Research on Optimization of Crop Planting Scheme Based on Simulated Annealing Algorithm

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Abstract. In response to the challenges of sustainable agricultural development posed by population growth and food demand, this study focuses on a rural area in North China, utilizing mathematical models and optimization algorithms for planting decision optimization. After preprocessing and visualizing cultivation data, two optimization models were developed: The first model maximizes crop profits by treating excess production as unsold inventory constraints while considering planting quantities, land suitability, and crop rotation restrictions, resulting in an optimal planting scheme for 2024-2030 with a total seven-year revenue of 40.126 billion yuan. The second model incorporates a 50% price reduction strategy for excess production, solved using a simulated annealing algorithm, achieving an optimized plan with a total revenue of 41.834 billion yuan over seven years. Comparative analysis demonstrates that the model employing the price reduction strategy exhibits greater practical applicability, robustness, and utility.

Keywords: Simulated Annealing Algorithm, Crop Planting Schemes, Optimization Model, Sustainable Development.

1. Introduction

In recent years, with population growth and increasing food demand [1], as well as constraints of climate conditions, geographic location, and infrastructure [2], how to realize the sustainable development of agriculture [3] under the limited arable land resources has become an urgent problem to be solved. At the same time, the development of big data, artificial intelligence, and other emerging technologies [4-5] has provided new ideas and methods for agricultural optimization decision-making. Traditional crop planting often relies on farmers' experience and intuition and lacks scientific analysis [6] and reasonable planting plans [7]. This kind of planting mode not only difficult to maximize the yield and economic benefits, but also may lead to the overuse of land resources and ecological environment damage. Therefore, there is an urgent need to introduce advanced mathematical models and optimization algorithms to systematically analyze crop planting problems and discuss the optimal planting strategies.

This study takes the countryside of North China as the object, first of all, preprocessing the basic data of existing arable land and crops in the countryside of North China, as well as the crop cultivation and related statistical data of the countryside in 2023, organizing and then carrying out the visualization and analysis of the data, and observing the crop cultivation situation as well as its market situation in 2023 intuitively by drawing histograms and other graphs, so that we can understand some of the data correlations and limitations. Then, to maximize the yield and economic benefits, firstly, consider the total output exceeding the corresponding expected sales volume part of the non-continuation of sales, combined with the climatic conditions [8], geographic location and infrastructure, and other conditions of constraints to establish the planting strategy optimization model. Crop profit maximization as the objective function will be more than part of the stagnant sales into the constraints of the output is not greater than the expected sales volume, in addition, to consider the number of planting, the crop can be planted [9], the crop can not be continuous cropping and other practical conditions to build constraints [10], through the simulated annealing algorithm [11-12] to predict the optimal planting of each crop in the next seven years. Then we consider the total production exceeds the corresponding expected sales volume part of the price reduction in the sale of the situation, modify the original objective function for more than part of the sales price in 2023 according to 50% of the price reduction in the sale, the establishment of a new optimization model, through the simulated annealing algorithm to predict the optimal planting plan for the next seven years of each crop.

2. Data source and preprocessing

2.1. Data source

The data for this study come from www.mcm.edu.cn. The basic situation of existing cultivated land and crops in a village in North China and the crop cultivation and related statistics in the town in 2023, the data include 1,201 acres of main open cultivated land, 9.6 acres of common greenhouses, 2.4 acres of smart greenhouses three types of cultivated land and information on common crops in 41, of which open cultivated land is dispersed into 34 plots of different sizes, including 4 types of flat dry land, terraced land, hillside land and watered land.

2.2. Data pre-processing

This study through the study of crop cultivation from 2023, to 2023 as the basis for predicting the next 7 years of the planting program, to achieve the goal of maximizing profits, first of all, data collection and collation, 2023 statistics of the relevant data in the unit price of the sale is not a definite value, this is due to the actual transaction, the sales price will be due to some specific circumstances for a small range of increase, for example, in the actual transaction, there will be buyers and sellers to negotiate the price, and the final transaction price will change, but its distribution is normal, so the research in this paper takes the mean value as the reference value of the unit price of sales.

