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Research on Optimization Model of Crop Planting Strategy Based on Linear Programming

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Abstract. With the advancement of China's rural revitalization strategy, exploring scientific planting strategies is becoming increasingly important for achieving sustainable development of rural economy. This article takes a village in Huabei Mountain District as the research object and establishes a linear programming model to optimize the planting strategy of crops, to maximize the economic benefits of the village from 2024 to 2030. Firstly, based on the crop yield per mu, cost, and sales price data in 2023, a linear programming model was established with the goal of maximizing total revenue. Then, by analyzing the constraints of crop selection, continuous planting, legume crop rotation, and area allocation in the plot, the constraints of the objective function were defined. For the overproduction part, this article calculates the objective function under the conditions of unsold waste and 50% price reduction for sale. The results show that under the condition of unsold waste, the maximum total revenue of the village from 2024 to 2030 is approximately 2.38 million; under a 50% price reduction, the maximum total revenue for the village is approximately 2.59 million, and the provided planting plan meets all constraints.

Keywords: Linear Programming, Robust Optimization, Penalty Factor, Monte Carlo.

1. Introduction

In recent years, China has vigorously promoted rural revitalization and sustainable agricultural development, which has played an important role in poverty alleviation and long-term economic growth [1]. This article takes a village in Huabei Mountain District as the research object, exploring scientific planting strategies to achieve long-term rural development. The region has consistently low temperatures and complex farming conditions, with most cultivated land only able to grow one season of crops per year [2]. The cultivated land in the village is divided into four categories: flat dry land, terraced land, hillside land, and irrigated land [3]. The types of crops suitable for planting are different, and the planting season is limited by climate [4]. Although ordinary greenhouses and smart greenhouses have increased planting options, they have put forward higher requirements for planning. The village also needs to follow the growth pattern of crops and cannot continuously plant the same crop on each plot [5]. It is necessary to ensure that legumes are planted once every three years to maintain soil health. In addition, the planting process also needs to avoid crops being too scattered to ensure ease of cultivation [6]. Therefore, how to efficiently utilize limited arable land, ensure planting continuity and soil health, while improving agricultural efficiency, has become an urgent problem to be solved.

2. Analysis of Farmland Type Data and Planting Data

Calculate the total sales volume of each crop (sales volume=planting area x yield per mu) by merging the primary keys of crops and plot types, combined with yield per mu. The processed data includes crop number, crop name, crop type, planting area, planting season, plot type, yield per mu, planting cost, sales unit price, and total sales volume. Finally, the sales unit price in was further processed.

This article calculates the average selling price of each crop by splitting and averaging the price range and summarizes the total sales volume and average price of each crop.

