Research on Agricultural Crop Planting Strategy Based on Robust Optimization Model: Addressing Uncertainty and Risk

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Abstract. This paper aims to solve the complex problems in agricultural planting through innovative methods, optimize the planting strategy, improve the economic benefits of agricultural production and its risk resistance ability, and contribute to the sustainable development of agriculture. To this end, an optimization model for crop planting strategies using an improved simulated annealing algorithm is proposed. Moreover, a hybrid optimization framework combining linear programming and dynamic simulated annealing is constructed to address the non-convex agricultural planting problems. Meanwhile, robustness constraints, including dynamic temperature decay, acceptance probability adaptation, and iteration regulation, are introduced to enhance the adaptability and reliability of the model. The experimental results based on the data in 2024 demonstrate that, under the uncertainties of sales volume (±5%) and planting area (±10%), the standard deviation of returns is reduced by 37%, which significantly improves the risk resistance ability of agricultural production. This provides strong support for the sustainable development of agriculture and also offers a new and effective approach for strategy formulation and risk management in agricultural production practices.

Keywords: Robust Optimization, Simulated Annealing Algorithm, Agricultural Optimization.

1. Introduction

This study focuses on a rural village in the mountainous region of North China, where low temperatures and limited arable land restrict crop cultivation to one season per year for most plots. The area consists of 1,201 mu (≈80.07 hectares) of cultivated land, with four types: flat dry land, terraced land, hillside land, and watered land. The watered land can support rice or two seasons of vegetables. Additionally, there are 16 ordinary greenhouses and 4 intelligent greenhouses, each with 0.6 mu of cultivated area. The study also considers planting constraints, such as crop rotation and management practices. Using 2024 data, the study will predict the total return over the next seven years by analyzing crop prices and yields, supplementing missing data for smart greenhouses, and confirming price anomalies. The benchmark sales unit price is calculated as the average of the highest and lowest unit prices in 2024.

In the academic research field of agriculture and optimization algorithms, relevant explorations have been continuously advancing. In 2008, Monticelli A J and others expounded on the principles of the simulated annealing algorithm, laying the foundation for the application of this algorithm[1]. In 2011, Guedes L P C and others combined the simulated annealing algorithm with the genetic algorithm to optimize the spatial sample configuration[2]. In 2013, Dong Y and others introduced the simulated annealing algorithm into the research of crop leaf area index[3]. In 2016, Li M and others enriched the research perspective on the optimization of crop planting structures[4]. In 2020, Wang F and Xu F published a paper titled "Analysis and Research of Simulated Annealing Algorithm and Parameters" in the conference proceedings of "Frontier Computing: Theory, Technologies and Applications (FC 2019) 8" published by Springer Singapore, analyzing the simulated annealing algorithm and its parameters[5].In 2022, Venkateswaran C and others expanded the application fields of this algorithm, while Randall M and others carried out research on crop planning under climate change[6-7]. In 2023, Yuan M and others optimized agricultural management from the perspective of the water-land-food relationship, and Angelini M C and others analyzed the application boundaries of the algorithm[8-9]. In 2024, Xia Y and others combined the simulated annealing algorithm with linear programming and applied it to the research of agricultural planting strategies[10].

Although existing studies have achieved fruitful results, the robustness of the algorithms is still insufficient when dealing with complex constraints. Therefore, this paper introduces an innovative point of robust optimization. Aiming at the optimization problem of agricultural planting under high-dimensional constraints, we propose a hybrid optimization framework, which makes up for the deficiencies in the algorithm's robustness in previous studies. It provides a new direction for the research on agriculture and optimization algorithms and further promotes the development of academic research in this field.

2. Optimization Framework and Model Construction for Agricultural Planting

2.1. Hybrid Optimization Framework

To achieve robust solution of non-convex agricultural cropping optimization problems under high-dimensional constraints, this study proposes a hybrid optimization framework that integrates linear programming and dynamic simulated annealing algorithms. The traditional methods are difficult to balance the coupled effects of uncertainties such as yield fluctuations (±10%) and annual price decreases (5%) with complex cropping constraints (e.g., three-year rotation of legumes). By introducing a dynamic temperature decay strategy, combined with solution improvement feedback, acceptance probability adaption and iteration number regulation mechanism, the algorithm's global convergence efficiency and local search accuracy in uncertain environments are significantly improved.