Subsequently, the basic situation of the existing arable land and crops in the countryside of North China and the crop cultivation in the countryside in 2023 and related statistical data are integrated to obtain the vegetable crops planted in 2023, their planting area, production, sales volume, sales price, and planting cost. Then the data were cleaned and checked for outliers and missing values.

2.3. Data encoding

This is a complex optimization problem that needs to consider several factors, such as plot type, crop type, planting season, cost-effectiveness, etc., to simplify the problem need to encode the data, where A, B, C, D, E, F, respectively, represents the flat dry land, terraced land, hillside land, water-sourced land, ordinary greenhouses, smart greenhouses, the 54 plots of land coded as $j \in \{1,2,3...,54\}$, for 41 kinds of crops based on their crop code as $i \in \{1,2,...,41\}$.

The summary statistics of the 15 single-season crops on flat and dry land, terraced land, and hillside land are shown in Figure 1:

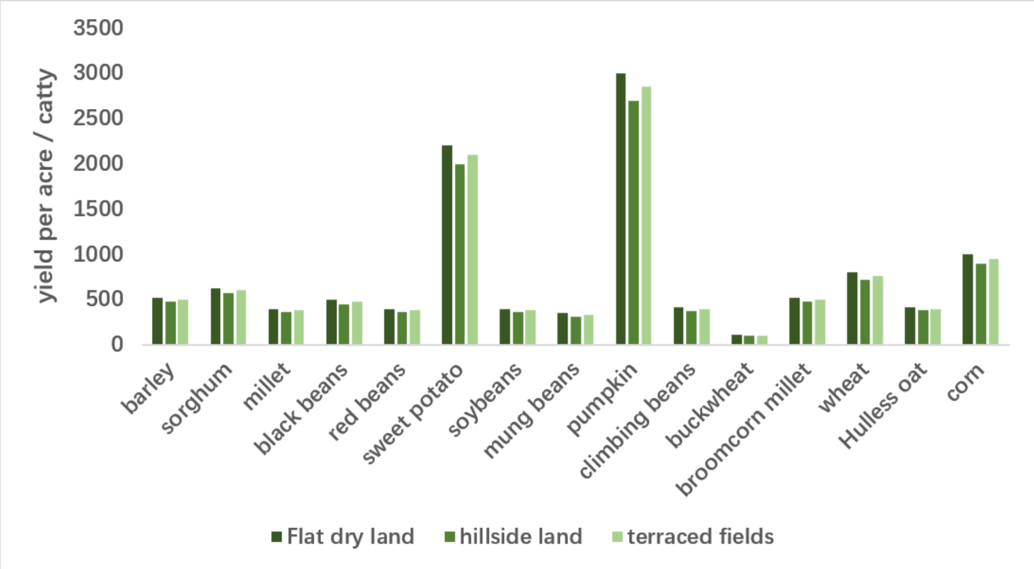

Figure 1. Acres of single-season crops in 2023

The analysis shows that the overall yield per acre of various crops in different plot types is more or less the same, and the yield per acre in flat and dry land has a greater advantage over terraced land and hillside land. Pumpkin and sweet potato have a greater advantage in yield per acre compared to other crops.

Then for the double quarter crops, this study counted the cultivated area of each crop in the first quarter for watered land, ordinary greenhouses, and smart greenhouses, as shown in Figure 2 below:

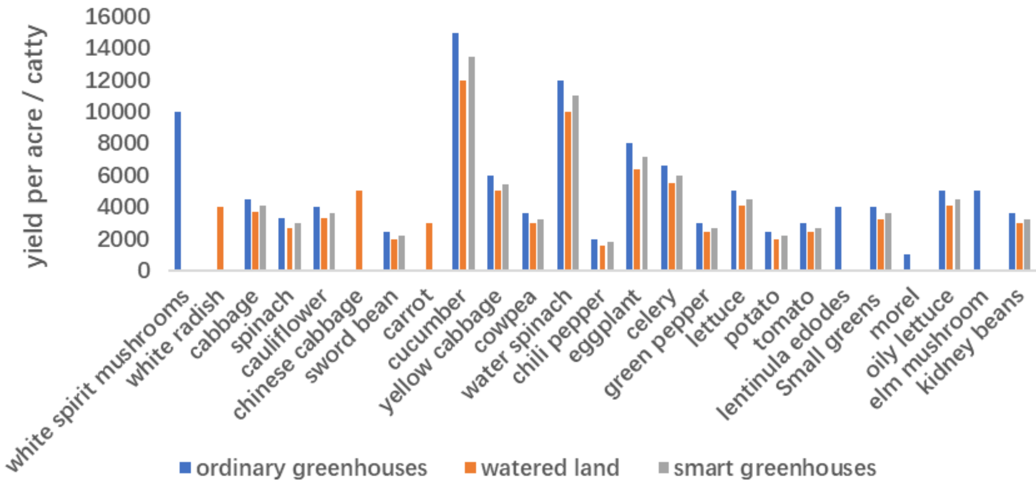

Figure 2. First quarter 2023 production by crop acreage

Combined with Figures 1 and 2, the analysis found that the acre yield of crops grown in greenhouses is higher than that of open cropland as a whole, but its cultivation cost is also higher than that of open cropland as a whole, so then the specific crops (i.e., crops that can be chosen to be planted on open cropland as well as the first season crops grown in greenhouses) are further analyzed, and a comparison of the cultivated area of each crop in the water-cured land, the common greenhouse and the cultivated area of the smart greenhouse can be found that the common greenhouses have the highest yield per acre, followed by smart greenhouses and lastly watered land, cucumber, and vacuoles have a greater advantage in yield per acre as compared to other crops.

3. Establishment of Crop Planting Optimization Model

Considering that in real life production may exceed the expected sales volume, here this study assumes two scenarios respectively, namely, the total production exceeds the corresponding expected sales volume partially stagnant and does not continue to sell and the total production exceeds the corresponding expected sales volume partially sells at a reduced price.

3.1. Total production exceeded the corresponding expected sales volume by a portion of slow sales

3.1.1. Identification of Decision Variables

Under the assumption that multiple variables for various crops remain stable for the next seven years (2024-2030), while the crops planted in each season need to be sold in the current season. If any excess produces stagnant sales it is completely wasted. From this, we introduce 0-1 integer variables expressed as follows:

$$x_{i,j,t} = \begin{cases} 1, \text{The ith crop is planted in year j} \\ 0, others \end{cases} \tag{1}$$

Where $t \in [1,7]$ denotes the seven years between 2024 and 2027, respectively, and the following constraints t are the same here.

3.1.2. Determining the objective function

In this study, it is necessary to calculate the optimal planting plan for the crops in this village from 2024 to 2030 under the condition that the expected sales volume, planting cost, planting cost, acreage production, and sales price are kept constant, so its profit Z has to be maximized, and then the objective function is

$$\max Z = \sum_{i=1}^{41}\sum_{j=1}^{54}\sum_{t=1}^{14}(B_{i,j}O_{i,j} - C_{i,j})S_{i,j,t}x_{i,j,t} \tag{2}$$

Where $B_{i,j}$ is the sales price per acre of the i crop in the j plot, $O_{i,j}$ is the sales price per acre of the i crop in the j plot, $C_{i,j}$ is the cost per acre of the i crop in the j plot, and $S_{i,j,t}$ is the expected acreage of the i crop in the j plot in the year t.

3.1.3. Planting quantity constraints

The data for 2023 remains stable for the next seven years, so it is taken as the expected sales volume, and the expected sales volume for the ith crop is denoted by M_i, then the sales volume for each crop is constrained to have

$$\sum_{i=1}^{41} O_{i,j}S_{i,j,t}x_{i,j,t} \le M_i \tag{3}$$

Since there is a limit on the acreage of all the planted plots, it is denoted by A_j (j denotes the j th plot). In the following, we add up the area of all the crops planted in the same plot with the restriction that there are

$$\sum_{i=1}^{41} x_{i,j,t}S_{i,j,t} \le A_j \tag{4}$$

For the planting scheme, this question takes into account the fact that to facilitate farming operations and field management, the area of the planting site for each season of the restricted crop needs to be larger than a constant a, so that the area of each crop planted in a single place is not too small, there are