2.1. Crop yield

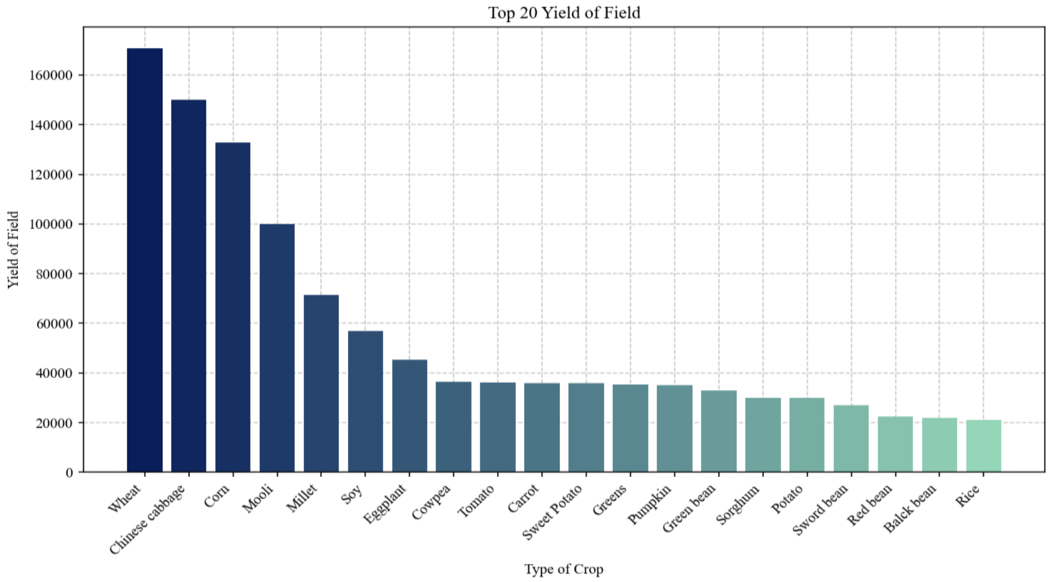

Figure 1: The top 20 crops in terms of crop yield.

As shown in Figure 1, wheat, Chinese cabbage, corn, white radish, and millet are crops with higher yields. These crops may have better adaptability or a wider planting area, which can provide stable food supply for villages [7]. In contrast, the yields of rice, black beans, red beans, adzuki beans, potatoes, and sorghum are relatively low, which may be limited by growth conditions, market demand, or planting area.

2.2. Average profit of crops

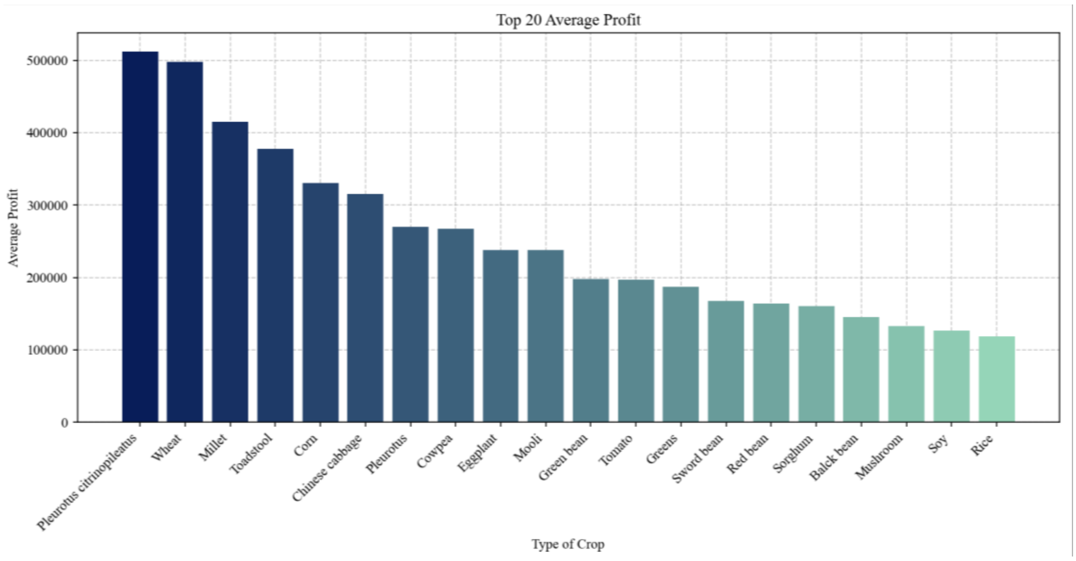

Figure 2: The top 20 crops with the highest average profit.

In the profit ranking of Figure 2, crops such as Ulmus chinensis, wheat, foxtail millet, morel mushrooms, and corn rank among the top. These crops not only have high yields, but also have good economic benefits, making them suitable as priority planting objects. In contrast, crops such as rice, soybeans, shiitake mushrooms, black beans, sorghum, and red beans have lower profits, which may be due to their lower market prices or higher planting costs [8]. For crops with lower profits, the planting area and input need to be further optimized.

3. Research on Optimization Strategies for Crop Planting

3.1. Establishment of Objective Function

In this optimization study, the goal is to maximize the net benefits that can be generated by planting different crops on all cultivated land between 2024 and 2030. Arable land is divided into single season plots, flat land plots, and double season plots (such as irrigated land and greenhouses). The objective function will consider different types of plots, crop types, sales revenue, unsold land treatment, and planting costs.

