} \geq 0\,, \forall i \in I \tag{7}$$

2.2. The structure of Monte Carlo simulation

First, collect the crop planting data for 2023, including sales volume, yield per acre, planting cost, and selling price [11]. Then, for the comprehensive consideration of the influencing factors, the uncertainties of crop sales, per mu yield, planting cost and selling price are introduced, and the changes in 2024-2030 are calculated according to the given fluctuation range.

The expected sales volume of crops in the next 7 years will fluctuate to some extent. For wheat and corn, the expected annual growth rate is between 5% and 10%, and their annual sales volume is set as:

$$Q_{j,t} = Q_{j,2023} \times \left(1 + r_j\right)^t, r_j \in [0.05, 0.10], j \in \{6,7\} \tag{8}$$

The expected yield of the remaining crops will fluctuate by ±5% relative to 2023, and the annual sales volume of the remaining crops is assumed to be:

$$Q_{j,t} = Q_{j,2023} \times \left(1 + r_j\right)^t, r_j \in [-0.05, 0.05], j \notin \{6,7\} \tag{9}$$

where $j = 6$ represents the wheat and $j = 7$ represents the corn.

The yield per mu in the next 7 years will change by ±10% per year, and the crop yield per mu in 2024-2030 can be expressed as:

$$S_{j,t} = S_{j,2023} \times \left(1 + v_j\right), v \in [-0.10, 0.10], \forall t \in T, j \in J \tag{10}$$

The planting cost will increase by an average of 5% per year in the next 7 years, and the planting cost of crops in 2024-2030 can be expressed as:

$$C_{j,t} = C_{j,2023} \times (1 + 0.05)^t, \forall j \in J, t \in T \tag{11}$$

In the next 7 years, the selling price will increase or decrease according to different crops, and the selling price of grain will remain unchanged. The selling price of vegetable crops changes from $R_{t,j}$, to $R_{2023,j} \times (1+0.05)^t$; The sales price of edible fungi, especially morels, decreases by 1%-5% every year, of which morels decrease by 5%, and the sales price of fungi can be expressed as:

$$R_{j,t} = R_{j,2023} \times (1 + r_j)^t, j \in \{38,39,40,41\} \tag{12}$$

For these uncertainties, we introduced Monte Carlo simulations to generate expected sales, yields per acre, planting costs, and selling prices for the next seven years (2024-2030). Through repeated iterations, the revenue distribution as shown in the figure is obtained.

Monte Carlo simulation method is a random simulation method based on probability and statistical theory, which can generate random values conforming to the probability distribution characteristics of random variables through random sampling and statistical simulation [12]. Taking sales volume, per mu yield, planting cost and selling price as random variables respectively, a random number sequence with uniform distribution in the corresponding variation interval can be generated by random number generator, which can be converted into a specific random number sequence according to the objective function and constraint conditions, and then 50 simulation tests are carried out for statistical processing to obtain the optimal planting plan and estimate the maximum profit value.

3. Results

3.1. Visual Distribution

In this paper, 80% of the theoretical sales in 2023 is taken as the expected sales volume, and the unit sales price of each crop is multiplied by the width of the unit sales price interval in each field by a random constant generated between zero and one, and the random value obtained is taken as the final unit sales price of this crop in that place [13]. Make a visual distribution diagram according to different yield per acre, planting costs and selling prices, which are shown in Figure 1.