2.1.1 Design of Dynamic Simulated Annealing Algorithm

The temperature update formula is defined as:

$$T_{k+1} = \alpha_k \cdot T_k \tag{1}$$

Among them. α_k is adapted to be a dynamic temperature decay factor, and its computation incorporates the following agricultural scenario features:

Improved feedback of the solution: with the growth rate of planting yield δ_f for the metrics. If a single iteration gain improvement exceeds 5% (i.e.,$\delta_f > 0.05$), Accelerated cooling to lock in quality solutions; and, conversely (i.e.,$\delta_f \leqslant 0.05$), Deceleration cooling to refine the search. The decay factor is adjusted to:

$$\alpha_\delta = 1 - \beta_1 \cdot \tanh\left(\frac{\delta_f}{0.05}\right) \tag{2}$$

Among them, β1=0.2, Ensure that sensitivity is balanced with stability by calibrating with historical return volatility data.

Acceptance probability adaptive: Probability of acceptance in combination with robust scenarios P_{accept} , when $P_{accept} > 0.3$ (i.e.,frequent acceptance of poorer solutions), indicating that the current temperature is too high and cooling needs to be accelerated to avoid invalid exploration; conversely (i.e.,$P_{accept} \leqslant 0.3$), reducing the decay rate to enhance local optimization.

$$\alpha_P = 1 - \beta_2 \cdot (1 - P_{accept}) \tag{3}$$

where, $\beta_2 = 0.15$ The robustness is verified by Monte Carlo simulation. Iteration number modulation: in the early stages of the algorithm (i.e.,$k \leqslant 100$), Hold to $\gamma = 0.1$ enhance global search; As the number of iterations increases($k > 100$), Gradual reduction to $\gamma = 0.05$,slowing down the rate of cooling to suit local refinement needs. The decay function is:

$$\alpha_k = \frac{1}{1+\gamma \cdot k^{0.8}} \tag{4}$$

The dynamic temperature decay factor integration equation is:

$$\alpha_k = \alpha_\delta \cdot \alpha_p \cdot \alpha_k \tag{5}$$

This strategy allows the algorithm to dynamically adjust the search intensity during the multi-scenario generation phase of robust optimization. In extreme scenarios with ±10% yield fluctuations, the algorithm automatically extends the high-temperature phase to avoid falling into a local optimum if the revenue growth rate is consistently below a threshold, while in price stabilization scenarios, it converges quickly to an efficient solution.

2.1.2 Collaboration between Robust Optimization and Algorithms

To cope with uncertainty, the objective function is extended to maximize the expected total return:

$$\max E[R_{total}] = \sum_{t=1}^{7} \sum_{s=1}^{S} w_s \cdot R_{t,s} \tag{6}$$

Where S is the number of uncertainty scenarios generated, is the weight of scenarios, and is the return under scenarios in year t. The dynamic simulated annealing algorithm is embedded by :

(1) Scenario parallel optimization: each scenarios runs the algorithm independently, and the temperature decay factor is adjusted in real time according to that scenario's with.

(2) Cross-scenario information sharing: quality solutions for each scenario are synchronized every 10 iterations to update the global temperature Tk to avoid repeated search for inefficient regions.

2.1.3 Algorithm performance verification

As shown in Table 2, after the introduction of the dynamic temperature strategy, the standard deviation of the robust model gain is reduced from the original 362,000 to 228,000 (37% reduction), and the number of convergence iterations is reduced by 42%. This shows that the dynamic adjustment mechanism effectively balances the contradiction of "exploration-utilization", and significantly improves the computational efficiency while protecting the risk resistance.

2.2. Construct an optimization model

2.2.1 Construction of an optimization model for grain crops

Among the uncertainty factors in the food category considered in this study are explained as follows:

(1) Expected sales volume S^t_{ij}: denotes the expected sales of the *i*-th crop on the *j*-th plot in year t, i.e., the acreage of a crop on a plot multiplied by the corresponding acreage yield and an adjustment factor of 0.97, where the expected sales in 2024 are S^0_{ij}.

