The Research on Planting Strategies of Crops Based on Linear Programming Model

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Abstract. This study investigates the optimization of crop planting strategies in rural areas using linear programming models. The paper presents two distinct models: one assumes stable sales volumes, while the other accounts for fluctuations in factors such as sales volume, planting costs, yield per acre, and price variations. These models are solved using the Cplex optimization tool, integrating data from specific land and crop scenarios to predict optimal planting strategies for the period from 2024 to 2030. Additionally, the models effectively estimate future profit fluctuations, providing valuable insights for agricultural decision-making. The results offer a scientific basis for rural crop planting strategies, helping farmers devise effective planting plans that improve land use efficiency and enhance agricultural productivity. This research contributes significantly to the practical application of linear programming in agricultural decision-making, supporting better management of resources and ensuring sustainable farming practices. Furthermore, the study provides theoretical support and methods that can be applied to future crop planting optimization research, thereby contributing to the broader field of agricultural economics and planning.

Keywords: Linear Programming Model, Crop Planting Strategy, Profit Forecasting, Cplex Solver.

1. Introduction

With the rapid development of the times, how rural areas can choose suitable crops based on actual conditions, optimize planting strategies, and facilitate field management is an important research topic. This paper mainly studies two cases. Case 1: Assuming that the expected sales volume, planting cost, yield per acre, and sales price of various crops remain stable relative to 2023, and that the crops planted each season are sold in the same season. If the total yield of a certain crop exceeds the expected sales volume for that season, the excess part cannot be sold. The paper aims to provide an optimal planting plan for crops from 2024 to 2030 under the assumption that the expected sales volume, planting cost, yield per acre, and sales price remain stable relative to 2023. Case 2: In cases where some crops' expected sales volume, planting cost, yield per acre, and sales price are starting to change, the paper designs an optimal planting plan for crops from 2024 to 2030.

Most literature on crop planting strategies takes a qualitative approach, using biological results combined with environmental factors to derive corresponding planting strategies [1-7]. However, there are fewer studies from a quantitative perspective that specifically consider crop planting. For example, Yang Yijiang et al. [8] and Sun Liquan [9] used dynamic programming methods to determine the optimal planting plans for crops in 2013 and 2015, respectively; Wang Shuai [10] and Dong Xiaohui et al. [11] analyzed changes in crop planting in 2024 based on land distribution.

Compared to the issues considered by Yang Yijiang et al. and Sun Liquan, our task is more complex, as we consider the optimal planting plan for multiple crops on different lands. We establish two linear programming models and, under certain assumptions, estimate the total profit of crops for 2024-2030, which can provide great insight for farmers' future decisions. Unlike Wang Shuai and Dong Xiaohui, who only analyzed data, we use linear programming methods to make the results more objective.

2. The Establishment of two Linear Programming Models

2.1. The establishment of the linear programming model

For Case 1, assuming that the expected sales volume, planting cost, yield per acre, and sales price for various crops remain stable relative to 2023, we will analyze the total yield and revenue, considering the unsold crop wastage in 2023. Below, we will provide a detailed analysis of the requirements and constraints.

Firstly, the total yield of each crop on the plot in 2023 is defined as follows:

$$T_{ij} = (P_{prod})_{ij} \times X_{ij}^{2023}, \tag{1}$$

Where $(P_{prod})_{ij}$ represent the yield per acre (mu/jin) of the i-th crop on the -th piece of land in 2023, and X_{ij}^{2023} denote the area (mu) allocated to the i-th crop on the j-th piece of land, with the principle of equal area distribution applied for mixed cropping on the j-th piece of land.

(1) Calculation of expected future sales volume:

Since it is difficult to obtain the future sales volume for each crop, and the expected sales volume is often influenced by many factors, we assume that the expected sales volume in 2023 is a multiple of the total sales volume, with the multiplier set as a random number between 0.65 and 1. Therefore, the expected sales volume of i-th crop on the j-th piece of land is expressed as:

$$Y_{ij} = r \times \tilde{T}_{ij} \tag{2}$$

Where $\tilde{T}_{ij}$ represents the total yield of crops on the plot of land in 2023.