$$S_{i,j,t} \ge a \tag{5}$$

3.1.4. Crop cultivation constraints

Each crop cannot be planted in consecutive heavy crops on the same plot, otherwise, it will affect the nutrient content of the land and lead to a reduction in crop yield. Therefore, the constraint section is constrained for single and double-season crops respectively

$$x_{i,j,t} + x_{i,j,t+1} \le 1, i \in [1,16] \tag{6}$$

$$x_{i,j,2t-1} + x_{i,j,2t} \le 1, i \in [17,41] \tag{7}$$

This study requires that all land in each plot (including the shed) be planted with a legume crop at least once in three years, i.e., the constraints are

$$\sum_{i=17}^{19} x_{i,j,2t-3} + x_{i,j,2t-2} + x_{i,j,2t} + x_{i,j,2t+1} + x_{i,j,2t+2} \ge 1, i \in [17,19], j \in [51.54] \tag{8}$$

On flat drylands, terraces, and hillsides, grain crops such as soybeans, black beans, red beans, mung beans, climbing beans, wheat, corn, grains, sorghum, millet, buckwheat, pumpkin, sweet potatoes, oat, barley, etc. can only be planted there in a single season, i.e., this constraint is

$$\begin{cases} x_{i,j,t} \le 1, j \in [1,26], i \in [1,15] \\ x_{i,j,t} = 0, others \end{cases} \tag{9}$$

On irrigated land, a single season of rice can only be grown in one season or two seasons of vegetables, so for a single season with

$$\begin{cases} x_{i,j,t} \le 1, j \in [27,34], i = 16 \\ x_{i,j,t} = 0, others \end{cases} \tag{10}$$

Bi-seasonal

$$x_{16,j,2t-1} + x_{i,j,2t} \le 1, (i \in [17,37], j \in [27,34], t \in [1,7]) \tag{11}$$

3.1.5. Two-season constraints on crop cultivation

Vegetables such as cowpeas, snap beans, kidney beans, potatoes, tomatoes, eggplants, spinach, peppers, cauliflower, cabbage, oleaginous vegetables, baby bok choy, cucumbers, lettuce, peppers, cabbages, yellow cabbages, celery, etc., can be planted in the first season on a watered field or a regular trellis or can be planted in the first season or the second season on a smart trellis on a watered field or a regular trellis, i.e., the constraint is

$$\begin{cases} x_{i,j,2t-1} \le 1, j \in [27,50] \\ x_{i,j,2t-1} \le 1, j \in [51,54] \\ x_{i,j,2t} \le 1, j \in [51,54] \\ x_{i,j,t} = 0, others \end{cases} \tag{12}$$

Which is $i \in [17,34]$.

Vegetables such as Chinese cabbage, white radish, and red radish can only be grown into the second season on watered land; edible mushrooms such as elm mushrooms, shiitake mushrooms, shirataki mushrooms, and morel mushrooms can only be grown in the second season in ordinary greenhouses. That is, the constraints are

$$\begin{cases} x_{i,j,2t} \le 1, j \in [27,34], i \in [35,37], t \in [1,7] \\ x_{i,j,2t} \le 1, j \in [35,50], i \in [38,41] \\ x_{i,j,t} = 0, others \end{cases} \tag{13}$$

where 2t denotes the second quarter.

Since grains (legumes) such as soybeans, black beans, red beans, mung beans, and climbing beans can only be grown on flat dry land, terraces, and hillsides, the

$$\sum_{i=1}^{5} x_{i,j,t-1} + x_{i,j,t} + x_{i,j,t+1} \ge 1 \quad \left(j \in [1,26], i \in [1,5] \right) \tag{14}$$

Cowpeas, cattle beans, and kidney beans can only be grown in the first season in watered land, the first season in ordinary greenhouses, the first season in smart greenhouses, and the second season, if the

$$\sum_{i=17}^{19} x_{i,j,2t-1} + x_{i,j,2t+1} + x_{i,j,2t+3} \ge 1 \text{ , } (j \in [27,50], i \in [17,19]) \tag{15}$$

3.2. Total production exceeds the corresponding expected sales volume at a reduced price

In the previous scenario, if the total production of a crop per season exceeds the expected sales, the excess will not be sold properly, resulting in the wastage of resources, which directly affects the total profitability of that crop. Therefore, when optimizing the planting scheme, this situation will be avoided or minimized as much as possible to ensure maximum utilization of resources.