Analyzing the data, the expected sales of wheat and maize have a tendency to increase, with an annual growth rate of between 5 and 10 percent, which gives the following results.

$$S^t_{ij} = S^0_{ij}(1+h)^t, t=1,2,...,7; i=1,2; j=1,2,...,26 \tag{7}$$

The expected sales of other crops may vary ±5% with respect to 2023, i.e., the expected sales for each year are:

$$S^0_{ij} = S^0_{ij}(1+h), t=1,2,...,7; i=1,2; j=1,2,...,26 \tag{8}$$

(2) Acre yield y^t_{ij}:denotes the acre yield of the *i*-th crop on the *j*-th plot in the *t*-th year. Because the annual mu yield will be affected by climate and other factors, so the annual mu yield up and down range of ± 10%. This relationship can be expressed as:

$$y^0_{ij}(1+h)^t, t=1,2,...,7; i=1,2,...,15; j=1,2,...,26 \tag{9}$$

(3) Planting cost c^{t}_{ij}: denotes the cost of planting the *i*-th crop on the *j*-th plot at the time of year t. The cost of planting the *j*-th crop is the average increase of 5% per year, i.e., the expected sales volume for each year.

The planting cost increases by an average of 5% per year, and the expression is shown as follows:

$$c^{0}_{ij}(1+0.05)^{t}, t=1,2,...,7; i=1,2,....,15; j=1,2,...,26 \quad (10)$$

(4) Selling price m^{t}_{i}: indicates the selling unit price of the *i*-th crop in year t.

The sales price of food crops is basically stable, i.e., it is equivalent to remain unchanged in 2024.

After taking into account the effects of various uncertainties, the objective function of total return minus planting cost minus crop return in excess of the expected sales volume was constructed as follows:

$$\max\ z=\sum_{t=1}^{7}\left\{\sum_{i=1}^{15}\sum_{j=1}^{26}[\min(x^{t}_{ij}y^{t}_{ij}, S^{t}_{ij})\ m_i]-c^{t}_{ij}x^{t}_{ij}\right\} \quad (11)$$

where denotes the acreage of the *i*-th crop planted on the *j*-th plot in year t.

The constraints have the following seven points:

(1) The total area planted with food crops is equal to the total area of 1092 acres of the above three types of cropland:

$$\sum_{i=1}^{15}\sum_{j=1}^{26}x^{t}_{ij}\leqslant 1092\ (t=1,2,...,7) \quad (12)$$

(2) The sum of the acreage of all types of crops grown on a given piece of land does not exceed the area of that piece of land:

$$\sum_{i=1}^{15}x^{t}_{ij}\leqslant a_j\,(j=1,2,...,26; t=1,2,...,7) \quad (13)$$

(3) Consider that each crop cannot be planted consecutively in the same plot, i.e., the area of the i-th crop to be planted in that plot in the next year has to be less than the area of the i-th crop not planted in that plot in the current year:

$$\begin{gathered} a_j - x^{t}_{ij}\geqslant x^{t+1}_{ij}\,(t=0,1,...,6) \\ x^{0}_{ij}=b_{ij} \end{gathered} \quad (14)$$

(4) In order to increase soil fertility, all plots are to be planted with a legume crop at least once in three years starting in 2024, i.e., the sum of the areas of a plot planted with a legume crop in the three years starting in 2024 is required to be greater than the area of the plot in order to ensure that a legume crop has been planted in each of the three years on the plot:

$$\sum_{s=0}^{2}\sum_{i=1}^{15}x^{t-s}_{ij}\geqslant a_j\,(j=1,2,...,26; t=3,4,5,6) \quad (15)$$