3.2. Objective function of unsold waste

In the case of unsold products, the excess production cannot be sold, so planting the excess will incur additional costs but cannot generate profits. The specific function construction process is as follows:

(1) Single season plot objective function

Single season plots refer to those plots that can only plant one season of crops per year, such as flat land, terraced fields, and hillside land [9]. On these plots, crops grow and sell within a single period, and any excess sales beyond expectations will be unsold, resulting in losses. The specific formula is as follows:

$$M_{single} = \sum_{y=2024}^{2030} \sum_{i \in singleplots} \sum_{k \in singleseason} (P_k \times \min(Y_k \times A_i, S_k) - C_k \times A_i) \times x_{iky1} \quad (1)$$

Among them, P_k is the selling unit price of the crop, Y_k is the yield per mu of the crop, A_i is the area of plot i, S_k is the expected sales volume of the crop, C_k is the planting cost of the crop, and the seasonal s=1 of x_{iky1} is 1. Whether or not to plant the crop KK (0-1 variable).

(2) Dual season plot objective function

Double season plots can plant two crops in a year, mainly irrigated land in this question. The characteristic of this type of plot is that it can be planted with the same or different crops in two seasons, so the contribution of the two planting seasons needs to be considered when calculating the income [10]. The specific formula is as follows:

$$M_{irrigated} = \sum_{y=2024}^{2030} \sum_{i \in irrigated} \sum_{k \in doubleseason} (P_k \times \min(Y_k \times A_i, S_k) - C_k \times A_i) \times (x_{iky1} + x_{iky2}) \quad (2)$$

(3) Objective function of ordinary greenhouse

A regular greenhouse is another type of land where two seasons of crops can be grown within a year. Greenhouses can regulate temperature and humidity, making them suitable for growing a variety of crops [11]. Like the double season plot, ordinary greenhouses also need to calculate the planting income for two seasons. The specific formula is as follows:

$$M_{greenhouse} = \sum_{y=2024}^{2030} \sum_{i \in greenhouse} \sum_{k \in g\_doubleseason} (P_k \times \min(Y_k \times A_i, S_k) - C_k \times A_i) \times (x_{iky1} + x_{iky2}) \quad (3)$$

(4) Objective function of smart greenhouse

Smart greenhouse is an agricultural facility that has undergone technological upgrades based on ordinary greenhouses, which can further optimize crop planting conditions and increase yields [12]. On such plots, the output of the two planting seasons needs to be calculated separately and compared with the expected sales volume to determine unsold losses.

$$M_{smartgreen} = \sum_{y=2024}^{2030} \sum_{i \in smartgreen} \sum_{k \in s\_doubleseason} (P_k \times \min(Y_k \times A_i, S_k) - C_k \times A_i) \times (x_{iky1} + x_{iky2}) \tag{4}$$

(5) Comprehensive objective function

The comprehensive objective function is the sum of the objective functions of all land types, representing the total net income of all land in the entire village:

$$M = M_{single} + M_{irrigated} + M_{greenhouse} + M_{smartgreen} \tag{5}$$

3.3. Objective Function for Price Reduction Processing

In the case of price reduction, the excess portion can be sold at 50% of the original price [13]. At this point, the objective function not only considers crops sold according to market demand, but also considers the revenue from selling excess crops at discounted prices. The definition of variables here is the same as that of unsold parts, with the only difference being that parts exceeding demand will be sold at a half discount.

(1) Single season plot objective function

For single season land parcels, the portion sold at a reduced price will be treated at 50% of the original price, which will reduce the loss of unsold parts. The specific formula is as follows:

$$\mathrm{M_{single}} = \sum_{y=2024}^{2030} \sum_{y=2024}^{2030} \sum_{i \in singleplots} \sum_{k \in singleseasons} \begin{pmatrix} P_k \times \min(Y_k \times A_i, S_k) + 0.5 \times P_k \times \max \\ (0, Y_k \times A_i - S_k) - C_k \times A_i \end{pmatrix} \times x_{ik(y,1)} \tag{6}$$

Among them, is the selling unit price of the crop, is the yield per mu of the crop, is the area of the plot, is the expected sales volume of the crop, is the planting cost of the crop, and the season=1. Whether to plant the crop or not (0-1 variable).