(2) Income calculation situation:

1) If there is no unsold surplus, meaning the total yield in 2023 is less than or equal to the expected sales volume, the revenue can be expressed as:

$$w_{ij} = \tilde{T}_{ij} \times p_{ij}, \tag{3}$$

Where $\tilde{T}_{ij}$ represents the total output of crops i on the j-th plot in 2023, and p_{ij} represents the selling unit price of crops i on the j-th plot.

2) There is unsold surplus, meaning the total yield in 2023 exceeds the expected sales volume, the revenue can be expressed as:

$$w_{ij} = Y_{ij} \times p_{ij}, \tag{4}$$

Where Y_{ij} represents the expected sales volume of crops i on the j-th plot, and p_{ij} represents the selling unit price of crops i on the j-th plot. For the excess unsold parts in this situation, they cannot be sold directly, resulting in waste.

Based on the two scenarios of a and b, we have obtained the expression for calculating the profit:

$$w_{ij} = \begin{cases} \tilde{T}_{ij} \times p_{ij} \ , if \ \tilde{T}_i \le Y_i' \\ Y_{ij} \times p_{ij} \ , if \ \tilde{T}_i \ge Y_i \end{cases} \tag{5}$$

Where $\tilde{T}$ represents the actual total yield of crops i in 2023, and Y_i' represents the expected total yield of crops in 2023. Our objective function is to maximize the total profit from 2024 to 2030, which is established as follows:

Objective function:

$$\max_X \sum_{k=2024}^{2030}\sum_{i=1}^{m}\sum_{j=1}^{n}((C_{cons}^{k})_{ij}\times(w^{k})_{ij}\times(P_{prod}^{k})_{ij}-(P_{\mathrm{cost}}^{k})_{ij})\times X_{ij} \tag{6}$$

Where C_{cons}^{k} represents whether the crop i in year can be planted on j-th plot type. $(w^{k})_{ij}$ represents the per-acre profit of the crop i in year on j-th plot. $(P_{\mathrm{cost}}^{k})_{ij}$ represents the cost price of the crop i in year for j-th plot.

For the situation in subsequent years, we only need to consider the following constraints:

(1) Each crop cannot be planted continuously in the same field (greenhouse).

At this point, it is only necessary to ensure that the elements of the constraint matrix for consecutive years are not equal, as shown in the following formula:

$$(C_{cons}^{k})_{ij}\neq(C_{cons}^{k+1})_{ij}\quad k=2024,2025,...,2029. \tag{7}$$

(2) All land should be planted with leguminous crops at least once within three years.

We only need to sum the constraint matrix for legume crops across three consecutive years and ensure the value is greater than or equal to 1, as shown in the following formula:

$$(C_{cons}^{k})_{\mathrm{bean},\ j}+(C_{cons}^{k+1})_{\mathrm{bean},\ j}+(C_{cons}^{k+2})_{\mathrm{bean},\ j}\geq 1\quad (k=2023,2024,...,2028). \tag{8}$$

(3) The planting areas of each crop cannot be too scattered.

The understanding that crop planting should not be too dispersed is as follows: To facilitate field management, crops should not be planted in too many plots, as this would lead to dispersion and complicate management. Therefore, in this study, each crop is limited to being planted on no more than 4 plots during the same period, which can be expressed by the following formula:

$$(C_{cons}^{k})_{ij}\leq 4\quad k=2024,2025,...,2029,\ j=1,2,...,n, \tag{9}$$

Where $i=1,2,3,...,m$.

(4) The planting area of a single plot cannot be too small.