Here this study considers another scenario, where although the portion that exceeds the expected sales volume still cannot be sold normally at the original price, it is allowed to be sold at a reduced price of 50% of the 2023 sales price. This means that while profits will be somewhat affected, they are not a total loss. This treatment provides some flexibility for growers, allowing some adjustment of yields to respond to changes in market demand, while still recovering some of the costs. Therefore, the constraints remain the same and only the objective function needs to be modified. The modified objective function is then

$$\sum_{i}^{41} \sum_{j}^{54} \sum_{t}^{14} (B_{i,j} M_i + 0.5 B_{i,j} (O_{i,j,t} S_{i,j,t} x_{i,j,t} - M_i) - C_{i,j} S_{i,j,t} x_{i,j,t}) \tag{16}$$

Where M_i is the projected sales volume of crop i. The projected sales of each crop M_i are obtained by calculating the sales-to-production ratio $\delta = 0.9197$ for North China in 2023 and then multiplying it by the projected production of each crop.

4. Application of Simulated Annealing Algorithm in Crop Planting Optimization

4.1. Planting scheme prediction based on simulated annealing algorithm

The study employs a simulated annealing algorithm to predict crop planting patterns for 2024-2030. Operating from a high initial temperature, the algorithm performs stochastic searches in the solution space while gradually decreasing temperature parameters. Its probabilistic "jump" mechanism allows acceptance of temporarily suboptimal solutions, enabling escape from local optima to achieve global optimization. This approach effectively balances local and global search capabilities, ensuring convergence to the globally optimal solution.

4.2. Proceeds from the portion of total production over the corresponding expected sales volume that is slow-moving

According to the above optimization model, it was solved using simulated annealing to derive the area of crops planted on different plots for seven years from 2024 to 2030, and the following analysis is based on the predicted planting area in 2024 as an example, as shown in Figure 3 below.

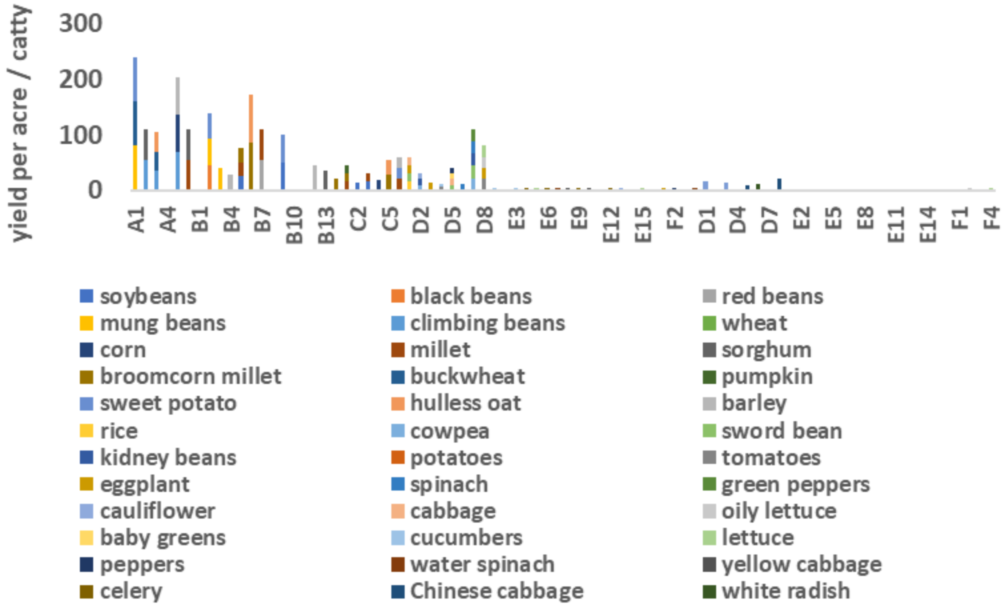

Figure 3. Bar chart of the projected area of crops planted in plots in 2024

It is easy to see that food crops significantly outnumber vegetable and fungi crops in terms of acreage planted, a readily apparent trend. It is particularly noteworthy that on the right-hand side of the chart, the planted areas of widely consumed vegetables such as cabbages, Chinese cabbages, and cauliflowers are more prominent than those of other vegetable crops, a finding that closely corresponds to our daily life experience, thus further strengthening the reasonableness and credibility of the data projections.

