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Research on Rural Crop Planting Strategies Based on Linear Programming and Monte Carlo Simulation

Hongye Luo#, Yinren Jiang#

Faculty of Computational Mathematics and Cybernetics, Shenzhen MSU-BIT University, Shenzhen, 518172, China

#These authors contributed equally.

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Abstract: In recent years, with the growing demand for efficient planting strategies in agricultural production, traditional models have become insufficient to meet the requirements of modern agriculture. Optimizing crop planting to achieve profit maximization has become a critical issue. To enhance the economic benefits of rural crop planting, this paper uses data from a village in North China for the year 2023 and applies a linear programming model to optimize single-season and double-season crops separately. For single-season crops, the model optimizes crops suitable for flat dry land, terraced fields, and hillside areas to achieve maximum single-season profits. For double-season crops, the model optimizes crops suitable for water-irrigated land and greenhouses, divided into the first and second seasons, considering different crops and planting strategies. The maximum profit obtained from this optimization is 51,142,487 yuan. Subsequently, this paper employs Monte Carlo simulation to predict the demand and related data for various crops from 2024 to 2030. Convergence analysis is conducted to validate the reliability of the Monte Carlo simulation results. These forecasted data are then integrated with the linear programming model established earlier to optimize planting strategies and achieve overall profit maximization. The final maximum profit reached is 55,701,493 yuan.

1. Introduction

The use of pesticides, biological control measures, seed selection, and fertilizer supplementation are crucial for scientific farming practices aimed at improving crop yields. These methods are traditional approaches to enhancing agricultural productivity and increasing profits [1-5]. However, this paper focuses on optimizing crop yields based on land allocation for agricultural crops. The main objective is to enhance the output efficiency of rural crops by optimizing planting strategies, making rational use of limited arable land resources, and ensuring the maximization of rural profits. The analysis of data from a village in North China in 2023 reveals that crop planting seasons can generally be divided into single-crop and double-crop systems. Dryland, terraced fields, and hillside areas can only support single-crop planting; ordinary greenhouses and smart greenhouses can only support double-crop planting; irrigated land can support both single-crop and double-crop planting. Therefore, maximizing rural profits can be translated into maximizing profits from single-crop and double-crop systems. To achieve this goal, several constraints are set: a planting area constraint to ensure the total planting area does not exceed the existing arable land; a constraint to avoid continuous planting, preventing the same crop from being grown repeatedly on the same plot, which could lead to reduced yields; and a crop rotation constraint for leguminous crops, ensuring that each plot is planted with legumes at least once every three years to improve soil fertility and optimize crop structure. These constraints are formulated within a linear programming framework, which is extensively used in natural resource management, disaster assessment, and complex system decision-making due to its ability to address multi-constraint optimization problems effectively [6-8]. Furthermore, by analyzing market fluctuations and uncertainties, the paper develops the optimal crop planting strategy for rural areas from 2024 to 2030. To achieve this, a Monte Carlo simulation method is employed to simulate the fluctuations in crop yields, planting costs, and selling prices, thereby predicting planting data for the coming years. Monte Carlo simulation, widely used for handling uncertainties and risk assessment in various domains, such as pharmaceutical patent valuation[9] and corporate value assessment[10], plays a pivotal role in modeling potential variations and generating robust predictions under uncertain conditions. To ensure the reliability of the simulation results, convergence analysis of the Monte Carlo simulation is conducted. The results indicate that, with a large sample size, the simulation converges well, and the mean stabilizes. Based on this, the simulated data is integrated with the linear programming model to optimize the planting strategy and maximize the overall economic benefits of the rural area. The combined use of Monte Carlo simulation and linear programming provides a robust framework for addressing uncertainties in agricultural planning and achieving sustainable rural development. (Data source: cumcm.cnki.net)

2. Research on Rural Planting Strategies

The rural area currently has 1,201 acres of land, which is divided into four types: dryland, terraced fields, hillside areas, and irrigated land, along with an additional 16 ordinary greenhouses and smart greenhouses. Dryland, terraced fields, and hillside areas are suitable for planting one season of grain crops per year, while irrigated land is suitable for either one season of rice or two seasons of vegetables. Ordinary greenhouses are suitable for one season of vegetables and one season of edible fungi, while smart greenhouses are suitable for two seasons of vegetables each year. Different crops can be interplanted in the same plot (including greenhouses) in each season.