“Too small” is a qualitative concept, and defining how small is “too small” is challenging. However, through data analysis from 2023, we obtained a reasonable result: the minimum area of a single plot is 0.3. Based on this, we can set the planting area for each plot as:

$$S_{ij}^{t}\geq 0.3\ (t=2023,...,2030), \tag{10}$$

In summary, we can establish the following linear programming model:

$$\begin{gathered}\max_X \sum_{k=2024}^{2030}\sum_{i=1}^{m}\sum_{j=1}^{n}((C_{cons}^{k})_{ij}\times(w^{k})_{ij}\times(P_{prod}^{k})_{ij}-(P_{\mathrm{cost}}^{k})_{ij})\times X_{ij}\\ s.t.\begin{cases}(C_{cons}^{k})_{ij}\neq(C_{cons}^{k+1})_{ij}\quad k=2024,2025,...,2029\\ (C_{cons}^{k})_{\mathrm{bean},\ j}+(C_{cons}^{k+1})_{\mathrm{bean},\ j}+(C_{cons}^{k+2})_{\mathrm{bean},\ j}\geq 1\quad (k=2023,2024,...,2028)\\ (C_{cons}^{k})_{ij}\leq 4\quad k=2024,2025,...,2029,\ j=1,2,3,...,n\\ S_{ij}^{t}\geq 0.3\ (t=2023,...,2030)\end{cases}\end{gathered} \tag{11}$$

2.2. The Establishment of a Linear Programming Model with Error Bars

Compared to Case 1, Case 2 features changes in factors such as expected sales volume, planting cost, yield per acre, and sales price. Therefore, we first analyze each parameter:

(1) Changes in expected sales volume.

There is a growing trend for wheat and corn in the future, with an average growth rate ranging from 5% to 10%.

$$(Y)_{kj}^{t}=(Y)_{kj}^{2023}\times(1+r)^{t-2023}\ ,r\in[5\%,10\%],\ k=w\text{heat, corn} \tag{12}$$

Where $(Y)_{kj}^{t}$ represents the expected sales volume of crops i in t-th year for j-th block of land, and r represents the average growth rate.

For other crops, the expected sales volume in the future will vary by approximately ±5% compared to 2023, with the following formula:

$$(Y)_{kj}^{t}=(Y)_{kj}^{2023}\times(1+r)^{t-2023}\ ,r\in[-5\%,5\%],\ k\neq \texttt{weat, corn} \tag{13}$$

(2) Changes in yield per mu: The annual yield per mu of all crops fluctuates by ± 10%.

$$(P_{prod})_{kj}^{t}=(P_{prod})_{kj}^{2023}\times(1+r)^{t-2023}\ ,r\in[-10\%,10\%], \tag{14}$$

Where $(P_{prod})_{kj}^{t}$ represents the annual yield of crops i on the j-th plot of land (mu).

(3) Changes in planting costs: The average annual increase in crop costs is about 5%.

$$(C_{\text{cost}}^{t})_{ij}=C_{2023}\times(1+r)^{t-2023}\ ,\ r\text{=5\%} \tag{15}$$

Where $(C_{\text{cost}}^{t})_{ij}$ represents the planting cost of crops i on the j-th plot of land in the year (yuan/acre).

(4) Changes in sales prices: Grain crop prices remain stable, vegetable crop prices show an upward trend of about 5%, and edible mushroom prices decrease by 1%-5% annually, with more significant drops in the price of morel mushrooms, around 5%. The formula is as follows:

$$\begin{cases} w_{ij}^{t}=w_{ij}^{2023}\times(1+r)^{t-2023}\ ,\ r\text{=5\%}, i=v\text{egetable crops} \\ w_{ij}^{t}=w_{ij}^{2023}\times(1-r)^{t-2023}\ ,\ r\in[1\%,5\%], i=\text{edible fungi} \\ w_{ij}^{t}=w_{ij}^{2023}\times(1-r)^{t-2023}\ ,\ r=5\%, i=\text{morel} \end{cases} \tag{16}$$

The revenue calculation formula assumes that sales exceeding the expected volume are sold at 50% of the sales price.