(2) Dual season plot objective function

On the double season plot, the method of price reduction sales is also applicable, and the profit function includes the crop planting situation of both seasons:

$$M_{irrigated} = \sum_{y=2024}^{2030} \sum_{i \in irrigated} \sum_{k \in doubleseason} \begin{matrix} (P_k \times \min(Y_k \times A_i, S_k) + 0.5 \times P_k \times \\ \max(0, Y_k \times A_i - S_k) - C_k \times A_i) \times (x_{ik(y,1)} + x_{ik(y,2)}) \end{matrix} \tag{7}$$

(3) Objective function of ordinary greenhouse

The unsold parts of ordinary greenhouses will also be sold at 50% of the price, reducing the losses caused by excess parts:

$$M_{greenhouse} = \sum_{y=2024}^{2030} \sum_{i \in greenhouse} \sum_{k \in g\_doubleseason} \begin{matrix} (P_k \times \min(Y_k \times A_i, S_k) + 0.5 \times P_k \times \\ \max(0, Y_k \times A_i - S_k) - C_k \times A_i) \times (x_{ik(y,1)} + x_{ik(y,2)}) \end{matrix} \tag{8}$$

(4) Objective function of smart greenhouse

The crop yield of smart greenhouses is higher, but the handling of unsold parts also needs to be considered. Price reduction sales will reduce the impact of unsold goods and bring more revenue to the village:

$$M_{greenhouse} = \sum_{y=2024}^{2030} \sum_{i \in greenhouse} \sum_{k \in g\_doubleseason} \begin{matrix} (P_k \times \min(Y_k \times A_i, S_k) + 0.5 \times P_k \times \\ \max(0, Y_k \times A_i - S_k) - C_k \times A_i) \times (x_{ik(y,1)} + x_{ik(y,2)}) \end{matrix} \tag{9}$$

(5) Comprehensive objective function

In the case of price reduction, the comprehensive objective function is still composed of the objective functions of the four types of land parcels, reflecting the income of all land parcels in different years and planting seasons.

$$\mathrm{M} = M_{single} + M_{irrigated} + M_{greenhouse} + M_{smartgreen} \tag{10}$$

3.4. Analysis of Constraints

After establishing the objective function, to ensure the rationality of the plan, various constraints during the planting process must be considered, which come from factors such as farmland type, planting method, crop type, planting time, rotation requirements, etc.

(1) Definition and Constraints of Decision Variables

$$\begin{gathered} x_{ik(y,s)} = 0.5 \times y1_{ik(y,s)} + y2_{ik(y,s)} \\ y1_{ik(y,s)} + y2_{ik(y,s)} \leq 1 \end{gathered} \tag{11}$$

This constraint defines the rule for variable values, which determines whether to plant a specific crop by combining with the variable and ensures that both and are not equal to 1, thus avoiding duplicate selections.

(2) Crop selection restrictions for single season plots

For single season plots and crops, as well as for each year y, crop selection satisfies the following constraints:

$$\sum_{k \in \text{ singleseason}} x_{ik(y,1)} = 1 \tag{12}$$

This constraint ensures that only one crop can be selected for planting on a single season plot each year.

(3) Crop selection restrictions for double season plots

For the double season plot $i \in$ irrigated, the crop range that $s = 1$ can choose in the first season of each year is $k \in \{16,17,...,34\}$, and the crop range that $s = 2$ can choose in the second season is $k \in \{16,35,36,37\}$. The corresponding constraints are:

$$\begin{gathered} \sum_{k=16}^{34} x_{ik(y,1)} = 1 \\ \sum_{k \in \{16,35,36,37\}} x_{ik(y,2)} = 1 \end{gathered} \tag{13}$$

Similarly, ordinary greenhouses and smart greenhouses also have similar crop selection restrictions, with crop ranges determined based on the type of plot.

