Optimization of Crop Planting Strategies Based on Monte Carlo Model under Dynamic Multifactor Analysis

Teng Zheng[1, †], Fengwei Wang [1, †, *], Xinyue Zhu[2, †]

[1] School of Computer and Information Engineering, Tianjin Agricultural University, Tianjin, China

[2] College of Agronomy and Resource Environment, Tianjin Agricultural University, Tianjin, China

† These authors also contributed equally to this work

*Corresponding author: 15054315312@163.com

Abstract. Based on crop statistics, this paper uses Monte Carlo intelligent algorithms to optimize crop cultivation between 2024 and 2030, aiming to develop a cultivation strategy that maximizes returns. First, this paper checked the completeness and accuracy of the data through data preprocessing, dealt with the stagnant sales situation in which the total crop production exceeded the expected sales volume, and categorized it into two scenarios of wastage and selling at a reduced price. Then, Monte Carlo Intelligent Algorithm was applied for crop planting strategy optimization. Further, the sales volume, mu yield, planting cost and volatility of sales price of each type of crops were added as constraints to enhance the realistic adaptability of the model. In addition, this paper quantified the linear relationship between the expected crop sales volume, sales price and planting cost using Spearman's phase relation, and further constructed a dynamic multifactorial crop planting optimization model, which considered the substitutability and complementarity of crops.

Keywords: Crop planting optimization; monte carlo intelligent model; spearman's correlation coefficient.

1. Introduction

The purpose of this paper is to explore the crop planting optimization scheme[1] for a village in the mountainous area by establishing a mathematical model and applying computer-related algorithms such as Monte Carlo Intelligence Model[1] and Spearman's correlation coefficient[3]. The study includes analyzing the planting benefits of different crops, the expected sales volume and its volatility, and developing an optimal planting strategy from 2024 to 2030 by combining factors such as plot type and planting season.

First, for the situation where the total crop production exceeds the expected sales volume, this paper adopts the Monte Carlo intelligent model for optimization and analyzes the planting scheme under the two scenarios of stagnant sales and selling at reduced prices. Secondly, the uncertainty and potential risks in the planting process are considered comprehensively[4], and the model is extended to reflect the impact of market fluctuations on planting costs and selling prices. Finally, by quantitatively analyzing the substitutability[5] and complementarity[6] between crops, the planting decision is further optimized to ensure maximizing the profit of crop sales.

2. Data Profiling

Given the complexity of the information and the wide range of data modules covered, such as data related to plots, crops, and sales, this section uses data profiling to sort out the information to ensure the accuracy of the analysis and the effectiveness of the decisions.

(1) Outliers and Missing Values Testing

After the test, the data set of 34 open-air plots and 20 greenhouses has complete information on plot name, plot type and plot area, with no intuitive missing values and outliers. The “pseudo-outliers” were analyzed and found to be a normal phenomenon, with no logical anomalies or data scale anomalies.

(2) Visual Analysis of Crop Classification

The information about crops suitable for planting in the countryside covers crop number, crop name and type. The crops that can be planted in the countryside are analyzed and classified into three major categories: grain, vegetables, and edible fungi. Among them, vegetable crops are the most diverse, covering 21 different vegetable varieties. Comparatively, the edible mushrooms category was the least diverse, with only four species of edible mushrooms suitable for cultivation in this area. In addition, there are 5 types of legumes in the food category, while 3 types of legumes are found in the vegetable category.

(3) Analysis of the Plot Hopper Cultivation in 2023

By analyzing the data, it can be found that in 2023, all open cultivated land, including flat and dry land, terraced land, hillside land and watered land, did not have the phenomenon of combined planting. Relatively, co-planting occurred mainly in the barns. Among the 16 ordinary greenhouses in 2023, one practiced crop co-planting; while all the four smart greenhouses practiced co-planting, and each type of co-planted vegetables occupied fifty percent of the greenhouse area.