The final projection for the next seven years of crop returns is a total of 40.126 billion yuan for the next seven years, as shown in Figure 4 below for each year.

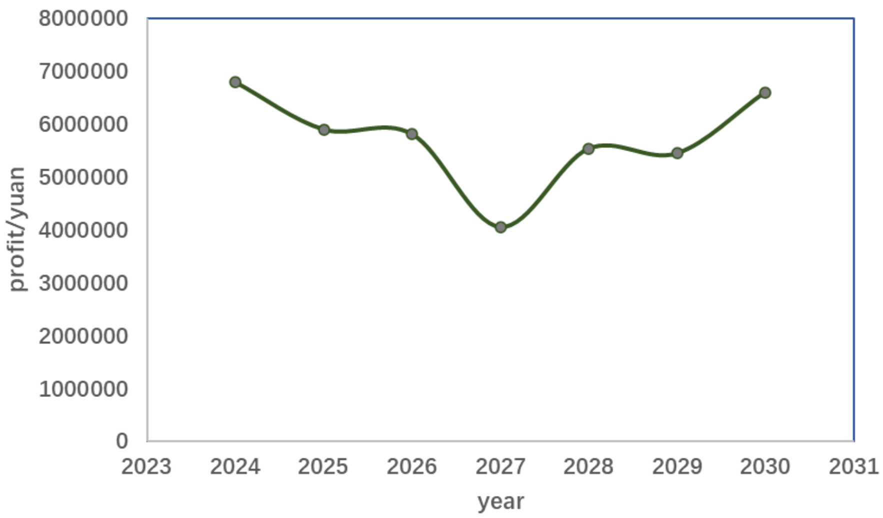

Figure 4. Seven-year returns scatterplot

It is observed that under the planting scheme of the optimization model, the returns of the next seven years are more than the returns of 2023 in all six years except that the returns of 2027 are close to the returns of more than 4 million in 2023, which reflects the superiority of the optimization model of this paper in maximizing the crop yield and economic benefits. Meanwhile, the fluctuation range of the returns is not very large, mainly fluctuating at more than 5 million, which further indicates the reasonableness of the predicted data.

4.3. Proceeds from price reductions for the portion of total production that exceeds the corresponding expected sales volume

When the portion that exceeds the expected sales volume still cannot be sold normally at the original price, but is allowed to be sold at a reduced price of 50% of the sales price in 2023, the optimal planting scenarios for the next 7 years are obtained by solving the solution, and to show the performance trend of these scenarios and the potential relationship between the data more intuitively, we plotted the surface graphs of the data for the different years, as shown in Fig. 5 below (2024 as an example):