Based on the above changes, the constraints are the same as in Case 1 and will not be repeated here. Therefore, we establish an optimization model.

$$\max{}_X \sum_{k=2024}^{2030}\sum_{i=1}^{m}\sum_{j=1}^{n}((C_{cons}^{k})_{ij}\times(w^{k})_{ij}\times(P_{prod}^{k})_{ij}-(P_{\text{cost}}^{k})_{ij})\times X_{ij}$$

$$s.t.\begin{cases} (C_{cons}^{k})_{ij}\neq(C_{cons}^{k+1})_{ij}\quad k=2024,2025,...,2029 \\ (C_{cons}^{k})_{\text{bean, }j}+(C_{\text{约束}}^{k+1})_{\text{bean, }j}+(C_{cons}^{k+2})_{\text{bean, }j}\geq 1\ （k=2023,2024,...,2028） \\ (C_{cons}^{k})_{ij}\leq 4\ \ k=2024,2025,...,2029,\ j=1,2,3,...,n \\ S_{ij}^{t}\geq 0.3\ (t=2023,...,2030) \end{cases} \tag{17}$$

3. Results

3.1. Results and analysis of the linear programming model

Given the complexity of the linear programming model in Case 1, traditional optimization methods seem difficult to solve. Therefore, we use the Cplex optimization toolbox to solve the problem.

Cplex Optimization Toolbox

Cplex is an advanced mathematical optimization tool primarily used to enhance operational efficiency, quickly execute strategies, and increase profits. By leveraging the mathematical optimization techniques provided by WebSphere ILOG CPLEX, more effective resource allocation decisions can be made. Cplex transforms complex decision problems into mathematical programming models, and its powerful optimization algorithms can quickly provide solutions for these complex models.

Solution for Case 1

Due to space limitations, only the optimal crop planting method for 2024 is analyzed. The optimal crop planting plan for 2024 is shown in Figure1.

The solution is a 41×82 matrix where the vertical axis represents crops, and the horizontal axis represents planting locations. A_i , B_i C_i represent different planting types ar, and the "-1" and "-2" indicate the first and second quarters, respectively.

From Figure 1, we can see that the solution aligns with our assumption: each plot can only have a maximum of two types of crops per quarter. Next, let's examine if certain constraints are met:

(1) Ordinary greenhouses are suitable for planting one season of vegetables and one season of edible fungi per year.

The locations of these greenhouses are identified in $E_1 - E_{16}$, and they only show planting in the first quarter, with vegetables and edible fungi, which aligns with the constraint.

(2) Due to seasonal factors, crops like cabbage, white radish, and red radish can only be planted in the second season on irrigated land.