(4) Categorized Comparative Analysis of the Average Selling Price of Each Crop

In this paper, the average value of each sales price range is taken as the representative sales unit price of the crop in different planting locations in 2023. In addition, crops 1-15 are widely grown mainly in open fields; Crops 17-34 are widely grown mainly in greenhouses. Rice and edibles are not included in this subgroup analysis. The unit sales prices of food crops are not very much related to the topography of cultivation, while vegetable crops have higher sales prices in the second season of the smart greenhouses.

3. Analysis of Planting Strategies under Stalled or Reduced Price Sales

Two scenarios will be analyzed for the portion of the total production of each crop season that exceeds the expected sales volume: waste from stagnant sales and selling at a reduced price of 50% of the 2023 sales price.

3.1. Establishment of the Objective Function in the case of stagnant sales

The objective function will consider a variety of constraints, such as plot type, planting season, and planting area. A combination of these constraints will be considered to ensure that the planting scenario developed will maximize profits in various market environments.

3.1.1 Establishment of Decision Variables

x_{ijv} : Area planted with the 3rd crop on the j th plot in the v th season. i : Crop number. $i = 1, 2, \cdots, 41$.

i : Number of the crop. $i = 1, 2, \cdots, 41$.

j : Number of the plot type $j = 1, 2, \cdots, 54$.

v : Season of planting. $v = 1, 2$.

y_{ij} : the acreage of the i rd crop on the j th plot.

3.1.2 Establishment of Objective Function

Objective function in case of stunting:

$$Max\left\{ Q_1 = \sum_{i=1}^{41}\sum_{j=1}^{54}\sum_{v=1}^{V}\left[p_{ij} \cdot \min\left(x_{ijv} \cdot y_{ij}, B_{ij} \right) - c_{ij} \cdot x_{ij} \right] \right\} \tag{1}$$

Where, Q_1 denotes the total profit in case of wastage due to excess stunting.

p_i denotes the selling unit price of the i th crop.

B_{ij} denotes the expected sales volume of the i th crop on the j th plot.

c_{ij} denotes the cost of growing the i th crop on plot j.

3.1.3 Delineation Constraints

(1) Constraints on Plot Cultivation Area

Whether it is open cultivation or greenhouse planting, the specific planting area should be less than or equal to the area of the plot. The planting area constraints are as follows:

$$\sum_{i=1}^{15} x_{ijv} \le S_j,\ j \in [1,26] \tag{2}$$

$$\sum_{i=16}^{37} x_{ijv} \le S_j,\ j \in [27,34] \tag{3}$$

$$\begin{cases} X_1 = \sum_{i=17}^{34} x_{ijv} \le S_j, v=1 \\ X_2 = \sum_{i=38}^{38} x_{ijv} \le S_j, v=2 \end{cases},\ j \in (35,50) \tag{4}$$

$$\sum_{i=17}^{34} x_{ijv} \le S_j, v \in (1,2),\ j \in (51,54) \tag{5}$$

(2) Constraints for Choosing Rice or Vegetables in Watered Land

Water-consumed land is suitable for planting rice in a single season and can also be planted with vegetables in two seasons, and it should be noted that simultaneous planting of rice and vegetables is not allowed in the same plot in the same year. Therefore, in order to clarify the constraints of watered land, 0-1 variables will be introduced to decide whether to plant a particular crop or not.

0-1 variable:

$$T_{ijv} = \begin{cases} 1, \text{Indicates selection of crop i} \\ 0, \text{Indicates that the i-crop is not selected} \end{cases} \tag{6}$$

The decision on whether to plant a specific crop can be constrained by a number of conditions. The following are some of the possible constraints that can influence the choice of crop to be planted:

$$\begin{cases} Z = \sum_{i=16} T_{ijv} = 1 \\ Z = \sum_{i=16} T_{ijv} = 0 \end{cases},\ j \in (27,34) \tag{7}$$

$$\begin{cases} A_1 = \sum_{i=17}^{34} T_{ijv} \le 1 \\ A_2 = \sum_{i=35}^{37} T_{ijv} \le 1 \\ Z + \dfrac{A_1 + A_2}{2} \le 1 \end{cases},\ j \in (27,34) \tag{8}$$

Where $Z=1$ indicates the choice to grow single-season rice; $Z=0$ indicates no choice to grow single-season rice.