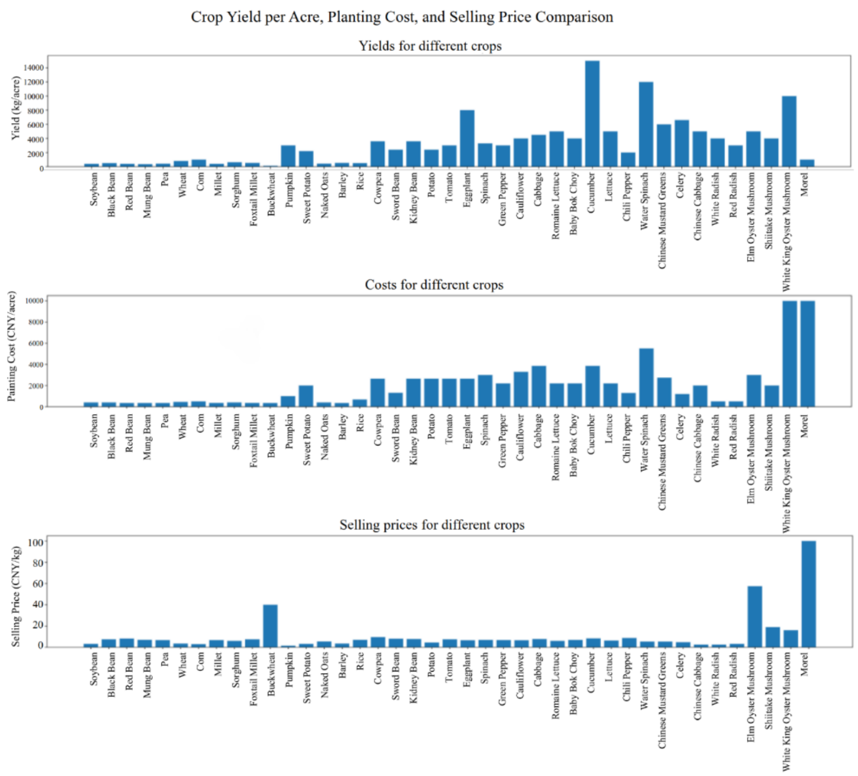

Figure 1: Yield per acre, planting costs and selling prices of different crops

3.2. Results of linear programming

In the process of solving, the optimal allocation of planting area is determined by the objective function, and different constraints are set according to the two scenarios. Jupyter tool is used to solve the model. The results are shown in Figure 2 and 3:

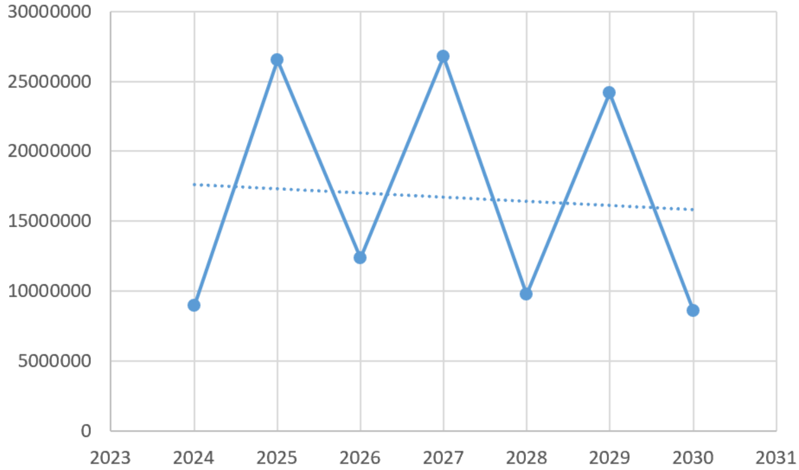

Figure 2: Total annual revenue chart in excess of slow-selling cases

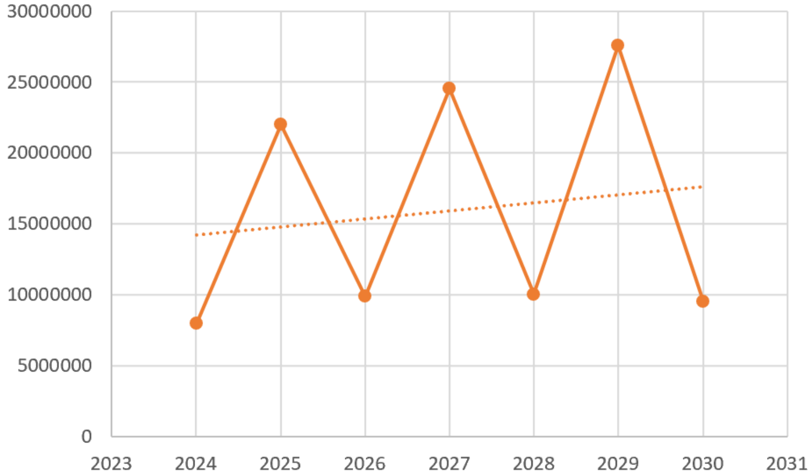

Figure 3: Total annual revenue chart in excess of markdown sales

As can be seen from the two figures, the annual return will show a cyclical trend in the next 7 years, and the annual return will show a downward trend in the case of more than all the unsalable parts, while the annual return will show an upward trend when the unsalable parts are reduced by 50%. The annual returns of the two cases are compared under the same coordinate to obtain Figure 4.

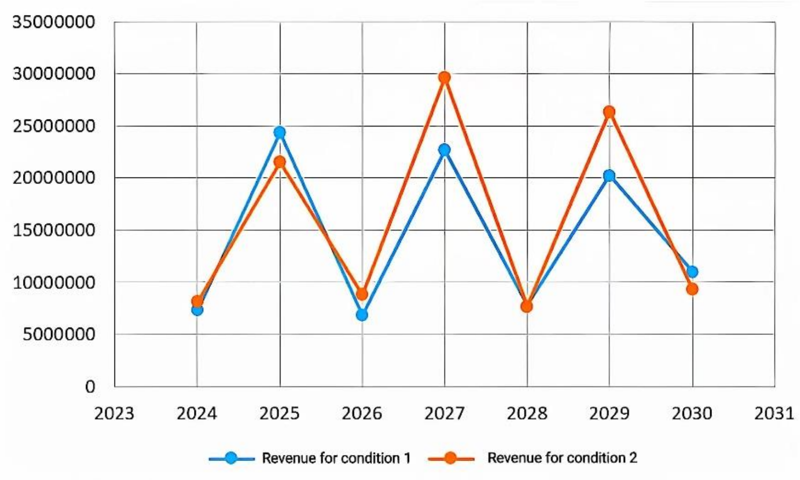

Figure 4: Comparison of the annual total revenue chart between the two conditions

In the two cases of direct waste of unsalable products whose total output exceeds the corresponding expected sales volume and price reduction treatment, Figure 4 shows that the annual total revenue in the next 7 years presents cyclical fluctuations, and repeat cropping may be the main reason for this phenomenon. Taking edible mushroom agricultural products with higher returns as an example, assuming that the sales volume and unit price of morel mushroom in the previous year are higher, its total income in the current year is higher. However, in order to avoid the negative effects of repeated cropping, such as soil nutrient imbalance, other types of agricultural products are planted in the second year, and their market demand and sales price may be lower than that of edible mushroom such as morel mushroom. This leads to a decrease in total revenue in the second year, and eventually shows rhythmic fluctuations.

By observing the trend lines in Figure 2 and 3, it can be found that the direct waste of unsalable products will lead to a downward trend of the trend line of the total income of agricultural products in 2024-2030, while the 50% reduction of the price of unsalable products shows an upward trend of the trend line of the total income of agricultural products in the same period of time. The main reasons for this phenomenon are as follows. First, when unmarketable products are directly wasted, the additional loss caused by their cultivation costs will cause the overall total income of agricultural products to decline, compared with the 50% reduction in the price of unmarketable products is a more aggressive marketing strategy. Although the price reduction will reduce the revenue per unit of product, it can stimulate sales growth, thereby increasing the total revenue through the "small profit, quick sales" way, attracting more price-sensitive consumers. At the same time, this strategy not only helps to increase the total revenue in the short term, but also may have a positive impact on the producer's long-term market position and establish more stable customer relationships. Therefore, compared with direct waste of resources, price reduction is a more sensible and sustainable sales solution, which can effectively reduce the loss of resources and bring benefits to consumers, to achieve a win-win situation.

If exceeding expected sales per waste is taken as the standard, the cultivated amount of each crop in 2024-2030 can be viewed as Figure 5.