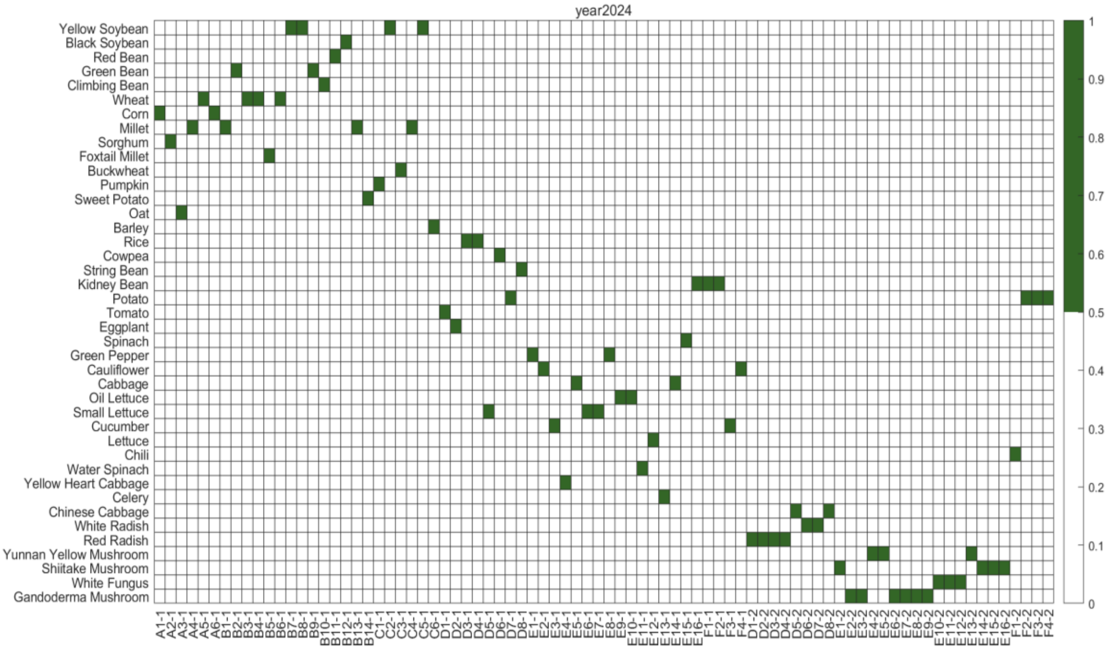

Figure 1. Optimal Crop Planting Plan for 2024

We identified the locations $D_1 - D_8$ of these crops in Figure 1, and the irrigated land positions meet the requirement for planting these crops only in the second quarter.

Other constraints are also satisfied, indicating that the solution is accurate and reasonable. Next, we will present the expected profit situation, shown in Figure 2.

From Figure 2, we can see that the profit in the first year is around 4.35 million, then drops to about 3.75 million in the second year, likely due to overstock and waste, causing a downward trend in profits in subsequent years. This pattern persists in later years, indicating the impact of waste caused by overstock.

Each year's profit fluctuates between 3.7 and 4.5 million, with a total profit of around 29.62 million, which aligns with actual conditions. The sharp decline in profit during the first two years is likely due to excessive waste from unsold stock, leading to profit decreases in the following years.

Overall, the solution aligns with real-world conditions.

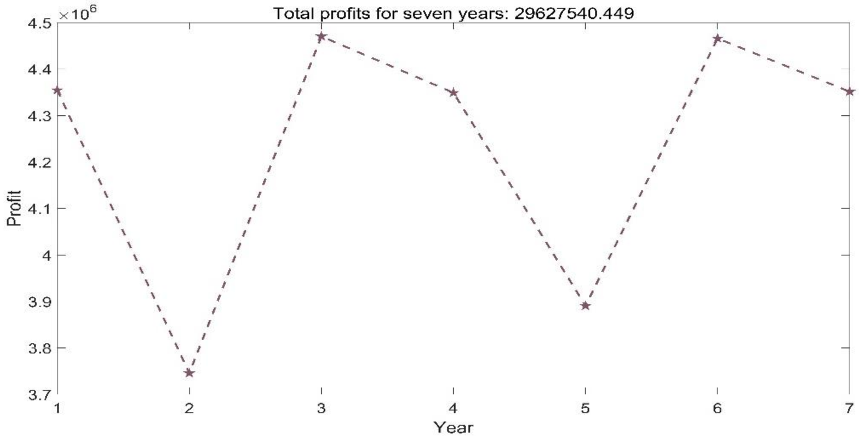

Figure 2. 7-year profit display situation

3.2. The results and analysis of the linear programming model with error bars

Considering the complexity of the linear programming model in Case 2, traditional optimization methods are difficult to solve. Therefore, we use the Cplex optimization toolbox to solve the problem.

Due to space limitations, we only present a comparison of the optimal planting plans for 2024 and 2025. They are shown in Figure 3 and Figure 4 respectively.