A_1 indicates the choice of planting crop i or not in the first season of plot j in the watered land.

A_2 indicates whether to choose to plant the i crop in the second season of plot j in the watered land.

(3) Constraints on Ordinary Greenhouses

In the first season, ordinary greenhouses can only grow all kinds of vegetables except Chinese cabbage, white radish and red radish. In the second season, the planting range is limited to edible mushrooms. The constraints for ordinary greenhouses are as follows:

0-1 variable constraints:

$$\begin{cases} B_1 = \sum_{i=17}^{34} T_{ijv} \le 1 \\ B_2 = \sum_{i=38}^{41} T_{ijv} \le 1 \end{cases}, j \in (35, 50) \tag{9}$$

Where B_1 indicates whether crop No. 1 was selected for planting in the first season in plot j of the common greenhouse.

B_2 denotes whether to plant the first crop in the second season of the j plot of the common greenhouse.

(4) Constraints on Intelligent Greenhouses

Smart greenhouses are suitable for growing vegetables in two seasons except cabbage, white radish and carrot.

0-1 variable constraints:

$$\begin{cases} C_1 = \sum_{i=17}^{34} T_{ijv} \le 1 \\ C_2 = \sum_{i=17}^{34} T_{ijv} \le 1 \end{cases}, j \in (51, 54) \tag{10}$$

Where C_1 indicates whether or not the i th crop is selected to be planted in the first season in plot j of the smart greenhouse;

C_2 indicates whether the choice of planting the i th crop was made in the second season of the smart greenhouse plot j.

(5) Constraints on Avoiding Re-insertion Planting

In the same plot (including the greenhouse), to avoid the problems of soil nutrient depletion and pests and diseases caused by continuous replanting, each crop should not be planted consecutively. This constraint is given as:

$$T_{ijv} + T_{ij \cdot v+1} \le 1, \forall i, j, v \tag{11}$$

(6) For the Constraint of Planting Legumes at Least Once in Three Years

To ensure that soil fertility is effectively maintained and enhanced, all land within each plot (including greenhouses) needs to be planted with legumes at least once in a three-year period. This constraint is given below:

$$\begin{cases} \sum_{v}^{v+2} T_{ijv} \geq 1, \text{Plots are planted in a single season} \\ \sum_{v}^{v+5} T_{ijv} \geq 1, \text{ Plots are planted in two seasons} \end{cases} \tag{12}$$

(7) Constraints for Combined Cropping

In order to ensure the convenience of farming operations and field management, the planting of each crop in each season should be avoided to be too dispersed, and at the same time, the planting area in a single plot (including greenhouses) should not be too small, therefore, it is stipulated that plots other than greenhouses will not be co-cultivated, and that at most two crops will be co-cultivated in the same plot, and that each type of vegetable will account for half of the area of that plot Based on this, the following constraints are set:

$$x_{ijv} \geq 0.5S_j, j = 1, 2, \cdots 54 \tag{13}$$

3.2. Model Selection in the Case of Lagging Sales

Facing the waste of stagflation caused by crop production exceeding the expected sales volume, this paper will use two models, Monte Carlo Intelligent Optimization Model and Simulated Annealing Algorithm, to formulate crop planting strategies during the period from 2024 to 2030. Eventually, through the sensitivity visualization analysis, it is found that the rate of change of yield under the Monte Carlo intelligent model is between 0.15 and 0.40, while the rate of change of yield under the simulated annealing algorithm is between 0 and 20, compared with the Monte Carlo simulation's sensitivity under the parameter is small, so the stability and reliability of Monte Carlo intelligent model is better.