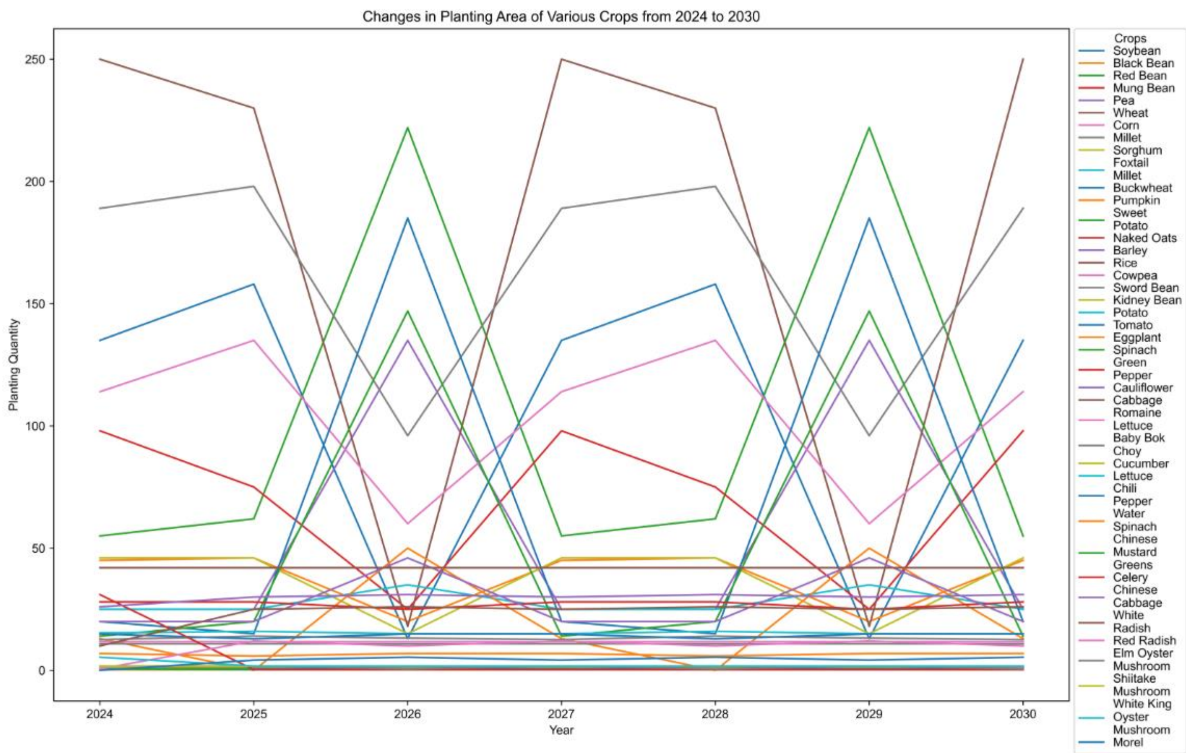

Figure 5: The planting area trend of all in the next 7 years

As can be seen from the graph, over the next seven years, the trend is roughly the same among some crops, while the trend is just the opposite among others. Crop tillage showed periodic changes, and with the change of year, the price elasticity of crops with larger cultivated area was greater, and the fluctuation of planting amount was larger.

If more than expected sales are sold at a 50% discount, the cultivated amount of each crop in 2024-2030 can be viewed as shown in Figure 6.