(4) The planting ratio for each plot per season is 1

For each type of plot, the crop planting ratio in each season must be 1, indicating that the total area has been allocated. For single season plot $i \in singleplot$.

$$\sum_{k\in \text{singleseason}} x_{ik(y,1)} = 1 \tag{14}$$

For the double season plot i ∈ irregated crop k ∈ doubleseason, crop k ∈ g_doubleseason, crop k ∈ s_doubleseason, and crop k ∈ s_doubleseason, the crop proportion constraint for each season is:

$$\sum_{k\in \text{doubleseason}} x_{ik(y,s)} = 1 \forall \text{s} \in \{1,2\} \tag{15}$$

(5) Continuous Planting Restrictions

To avoid planting the same crop on a certain plot for multiple years in a row, the following constraints have been set to ensure that the same crop is not repeatedly planted in adjacent years or seasons:

$$\begin{gathered} x_{ik(y,1)} + x_{ik(y+1,1)} \leq 1 \\ x_{ik(y,1)} + x_{ik(y,2)} \leq 1 \\ x_{ik(y,2)} + x_{ik(y+1,1)} \leq 1 \end{gathered} \tag{16}$$

This constraint applies to all single season and double season plots, ensuring diversity in planting decisions.

(6) Crop rotation constraints for leguminous crops

Within each consecutive three years, leguminous crops (such as leguminous crops) must be planted at least once to maintain soil fertility [14]. For a single season plot, the rotation constraint for leguminous crops is:

$$\sum_{k\in \text{beancrops}} \sum_{y=y_{\text{start}}}^{y_{\text{start}}+2} x_{ik(y,1)} \geq 1 \tag{17}$$

For double season plots, greenhouses, and smart greenhouses, the rotation constraint for legume crops is:

$$\sum_{k\in \text{beancrops}} \sum_{y=y_{\text{start}}}^{y_{\text{start}}+2} \left(x_{ik(y,1)} + x_{ik(y,2)}\right) \geq 1 \tag{18}$$

This constraint ensures the reasonable arrangement of legume crop planting during the planting cycle of each plot.

3.5. Model solving

The objective function designed in this article involves both continuous and binary variables, therefore it can be classified as a mixed integer linear programming problem (MILP). The core objective of this model is to maximize the overall revenue of the village in the coming years by optimizing crop planting schemes on different plots. To achieve this goal, this article defines continuous variables that include crop planting decisions and auxiliary binary variables to constrain the selection of specific crops. The model includes detailed objective functions and constraints, considering factors such as plot type, seasonality, crop selection, climate, and market volatility.

After building the model, this article used the open-source linear programming solver PuLP to solve the MILP model. The results show that the planting results of various crops align with the natural growing habits of each plant. During the first quarter of 2024, the main crops cultivated included black beans, red beans, corn, sorghum, potatoes, and eggplants. In the second quarter, the focus shifted to rice, elm mushrooms, potatoes, tomatoes, and eggplants, among others.

The experimental results indicate that, assuming there is no unsold surplus or waste, the maximum total revenue for the village from 2024 to 2030 could reach ¥23,851,196.96. However, when crops are sold at a 50% discount, the maximum total revenue for the village increases to approximately 2.59 million. These findings highlight the potential for optimizing revenue through effective crop planting strategies.

4. Conclusions

The model in this article introduces fluctuation ranges for various factors such as price, yield, and planting costs, making decision-making more robust and able to cope with future market, climate, and other changes. The model also considers changes in different land types, crop types, and years, and can develop dynamic and flexible planting strategies. By introducing random factors such as pest risk, the model's ability to cope with unforeseeable risks in actual agricultural environments has been enhanced. At the same time, the optimized planting plan meets various constraints, including crop selection, continuous cropping, legume crop rotation, and land area allocation, while significantly improving the economic benefits of the village. This provides scientific guidance and reference strategies for achieving the strategic goals of rural revitalization. Future research can explore optimized planting schemes under different market fluctuations and policy changes to further improve the sustainability of agricultural economy.

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