The steps of the Monte Carlo intelligent model are as follows:

(1) Define the Objectives and Requirements for Conducting the Simulation

This section requires the development of the optimal planting program for crops from 2024 to 2030. In this paper, we will maximize the annual crop sales profit to reflect the optimal crop planting strategy.

(2) Construct the Objective Function

$$MaxQ_1 = \sum_{i=1}^{41} \sum_{j=1}^{54} \sum_{v=1}^{V} \left[p_i \cdot \min\left(x_{ijv} \cdot y_{ij}, B_i\right) - c_{ij} \cdot x_{ij} \right] \tag{14}$$

(3) Generate Randomized Planting Strategy for Simulation

Randomly generated planting program, that is, in a plot of land in a certain season randomly select a suitable crop planting. The randomly selected crop should meet the limitations of the plot type and the limitations of the cultivable season.

(4) Repeat Simulation

To get more accurate results, generate many random data, repeat the above steps many times, and will calculate the annual crop sales profit for statistics, and finally will select the crop with the largest sales profit.

(5) Analysis of Results

The results will be screened and analyzed.

3.3. Solving the Model in the Case of Stagnation

The Monte Carlo intelligent model is used to solve the optimal strategy of crop planting program for each year from 2024 to 2030. Based on the determination of the planting strategy of crops during the period of 2024~2030, the maximum sales profit for each year is then derived as shown in table 1 below.

Table 1. Maximum Sales Profit in the Case of Stagnant Sales from 2024 to 2030

Year	Profit on sales (yuan)
2024	17701463.58
2025	17247119.42
2026	17053556.92
2027	18074456
2028	17941400.58
2029	18023659.67
2030	19127890.83

The cost and profit for the stagnant sales case 2024~2023 are visualized in Fig. 1 below.

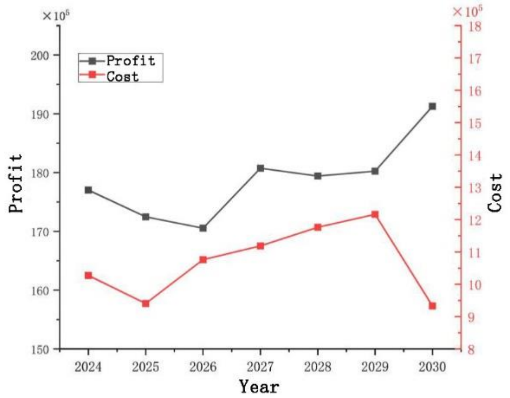

Fig. 1 Line graph of profit on sales between 2024~2030 in case of stagnant sales

Through the above Fig. 1, it is found that in the years 2024~2029, the profits are all basically stable, all around 18 million, but in the year 2030, the profits are raised more, through the figure, it is found that it may be related to the rapid decrease of the cost, and the possible reason is some kind of breakthroughs in agricultural technology. Except for the special case in 2023, in the period of 2024~2029, the basic profit and cost are interacting with each other, when the profit becomes bigger, the cost needed also becomes bigger, which is more in line with the law of the market.

3.4. Modeling of the Situation in the Case of Price Reduction Sales

Exceeding the expected sales volume of the part of the price reduction in accordance with 50% of the sales price in 2023 and exceeding the part of the stagnant waste treatment is a different treatment of the same objective of the situation, so the decision variables and constraints in the case of a 50% price reduction are the same as the stagnant sales situation. This section still establishes the optimization model of crop planting scheme based on Monte Carlo intelligent model.

3.5. Solving the Model in the Case of Price Reduction

The Monte Carlo intelligent model is used to solve the optimal strategy of crop planting program for each year between 2024~2030. Based on the determination of the planting strategy of crops during the period 2024~2030, the maximum sales profit for each year is then derived, as shown in table 2 below.