(5) In order to ensure that the planting plots of each type of crop are not overly dispersed, it is necessary to determine, based on the data of 2024, on which type of cultivated land the crop has the highest yield per mu. The planting area on the cultivated land with the highest yield per mu should account for 60% of the total planting area of this crop. Among them, $x^{t}_{ik_a}$ represents the sum of the planting areas of the *i*-th type of crop on the k_a-th ($a=1,2,3$) type of cultivated land in the *t*-th year:

$$\frac{x^t_{ik_a}}{\sum_{j=1}^{26} x^t_{ij}} \geqslant 0.6\,(i=1,2,...,15,t=1,2,...,7)$$

$$x^t_{ik_1} = \sum_{j=1}^{6} x^t_{ij}$$
$$x^t_{ik_2} = \sum_{j=7}^{20} x^t_{ij} \quad (16)$$
$$x^t_{ik_3} = \sum_{j=21}^{26} x^t_{ij}$$

The appropriate plot types for each type of crop in the food category are represented by the following letters: flat and dry land, terraced land, and hillside land.

(6) When planning for the cultivation of two quality crops on the same piece of land, the area allocation strategy needs to be carefully designed to maximize economic benefits, the specific needs of the crops and the ease of field management. Among them X^t_{ij} is a 0-1 variable indicating whether crop type *i* is planted on plot j in year *t*, and takes the value 1 if planted and 0 otherwise:

$$X^t_{ij} = \begin{cases} 1, plant \\ 0, unplant \end{cases}$$

$$\sum_{i=1}^{15} X^t_{ij} \leqslant \alpha\ (j=1,2,...,26) \quad (17)$$

$$\alpha = \begin{cases} 2, & a_j \epsilon (0.6, 6) \\ 3, & a_j \epsilon (10, 40) \\ 8, & a_j \epsilon (44, 86) \end{cases}$$

(7) In order to prevent the planting area of each crop in a plot from being too small, which would result in an increase in the cost of management as well as other related expenditures such as labor, the present study stipulates that the planting area of the *i*-th crop in the *j*-th plot at year t in the model for the grain category (excluding rice) should not be less than 2 acres:

$$x^t_{ij} \geqslant 2, t=1,2,...,7; i=1,2,...,15; j=1,2,...,26 \quad (18)$$

2.2.2 Construct an optimization model for vegetable crops

Vegetable crops are grown only in irrigated land, ordinary greenhouses, and smart greenhouses, and all of them, except rice, are semi-seasonal crops, and their growth takes only one season in the corresponding plots. In this study, 7 years are divided into 14 seasons, 2025 corresponds to the 1st and 2nd seasons, 2026 corresponds to the 3rd and 4th seasons, and so on, the first and second seasons in 2024 are the -1 and 0 seasons, respectively. Rice is a single-season crop, so if it is planted in the first season, it is also planted in the second season and the area planted is equal.

The uncertainty factors considered for vegetable crops (including rice) are shown below:

Expected sales volume

Expected sales of vegetable crops are the change in value from 2024, so the expected sales in the robust environment are:

$$S^{t+1}_{ij} = S^0_{ij}(1+h_t), i=17,...,34 \quad (19)$$

Yield per acre

The acreage of vegetable crops will fluctuate from year to year in the range of so the robust environment is considered under acreage of:

$$y^{t+1}{}_{ij} = y^{0}{}_{ij}(1+h_t)^{t+1} \tag{20}$$

Cost of cultivation

The cost of growing vegetable crops increases by 5% per annum, i.e.

$$c^{t+1}{}_{ij} = c^{0}{}_{ij}(1+0.05)^{t+1} \tag{21}$$

Unit price of goods sold

The first is that the unit price of rice grown in irrigated land remains unchanged; the second is that the unit price of the remaining vegetable crops increases by 5 per cent per annum, namely.

$$m^{t+1}{}_{i} = m^{0}{}_{i}(1+0.05)^{t+1} \tag{22}$$

The third is a steady decline in unit prices of edible mushrooms by 1% to 5% per year, with a robust modeling of unit prices of

$$m^{t+1}{}_{i} = m^{0}{}_{i}(1+h_t)^{t+1}, i = 38, ..., 41 \tag{23}$$

The revenue from vegetable crops consists of seven parts, mainly based on the types of vegetables grown in different plots and quarters. The first part is the revenue from growing rice on watered land; the second part is the revenue from growing vegetables on watered land, ordinary greenhouses, and smart greenhouses in the first quarter; the third part is the revenue from growing Chinese cabbage, carrots, and white radishes on watered land in the second quarter; the fourth part is the revenue from growing edible mushrooms in ordinary greenhouses in the second quarter; the fifth part is the revenue from growing vegetables in smart greenhouses in the second quarter; and the last two parts are, first, the total revenue from all the products of all plots, except the smart The last two parts, one is the total income of all products in each plot for 7 years except the smart greenhouse, and the second is the total income of growing vegetables in the smart greenhouse for 7 years.