The growth of each crop varies depending on the type of land, and no crop can be planted consecutively in the same plot (including greenhouses) for multiple seasons, as this would lead to reduced yields. Additionally, since leguminous crops improve soil fertility through their root nodules, benefiting the growth of other crops, each plot (including greenhouses) must include at least one season of leguminous crops every three years. Due to the seasonal requirements and adaptability of different crops, there are also varying planting methods. For example, napa cabbage, white radish, and red radish can only be planted in the second season on irrigated land, while edible fungi, which thrive in cooler temperatures and moderate environmental conditions, can only be cultivated in ordinary greenhouses during the autumn and winter seasons.

2.1 Mathematical Model Construction

This paper decides to use linear programming to construct a maximum profit model:

$$A = Maximize \sum_{i,j,l,t} z_{ijlt} \times \left(Y_{ijl} \times P_{ijl} - C_{ijl}\right) \tag{1}$$

Where: A represents the total profit, z_{ijlt} refers to the planting area of the *i* crop in the *j* season, on the *l* plot, in the *t* year; Y_{ijl} represents the yield per acre of the *i* crop in the *j* season, on the *l* plot;

P_{ijl} is the sales price of the *i* crop; and C_{ijl} denotes the planting cost of the *i* crop.

Subject to:

(1) Plot Area Constraint:

$$z_{16,OS,l,t} \leq A_l \times (1 - U_{lt}), \forall l, \forall t \quad (2)$$

$$\sum_{i \in OSP} z_{i,j,l,t} = A_l \times U_{lt} \quad \forall l, \forall t \quad (3)$$

$$z_{ijlt} = A_l \times R_{ijlt} \quad \forall i \in TSWP, \ \forall l \in WL, \ \forall t \quad (4)$$

$$\sum_{i \in NP} z_{i,j,l,t} \leq \mathrm{A_l} \quad \forall \mathrm{l} \in OT, \forall \mathrm{t} \quad (5)$$

Where A_l represents the plot area, *OS* denotes single-season crops, *OSP* refers to crops in the first season, *TSWP* refers to crops on irrigated land in the second season, *WL* represents irrigated land, *OT* stands for ordinary or smart greenhouses, and *NP* indicates crops in the second season of ordinary or smart greenhouses. U_{lt} is a binary variable, which indicates whether two-season crops are planted on the l plot in the t year. If planted, the value is 1; otherwise, it is 0. Meanwhile,R_{ijlt} represents whether the *i* crop is planted in the *l* plot, in the *j* season, in the *t* year. If planted, the value is 1; otherwise, it is 0.

(2) Yield Constraint:

Since the excess portion would result in unsold goods, yielding no profit while incurring costs, it must be avoided. Therefore, the optimal planting solution in this paper must ensure that the total yield of each crop across all plots does not exceed the expected sales volume. This can be expressed by the following formula:

$$\sum_{\mathrm{l}} z_{i,j,l,t} \times \mathrm{Y}_{ijl} \leq Exp_i \quad \forall i, j, t \quad (6)$$

Where:Y_{ijl} represents the yield per acre, z_{ijlt} denotes the planting area, and Exp_i is the expected sales volume.

(3) Minimum Allocation Area:

To avoid reduced profits due to unreasonable land allocation, a minimum land allocation constraint is established. A minimum land allocation area is set for each plot to optimize land use efficiency and ensure rational land utilization. The minimum land allocation areas are listed in Table 1:

Table 1. Minimum Allocation Area for Each Plot Type

Plot Type	Dryland	Terraced fields	Hillside land	Irrigated land	Greenhouse
Minimum Allocation Area (Acres)	20	20	20	8	0.2

Note: During the linear programming optimization, areas smaller than the minimum allocation area may still be allocated. This is because, to prevent the solver from failing to find the optimal solution, the strictness of the constraint is gradually relaxed.