Table 2. Maximum Sales Profit with Reduced Prices from 2024 to 2030

Year	Profit on sales (yuan)
2024	19900666.08
2025	20676491.75
2026	19249951.5
2027	21890351
2028	20109737.58
2029	19556352.17
2030	21494080.83

3.6. Comparative Analysis of Two Scenarios for Handling the Excess of Sales Volume

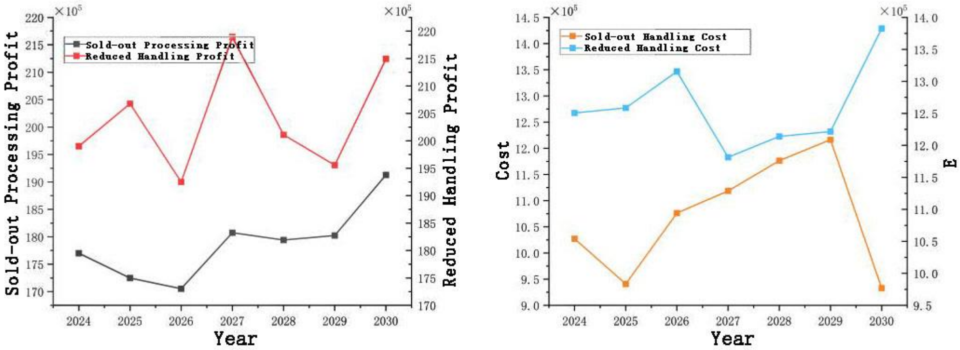

Fig. 2 Comparison of cost and sales profit for the two scenarios for the period 2024~2030 Line Chart

Through the above Fig. 2, comparing the waste generated by stagnant sales and the case of selling at 50% price reduction of the sales price in 2023, the profit of the price reduction treatment is significantly higher than the profit of stagnant sales and waste, and at the same time their profits in the overall aspect are in the same trend. On the contrary in terms of cost, the cost of price reduction treatment is significantly higher than the cost of waste treatment, it can be inferred that price reduction treatment requires more labor, storage costs, but through the combination of profit analysis, it can be inferred that more sales are made by selling at a reduced price.

4. Optimization of Crop Planting under Multiple Variables

In real agricultural production, the expected sales volume of crops, acreage, planting costs, and sales prices are affected by a variety of factors, which may fluctuate from year to year.

4.1. Establishment of Monte Carlo Optimization Model

The objective function in this section will be related to the actual situation, and the part of the total crop production that exceeds the expected sales volume will be subject to a price reduction by 50% of the sales price in 2023. The objective function is the same as that in the previous section for the case of selling at a reduced price.
Summary of additional constraints:

$$s.t.\begin{cases} B_{ijvt} = B_{ijv\cdot(t-1)} \cdot \left(1+\alpha_{ijvt}\right), i = 6,7 \\ B_{ijvt} = B_{ijv\cdot(t-1)} \cdot \left(1+\beta_{ijvt}\right), i \in \left(1\sim 5, 8\sim 41\right) \\ y_{ijt} = y_{ij\cdot(t-1)} \times \left(1+\gamma_{ijt}\right), i = 1,2,\cdots,41 \\ c_{ijt} = c_{ij\cdot(t-1)} \times \left(1+0.05\right) \\ p_{ijt} = p_{ij2023}, i = 1,2,\cdots,16 \\ p_{ijt} = p_{ij\cdot(t-1)} \times \left(1+\nu_{ijt}\right), i = 38,39,40 \\ p_{ijt} = 0.95 p_{ij\cdot(t-1)}, i = 41 \end{cases} \tag{15}$$

4.2. Solution of the Model

To guarantee the accuracy and reliability of the Monte Carlo estimates of crop sales profit and to develop a profit-maximizing crop planting scheme, several 200 iterations was set. Fig. 3 is a visualization of the iteration process.