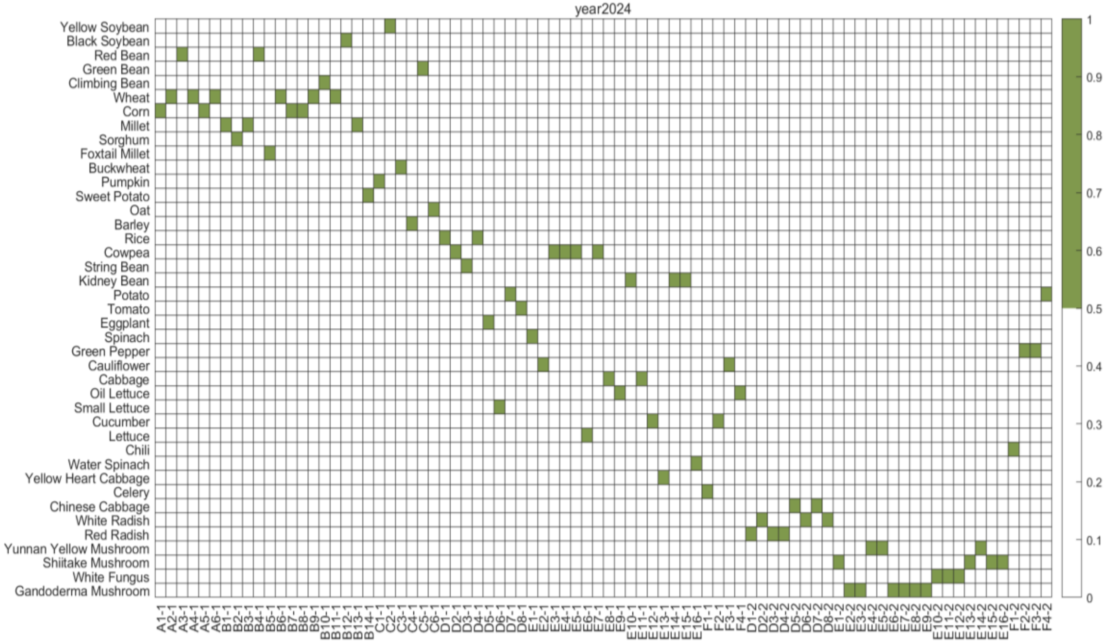

Figure 3. The optimal planting plan for 2024

Based on the changes in expected sales volume, planting costs, yield per acre, and sales prices, we analyze the results as follows:

(1) Increase in wheat and corn sales volume:

Due to the expected increase in sales volume, we observe 6 plots of land for wheat and 4 for corn in 2024, and 4 plots of land for both wheat and corn in 2026. This may be due to increased supply leading to reduced planting in rural areas.

(2) 1%-5% decrease in edible fungus sales prices:

From Figure 4, we observe a slight decline in edible fungus planting, likely due to the small decrease in price, which isn't fully captured in a one-year gap.