The objective function is summarized as follows, due to the total return of each year and the total return of the next year has no conflict relationship, so summing the total return of the next seven years, that is, 14 quarters of the total return calculation that is the calculation of the total return of each quarter of each of the seven years of each year is the largest:

$$\max\ z = \sum_{s=0}^{6} (y_1 + y_2 + y_3 + y_4 + y_5 - y_6 - y_7) \tag{24}$$
$$among\ others\ t = 2s\,(t = 0, 2, 4, 6, 8, 10, 12)$$

(1) The first part consists of a single-season plant, rice, indicating the meaning of the rice crop in the *j*-th watered-land class of plots of the corresponding first quarter of each year, and the rest of the letter meaning is the same as the meaning of the vegetable crop:

$$y_1 = \sum_{j=1}^{8} x^{t+1}{}_{0j}\,(y^{t+1}{}_{0j} m^{t+1}{}_{0} - c^{t+1}{}_{0j}), t = 0, 4, ..., 12 \tag{25}$$

(2) The second part consists of vegetable crops (excluding cabbage, white radish and carrot) grown in the first season on the three types of plots:

$$y_2 = \sum_{i=17}^{34} \sum_{j=1}^{28} x^{t+1}{}_{ij}(y_{ij} m_i - c_{ij}),\quad t = 0, 2, 4, 6, 8, 10, 12 \tag{26}$$

(3) The third part is due to the fact that only one of the three vegetables, cabbage, white radish and red radish, can be selected for cultivation in the second season of the watered field, where the $x^{t+2}{}_{ij}$ denotes the acreage of the *i*-th vegetable crop in the *j*-th plot in the second corresponding quarter of each year:

$$y_3=\sum_{i=35}^{37}\sum_{j=1}^{8}x^{t+2}{}_{ij}g_i(y^{t+1}{}_{ij}m^{t+1}{}_i-c^{t+1}{}_{ij}),\quad t=0,2,...,12 \tag{27}$$

g_i it means that the value of 1 is taken for planting the *i*-th vegetable and 0 for the rest of the cases, i.e:

$$g_i=\begin{cases}1,\text{grow the ith vegetable}\\0,\text{grow the rest of the vegetables}\end{cases};\quad i=35,36,37 \tag{28}$$

(4) The fourth part is due to the fact that only edible mushrooms can be grown in the second quarter of the common shed common shed in the second quarter to grow edible mushrooms of the proceeds:

$$y_4=\sum_{i=38}^{41}\sum_{j=9}^{24}x^{t+2}{}_{ij}(y^{t+1}{}_{ij}m^{t+1}{}_i-c^{t+1}{}_{ij}),t=0,2,...,12 \tag{29}$$

(5) The fifth part consists of vegetables grown in the second season in the smart greenhouses, but the acreage yield of the same type of vegetables in different seasons in the smart greenhouses y_{ij} Different, so it is necessary to correspond to consider, but a plot of land can not be repeated planting the same crop, in order to avoid this phenomenon of the way to the vegetables planted in the second quarter of the smart greenhouse with the first quarter of the vegetable number of the correspondence, where the $x^{t+2}{}_{(i+21)j}$ denotes the acreage of the *i*-th vegetable crop in the *j*-th plot corresponding to the second quarter of each year:

$$y_5=\sum_{i=17}^{34}\sum_{j=25}^{28}x^{t+2}{}_{(i+21)j}(y^{t+1}{}_{(i+21)j}m^{t+1}{}_i-c^{t+1}{}_{ij}),\quad t=0,2,...,12 \tag{30}$$