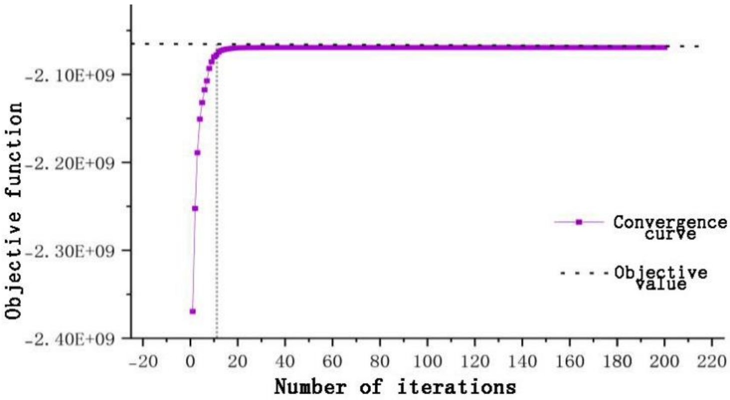

Fig. 3 Monte Carlo simulation iteration diagram

In this section the total production of the crops among the objective function in excess of the expected sales volume is sold at 50% of the sales price in 2023. The visualization of the maximum sales profit for each year yields that the profit and cost are opposite, indirectly reflecting the fact that the profit decreases probably due to the increase in cost and the constant sales volume, especially in the years 2026-2028 it can be found that the cost and profit are negatively correlated.

5. Substitutability and Correlation Analysis

Substitutability of crops refers to the substitution of two or more crops when they are similar in use, nutritional value or consumer preference. Complementarity of crops, on the other hand, refers to the interdependence of two or more crops in the consumption process, where an increase in the sales of one crop tends to lead to an increase in the sales of the other.

In this section, crops are categorized into five groups, namely grains, grains (pulses), vegetables, vegetables (pulses) and edible mushrooms.

5.1. Spearman's Correlation Analysis

The calculation of Spearman's correlation coefficient is based on rank transformation, and the specific steps are as follows:

(1) Sorting and Assigning Ranks

Sort the two variables X and Y separately and assign each data point a unique ranking (rank). If there are identical data values (called “flat rank”), the rank of these values is the average of their sorted positions.

(2) Calculating the Rank Difference

Calculate the difference between the ranks of each pair of variables.

(3) Calculate the Correlation Coefficient

The correlation between the ranks of two variables is calculated using the formula for Spearman's correlation coefficient. The formula is:

$$\rho = 1 - \frac{6\sum d_i^2}{\mathrm{n}\left(n^2 - 1\right)} \tag{16}$$

Where d_i is the difference between the ranks of each pair of variables and n is the sample size. The value of ρ ranges from $[-1,1]$, $\rho = 1$ indicates a perfect positive correlation, $\rho = -1$ indicates a perfect negative correlation, while $\rho = 0$ indicates no linear relationship.

Spearman's coefficients between the two variables were calculated separately for the cost of cultivation, average selling price and sales volume in each crop type, and some of the results are shown in Fig. 4 below.

Fig. 4 Heat map of Spearman's correlation coefficient matrix

First, both grain and grain (legume) crops exhibit a weak negative correlation between planting cost and selling unit price, which means that grain crops with high planting cost may not necessarily be highly profitable.

Secondly, the relationship between planting cost and unit sales price of vegetable and vegetable (bean) crops is also weakly correlated.

For edible mushroom crops, the weak correlation between planting cost and selling unit price may stem from the uniqueness and high value-added nature of this market.

5.2. Establishment and Solution of Monte Carlo Crop Planting Optimization Model

This section further synthesizes the substitutability and complementarity between different crop types, as well as the correlation between the expected sales volume, sales price, and planting cost of crops.

5.2.1 The Correlation of Introduced Variables

$$\begin{cases} p_{it} = p_{i,t-1} \times \left(1 + \rho_{L\_p\_B} \times \dfrac{B_{it} - B_{i,t-1}}{B_{i,t-1}}\right) \\ c_{it} = c_{i,t-1} \times \left(1 + \rho_{L\_c\_B} \times \dfrac{B_{it} - B_{i,t-1}}{B_{i,t-1}}\right) \end{cases} \tag{17}$$

Where $\rho_{L\_p\_B}$ and $\rho_{L\_c\_B}$ are the Spearman's correlation coefficients between the unit sales price and the expected sales volume of the L crop types, and the Spearman's correlation coefficients between the cost of cultivation and the expected sales volume of the L crop types, respectively.