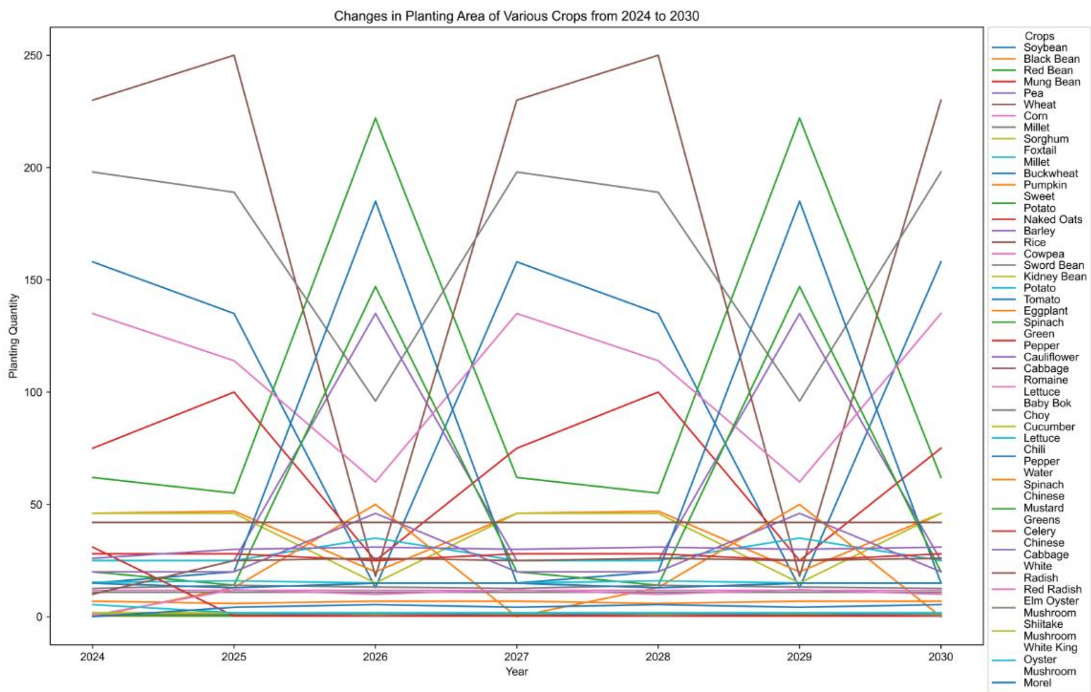

Figure 6: The planting area trend of all in the next 7 years

As can be seen from the graph, the trend in the next seven years is roughly the same among some crops, and the trend is just the opposite among some crops, and most major crops show cyclical fluctuations. Major food crops, such as wheat and various pulses, have fluctuated greatly. Compared to the total waste of exceeding expected sales, the trend of several major cultivated crops in 2024-2025 and 2027-2028 is just the opposite.

3.3. Results of Monte Carlo simulation

By combining Monte Carlo method with linear programming, a highly adaptive stochastic simulation model is constructed. The model takes into account the fluctuations of key factors such as sales, production, planting costs and prices in a highly variable market and complex environmental conditions. The projected annual total revenue for 2024-2030 is shown in Figure 7 below.

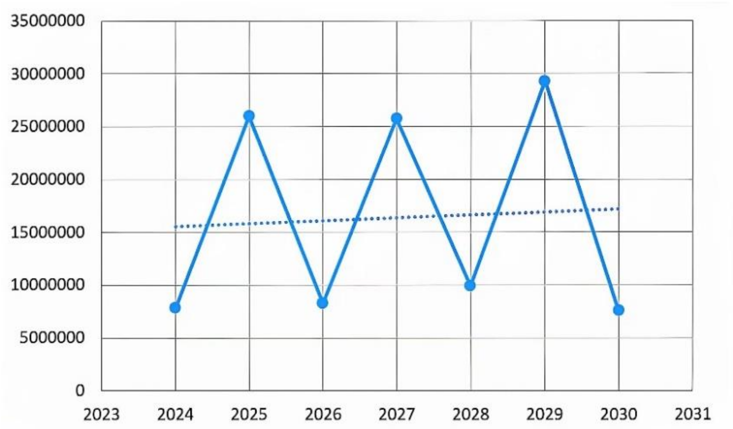

Figure 7: Total annual revenue chart

Forecast data show an increase in annual total earnings volatility in 2024-2030. Despite the rising cost of planting and the uncertainty of selling price, the total revenue was improved through effective strategy adjustment.

The model leverages the power of Monte Carlo simulation to constrain scenarios according to the market. Then, the planting strategy was optimized by linear programming. After rigorous analysis and calculation, the results clearly show that when facing the uncertainty of the market, the planting scheme should not be limited to a single model, but should develop in a more diversified direction. The projected 2024-2030 planting area of 41 crops divided into four groups is shown in Figure 8.