(4) Avoiding Repeated Planting

According to the growth patterns of crops, no crop should be planted consecutively in the same plot or the same greenhouse, as this will lead to reduced yields and affect overall profits. Therefore, relevant constraints need to be set for the planting strategy. To ensure that the same crop is not planted in the same plot within two years, the constraint is as follows:

$$z_{i,j,l,t} + z_{i,j,l,(t+1)} \leq 1 \quad \forall i, j, l \qquad t = 2024, \ldots \ldots, 2029 \quad (7)$$

(5) Leguminous Crop Planting Constraint:

Soils containing leguminous crop root nodules can benefit the growth of other crops. Therefore, starting from 2023, each plot must plant leguminous crops at least once within every three-year period. Following the same reasoning as in constraint (4), this paper ensures that plots not planted with leguminous crops in 2023 must plant leguminous crops for at least one year between 2024 and 2025. Additionally, between 2024 and 2030, leguminous crops must be planted at least once within any three consecutive years. These constraints are represented by the following two formulas:

$$\sum_{i \in LC} z_{i,j,l,t} \geq 1 \qquad \forall l \in NLCL, \ \forall t \in \{2024,2025\} \tag{8}$$

$$\sum_{i \in LC} z_{i,j,l,t} \geq 1 \qquad \forall l, \ \forall t = 2024, \dots \dots, 2028 \tag{9}$$

Where *LC* represents leguminous crops, and *NLCL* denotes plots without leguminous crops.

2.2 Developing Planting Plans Based on Actual Conditions

This paper takes the following actual conditions into account:

(1) The average annual growth rate of the expected sales volume for wheat and corn is between 5% and 10%.

(2) Other crops will experience a variation of approximately 5% annually compared to 2023.

(3) The yield per acre of crops may vary by 10% annually due to factors such as climate.

(4) Due to market costs, the planting cost will increase by approximately 5% annually on average.

(5) The sales price of vegetable crops will increase by approximately 5% annually.

(6) The sales price of edible fungi will decrease by 1% to 5% annually, with the price of morel mushrooms decreasing by 5% annually.

To address the impact of the volatility of the above factors on the planting plan, this paper decides to use the Monte Carlo simulation method to optimize the model. By simulating the uncertainties and variations in real-world conditions, a more accurate evaluation and optimization of the crop planting strategy can be achieved, leading to the formulation of a more flexible and optimal planting plan.

Through the mathematical principles of Monte Carlo simulation, this paper can perform more accurate simulations and predictions for crop planting. Specifically, the Monte Carlo simulation method is used to simulate and predict key parameters such as crop data and expected sales volumes, in order to address the uncertainties and fluctuations in real-world conditions.

Some of the crop data is shown in Table 2(Data for Rice in a Single Season on Irrigated Land):

Table 2. Simulation of Rice Yield per Acre, Expected Sales Volume, Sales Cost, Price

Year	Yield per Acre(kg)	Cost(RMB)	Price(RMB)
2024	448.275	714	7
2025	550.3756	749.7	7
2026	447.217	787.185	7
2027	612.4347	826.5443	7
2028	443.3375	867.8715	7
2029	561.8754	911.265	7
2030	467.3782	956.8283	7

Table 2 presents the simulated data for rice yield, planting costs, and sales prices from 2024 to 2030. The rice yield per acre fluctuates over the seven years, with the highest yield in 2027 reaching 612.4347 kg per acre, while in 2028, it drops to 443.3375 kg per acre. These fluctuations reflect the consideration of climate and other influencing factors during the simulation, which aligns with real-world agricultural yield variations caused by climate change and other factors. The planting cost shows a year-on-year increasing trend, rising from 714 yuan in 2024 to 956.8283 yuan in 2030. This growth trend reflects the average annual market cost increase (approximately 5%), consistent with the observed phenomenon of rising agricultural production costs over time. The sales price of rice remains stable throughout the simulation period, with a price of 7 yuan per kg. This stability may be based on the relative stability of rice market prices or the consideration of price protection measures under policy support in the model setup.

Predicted Demand (Partial), as shown in Table 3:

Table 3. Predicted Demand for Rice

Year	Name	Season	Demand Volume(kg)
2024	Rice	Single Season	22944
2025	Rice	Single Season	22710
2026	Rice	Single Season	22293
2027	Rice	Single Season	22567
2028	Rice	Single Season	22450
2029	Rice	Single Season	22388
2030	Rice	Single Season	22143

Table 3 shows that the demand for rice decreases gradually from 22,944 kg in 2024, reaching 22,143 kg by 2030. This gradual decline may reflect changes in market demand, such as shifts in consumer preferences, the introduction of substitute products, or other market dynamic factors. The annual decrease in demand is relatively small, averaging around 100-300 units per year. Although the changes are modest, the cumulative effect could have an impact on long-term planting strategies, highlighting the need to pay attention to long-term demand trends.