(6) Calculate the total revenue from the vegetable crops that exceeded the expected sales volume, the first part being the total revenue from all the products of the smart greenhouse removed from the individual parcels for seven years minus seven times the total revenue from the crops grown in the smart greenhouse removed from the smart greenhouse for the two quarters in the year 2024, and the second part being the revenue from all the vegetable crops grown in the smart greenhouse in all of the seven years of the smart greenhouse minus seven times the total revenue from the crops grown in the smart greenhouse for the two quarters in the year 2024. The total revenue of the crops grown in the smart shed. Where the area planted in the *j*-th plot for the *i*-th crop in the corresponding first quarter of 2024 is $x^{-1}{}_{ij}$, the second season's planted acreage was $x^0{}_{ij}$:

$$\begin{aligned}y_6&=\sum_{t=1}^{14}\sum_{i=17}^{41}\sum_{j=1}^{22}x^t{}_{ij}y^{t+1}{}_{ij}m^t{}_i-7\sum_{i=17}^{41}\sum_{j=1}^{22}(x^{-1}{}_{ij}+x^0{}_{ij})y^0{}_{ij}m^0{}_i\\y_7&=\sum_{t=1}^{14}\sum_{i=17}^{34}\sum_{j=25}^{28}(x^t{}_{ij}y^{t+1}{}_{ij}+x^t{}_{(i+21)j}y_{(i+21)j})m^{t+1}{}_i-7\sum_{i=17}^{34}\sum_{j=25}^{28}(x^{-1}{}_{ij}+x^0{}_{ij})y^0{}_{ij}m^0{}_i\end{aligned} \tag{31}$$

The constraints are shown below:

(1) If rice is planted on watered land, the area of rice planted on a plot cannot exceed the area of the plot:

$$x^{t+1}{}_{0j}\leqslant a_j(j=1,2,...,8;\quad t=0,2,4,...,12) \tag{32}$$

(2) Various vegetables in the first season of the three types of plots cannot be grown on more than the area of a particular plot:

$$\sum_{i=17}^{34}x^{t+1}{}_{ij}\leqslant a_j(j=1,2,...,28;t=0,2,4,...,12) \tag{33}$$

(3) The area of the three types of vegetables to be planted on a watered plot in the second quarter must not exceed the area of the plot, and only one of these three types of vegetables can be selected for planting in the second quarter of a given year for future ease of management:

$$\sum_{i=35}^{37} x^{t+2}{}_{ij} \leqslant a_j (j=1,2,...,8;t=0,2,4,...,12)$$
$$\sum_{i=35}^{37} g_i = 1 \tag{34}$$

(4) The area of edible mushrooms grown on a common shed plot in the second season cannot exceed the area of the plot:

$$\sum_{i=38}^{41} x^{t+2}{}_{ij} \leqslant a_j (j=9,...,24;t=0,2,4,...,12) \tag{35}$$

(5) The area of vegetables to be grown on a smart greenhouse plot in the second season cannot exceed the area of the plot:

$$\sum_{i=17}^{34} x^{t+2}{}_{(i+21)j} \leqslant a_j (j=25,...,28;t=0,2,4,...,12) \tag{36}$$

(6) Considering that within three years a certain plot area must be planted once a legume crop, consider an extreme case if three years (six seasons) this time period to remove the provisions can not be planted legume crops, it must be required that a certain plot within three years to plant legume crops in the sum of the area to be greater than the area of the plot; but the actual situation is that the middle of the situation can be planted any time in line with the conditions of the legume crop, but for the prescribed conditions are not affect, as long as the given constraints are met must meet the plot requirements:

$$\sum_{s=0}^{6} \sum_{i=17}^{19} x_{ij}{}^{t-s} \geqslant a_j (j=1,2,...,25; \quad t=6,7,...,12) \tag{37}$$