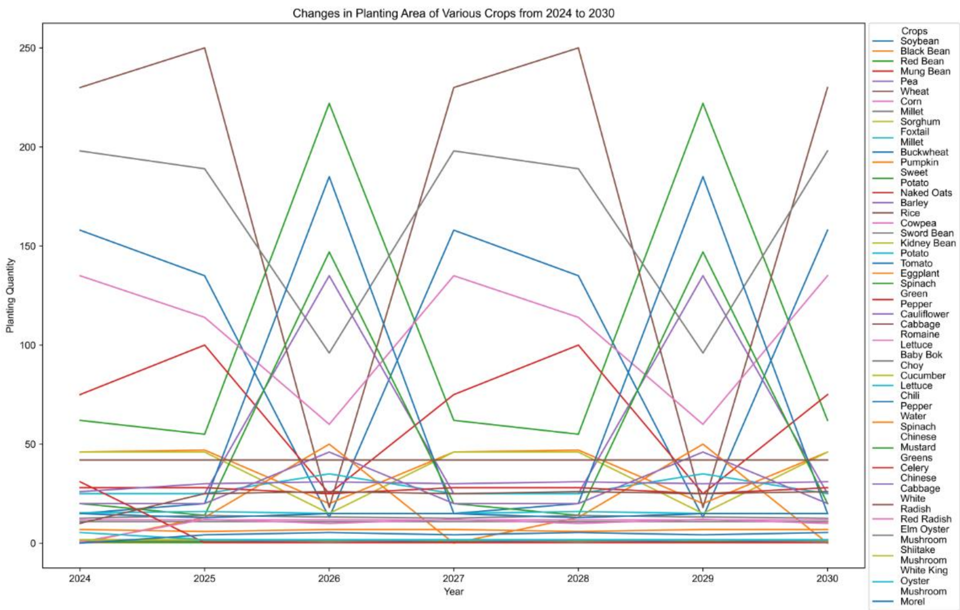

Figure 8: The planting area trend of all in the next 7 years

As can be seen from the figure, the change of planting area of all crops is significantly flatter than that without considering weather and market factors, and the change of planting area of all crops tends to be stable with the growth of years. Among them, the sales volume of edible fungi is declining year by year, and the planting area is gradually smaller, and it may no longer be cultivated by 2030. Although the sales price of edible fungi is high, the decrease in sales volume leads to the decrease in revenue. Compared with the previous unsalable waste or lower price treatment, the decrease in sales volume has a greater impact on the sales volume of edible fungi. According to different market situations, flexible and dynamic adjustment of crop types and the corresponding planting proportion can effectively reduce market risks, and thus achieve a significant increase in the overall income.

4. Conclusions

This paper addresses the problem of optimizing crop planting strategies within the context of rural agricultural environments. Recognizing the complexities and uncertainties inherent in agricultural planning, a comprehensive model is proposed that synergizes the methodologies of linear programming and the Monte Carlo simulation. This model is specifically designed to consider a multitude of uncertain factors, including predicting sales volumes, planting costs, and yield variability, among others. Through detailed analysis and simulation, the results of this study compellingly demonstrate that the adoption of a diversified planting plan, characterized by its flexibility to make dynamic adjustments in response to evolving market scenarios, can serve as an effective means of mitigating market risks and substantially enhancing overall financial returns. This strategic approach promotes resilience within the farming system. It holds significant promise for enhancing production efficiency, thereby contributing to the sustainability and profitability of rural agricultural practices.

Nonetheless, the study has its limitations. The model may not yet capture the full spectrum of factors that influence crop planting decisions in rural settings. Consequently, future research should focus on further refining the model and incorporating additional factors that may impact the optimization strategy. This could include considerations such as climate change impacts, soil health, and technological advancements in agricultural practices. By addressing these additional factors, future studies can enhance the precision and practicality of the optimization strategy, thereby contributing to more sustainable and profitable agricultural practices in rural communities.

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