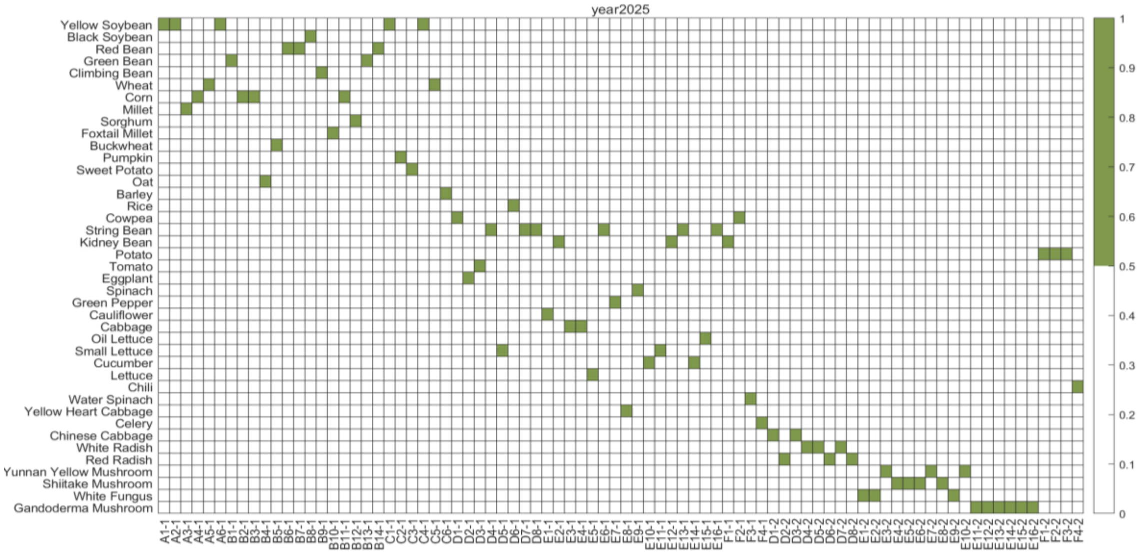

Figure 4. Optimal Planting Plan for 2025

Other trends can also be analyzed similarly, but are not elaborated here.

To better illustrate the profit situation, we generated 50 sets of random numbers and created a profit chart with error bars. This allows for a clearer analysis of each year's performance, as shown in Figure 5.

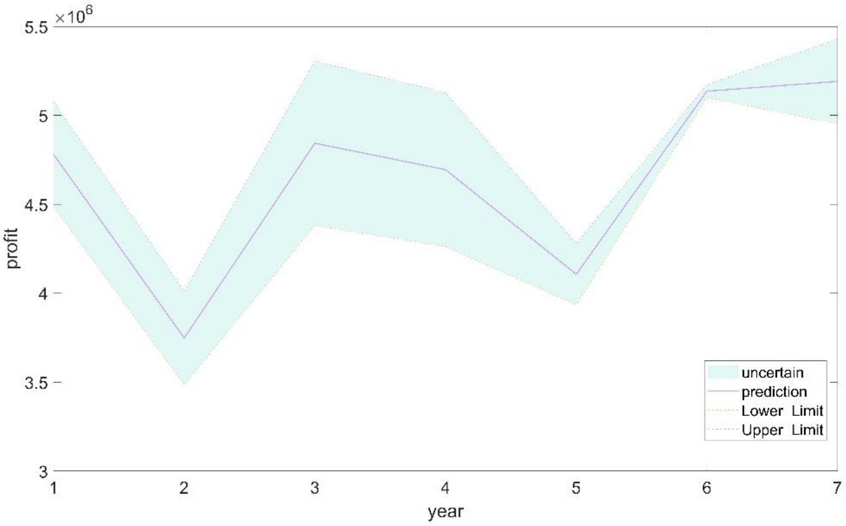

Figure 5. Profit with error margin for the next 7 years

We generated 50 sets of random numbers to create Figure 5, which clearly shows significant profit fluctuations in the next 3-4 years, likely due to larger variations in indicators. However, the fluctuations are smaller in the 1-3 and 5-7 year periods. This analysis provides a general range for economic profit fluctuations and offers valuable insights for rural planting and developing optimal planting strategies.

4. Conclusion

This study developed a linear programming model to explore the optimization of crop planting strategies in rural areas. Two different models were designed to predict the optimal planting plans for 2024-2030, considering factors such as unsold stock, expected sales volume, planting costs, and yield per acre. Using the Cplex optimization tool, specific planting plans and future profit forecasts were derived, offering significant guidance for rural crop planting decisions. The study not only provides quantitative decision support for farmers but also offers a theoretical basis for improving land use and agricultural productivity, with potential for broader application.

And future research could explore enhancing the model's applicability and accuracy by addressing complex factors such as climate change and market demand fluctuations.

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