5.2.2 Considering the Substitutability and Complementarity of Crops

Consider multiple influencing factors (e.g., expected sales volume, sales price fluctuations, etc.) in the decision-making of crop planting options, and assess the risks and benefits of different planting options by modeling changes in these factors.

(1) Decision problem definition: for the period from 2024 to 2030, based on the existing constraints, a scientific decision is made on the planting scheme of each crop on all plots.

(2) Goal setting: maximizing profit as the core goal of decision making.

(3) Simulation number setting: the maximum number of iterations of Monte Carlo simulation is pre-determined to ensure the efficiency of the simulation and the reliability of the results.

(4) Stochastic fluctuation simulation: using random number generation technology to simulate the fluctuation of each key factor in the actual planting process, such as weather changes, soil conditions, etc.

(5) Simulation operation and calculation: Substitute the simulated fluctuation factors into the yield calculation model to evaluate the yield of each planting scheme.

(6) Iterative simulation: Repeat steps 4 and 5 until the preset maximum number of simulations is reached or the yield results show a stable convergence trend.

(7) Determination of optimal scheme: based on the simulation results, analyze, and determine the optimal planting scheme with minimum risk and maximum return.

Through the above steps, the optimal planting scheme for each of these seven years was obtained and the total profit for each year was calculated. These data were visualized as shown in Fig. 5 below.

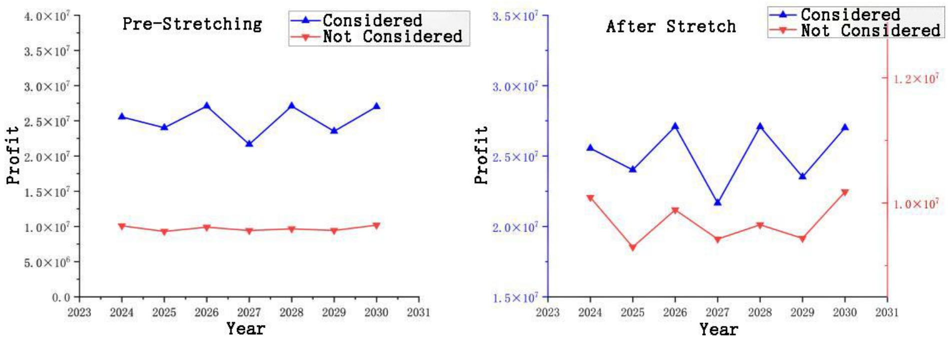

Fig. 5 Comparison of profits obtained from different planting schemes

Fig. 5 shows a comparison between the profits planned for the years 2024-2030, considering the substitutability and complementarity of crops and the correlation between the marketing indicators, and the profits of the planting scenarios developed without taking these factors into account. From this, it can be clearly observed that the planting strategy proposed before optimization significantly outperforms the scenario considering substitutability and correlation in terms of annual profit. However, it is worth noting that the planting plan that considers substitutability and correlation shows a more stable trend in terms of the profit target, which suggests that it has a stronger advantage in terms of risk management and can effectively smooth out profit fluctuations.

6. Conclusion

This paper investigates how to maximize sales profit under different market conditions by applying a Monte Carlo intelligent model to the problem of growing crops in a village from 2024 to 2030. The study first considered two cases to deal with the situation of exceeding the expected sales volume: stagnant waste and selling at reduced prices and solved the optimal planting scheme by Monte Carlo intelligent algorithm. Then, uncertainty factors such as expected crop sales volume, mu yield, planting cost and sales price fluctuation were added to further optimize the planting strategy. Finally, the correlation between different crops was comprehensively analyzed by combining the substitutability and complementarity between crops to derive a more optimized planting scheme. The results show that taking these uncertainties and inter-crop relationships into account can significantly improve profits and provide farmers with stable and reliable planting decisions.

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