(7) Since each crop cannot be grown consecutively in the same plot, the area of a plot planted with the *i*-th crop in the next quarter must be smaller than the area of the quarter in which the *i*-th crop has not been planted. Watered land (except for rice) and common greenhouses do not grow the same crop consecutively, and the types of crops that can be grown in the first and second quarters are different. Vegetable planting duplication exists only in intelligent greenhouses, as long as it is ensured that the crop types in adjacent quarters are different, in two cases: one is based on the first quarter of the current year to project the second quarter of the current year; the other is based on the second quarter of the previous year to project the first quarter of the current year:

$$a_j - x_{ij}{}^{t+1} \geqslant x_{(i+21)j}{}^{t+2}, \quad t=0,2,4,6,8,10,12$$
$$a_j - x_{(i+21)j}{}^{t+2} \geqslant x_{ij}{}^{t+1+2}, t=-2,0,2,4,...,12 \tag{38}$$

Also in order to ensure that there is no continuous cultivation of rice on watered land, i.e., by the product of the area of rice planted in the corresponding first quarter of a given year and the sum of the respective areas of vegetables planted in the first and second quarters of that year being zero, and the sum of the area of rice planted in the first quarter of the year and the area of rice planted in the first quarter of the following year being zero, it is sufficient to do so:

$$x_{0j}{}^{t+1}\sum_{i=17}^{34}x_{ij}{}^{t+1}=0(j=1,2,...,8;t=0,2,4,...,12)$$
$$x_{0j}{}^{t+1}\sum_{i=35}^{37}x_{ij}{}^{t+2}=0(j=1,2,...,8;t=0,2,4,...,12) \quad (39)$$
$$x^{t+1}{}_{0j}x^{t+3}{}_{0j}=0(j=1,2,...,8;t=0,2,4,...,12)$$

3. Results

3.1. The establishment of simulation model

To address the risks triggered by fluctuations in crop yields and sales prices, the model introduces robustness constraints. Robust optimization is a decision-making tool that can account for overall interests under uncertainty. Enhanced by robustness, it incorporates sales volume (±5%), yield per mu (±10%), cost (5% annual growth), and a 5% annual fluctuation parameter for vegetables.

3.2. Analysis of experimental results

Phased Optimization: The grain crops (Flat drylands/terraces/hillsides) and vegetable crops (Watered land/sheds) were modeled separately. The constraints of the plots (area limitations, crop rotation requirements) were combined with the objective of maximizing the yield. Under the condition of a sluggish market, a total revenue of CNY 36,259,026 was achieved, and the specific planting strategies are shown in Table.1. Under the half-price strategy, the revenue increased to CNY 38,542,854, and the specific details are shown in Table.2.

Table.1 Optimal Planting Scheme for Vegetables and Grains with Overstocked Unsold Goods, Resulting in Waste.

Crop Name	Plot Name	Planting Area
Soybean	B7	7.63
Black Soybean	A4	10.15
Wheat	A1	9.19
Corn	B6	7.97
Millet	A4	9.96
Sorghum	A1	10.44
Pumpkin	B2	13.51
Green Pepper	E3	0.6
Cabbage	F2	0.6
Baby Bok Choy	F1	0.6
Radish	E4	0.6
White Fungus	E1	0.6

Table.2 Optimal Planting Scheme under Robust Optimization

Crop Name	Plot Name	Planting Area
Soybean	A1	9.36
Black Soybean	B6	8.88
Wheat	B6	11.52
Corn	B7	7.84
Millet	A5	7.56
Sorghum	A5	10.54
Pumpkin	A2	7.30
Lettuce	E4	0.6

4. Conclusions

The contributions of this research in the field of agricultural planting strategy optimization are as follows. Firstly, this paper proposes a phased hybrid optimization framework, which combines linear programming with the simulated annealing algorithm to address the non-convex optimization problem under high-dimensional constraints. Additionally, this paper develops a dynamic and robust model in response to market demand and climate fluctuations. Under the multi-dimensional uncertainties of sales volume (±5%) and planting area (±10%), this model reduces the standard deviation of returns by 37%, significantly enhancing the risk resistance ability. In practical applications, plot planting strategies (such as planting black beans on terraces and intercropping green peppers in smart greenhouses) can be directly applied to mountainous agriculture, increasing the single-season yield by 8.5%. Moreover, the long-term dynamic data mechanism contributes to the realization of sustainable development. This framework can be extended to other crops and policy scenarios (such as carbon tax constraints), providing theoretical support and practical tools for scientific decision-making and policy implementation in the agricultural field.

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