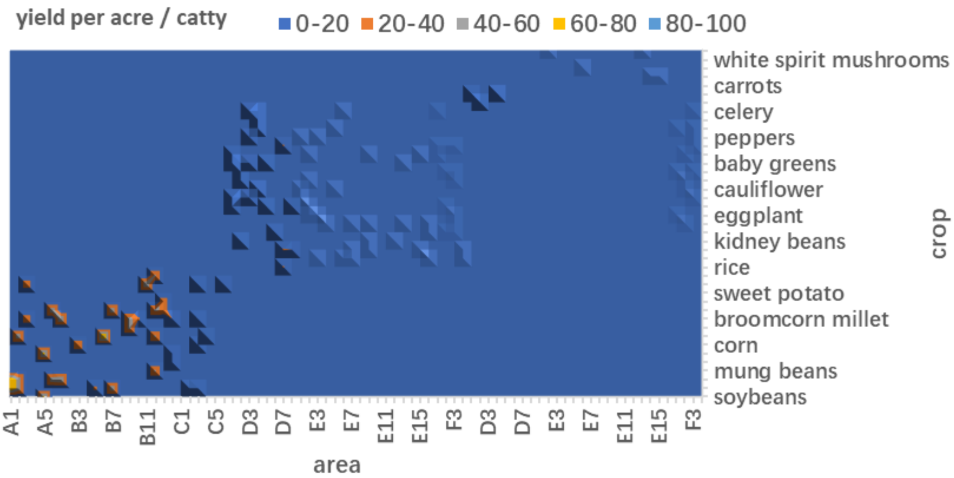

Figure 5. Surface of planting program projections for 2024

The analysis reveals that it can be concluded that it is mainly distributed in the three regions of the map, while crops such as soybeans, climbing beans, and maize have a significant sometimes in the area under cultivation.

Then statistically project the returns for the next seven years and plot a scatterplot against the first scenario, as shown in Fig. 6 below.

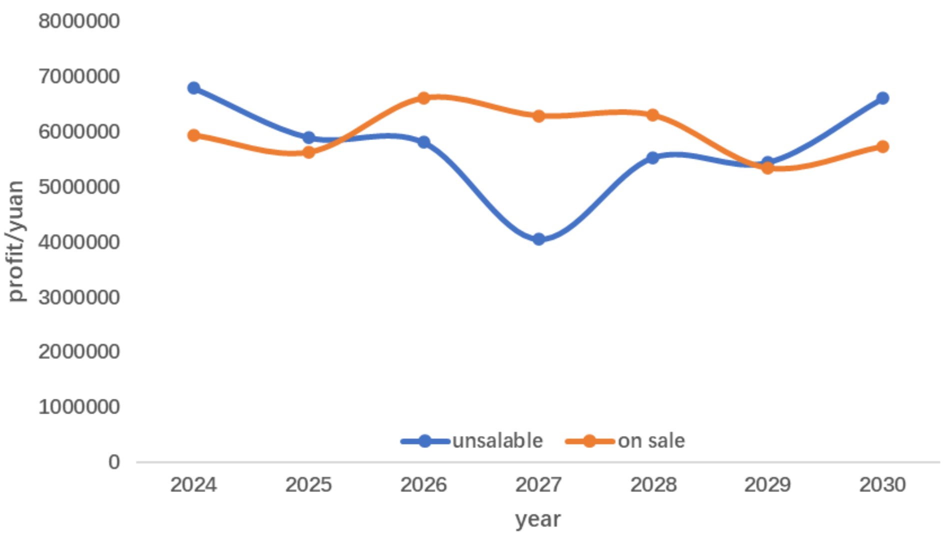

Figure 6. Scatterplot comparing the returns of the two scenarios

The total return of the next 7 years is 41.834 billion yuan , through the analysis, it can be seen that the planting scheme obtained by using the total production over the corresponding expected sales volume partially stagnant sales is too insurance, for the emergence of the production over the sales volume processing ability is poor, and can't achieve the maximum economic benefits, resulting in the predicted return of the volatility of the larger, and the use of the reduced price sales strategy will prevent this situation to a certain extent, the At the same time, the total return of using the price reduction sales strategy is more than that of the stagnant sales strategy. In summary, the mathematical model of using the price reduction sales strategy is more in line with the practical requirements, and the prediction results are reasonable, with better risk-resistant ability and economic benefits.

5. Conclusion

Based on agricultural data from a North China village in 2023, this study developed two mathematical optimization models to address crop planting strategies for 2024-2030. The first model treats excess production as unsold inventory with profit maximization as the objective function, while the second model incorporates a 50% price reduction strategy for excess production. Both models, solved using simulated annealing algorithms, consider practical constraints including planting quantities, land suitability, and crop rotation restrictions. Comparative analysis shows that both optimization models achieved higher revenues compared to the 2023 planting scheme, with the price reduction model demonstrating greater practical value. While the study is limited by its single data source, the methodology proves effective for agricultural planning optimization. The study provides a valuable reference for sustainable agricultural development by successfully combining mathematical modeling with practical agricultural constraints. Future research could explore multiple data sources and alternative optimization algorithms.

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