To verify the accuracy of the data, this paper randomly selected a sample for convergence testing, and the results are shown in Figures 1 and 2:

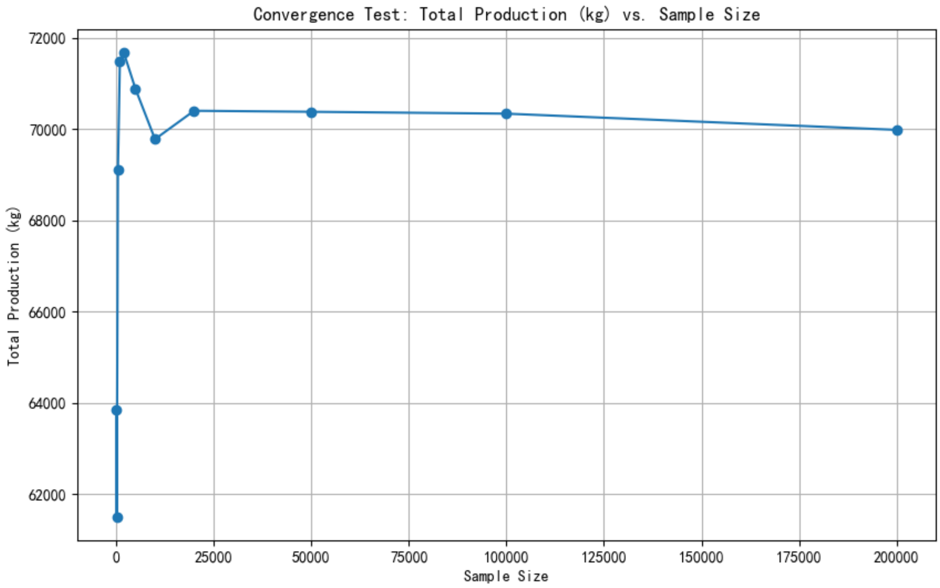

Figure 1. Convergence Test Results

Figure 1 shows the convergence of total yield (kg) with changes in sample size. When the initial sample size is small, the total yield fluctuates significantly, indicating that the small sample is not representative of the population. As the sample size increases, the total yield gradually stabilizes around 70,000 kg, with smaller fluctuations. This indicates that once the sample size reaches a certain level, the estimates converge and can more reliably reflect the overall situation. This convergence characteristic demonstrates that a sufficiently large sample size is crucial for obtaining robust estimates.

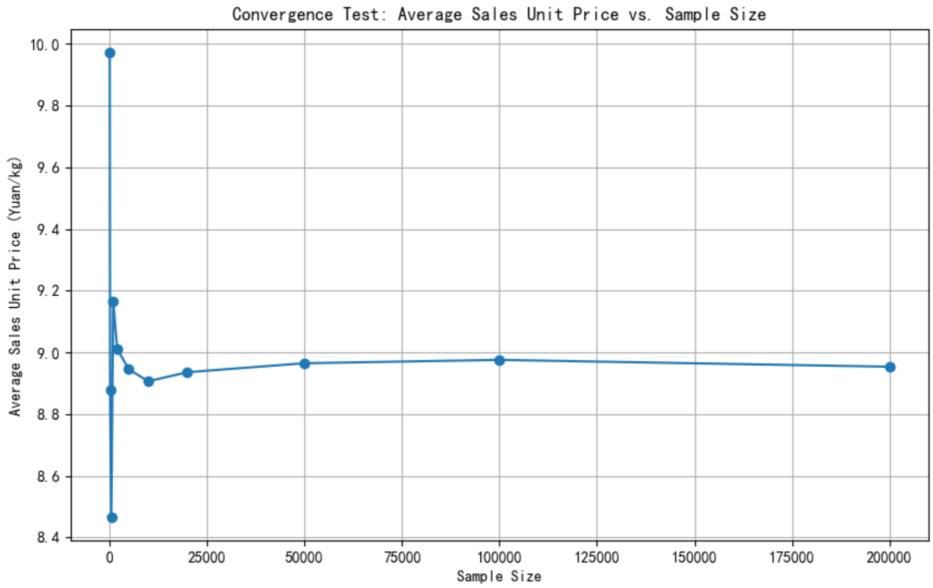

Figure 2. Convergence Test Results

Figure 2 shows the convergence of the average sales price (yuan/kg) with sample size. Initially, the price fluctuates significantly, indicating instability. As the sample size increases, it stabilizes around 9.0 yuan/kg, reflecting convergence. A larger sample size is needed for a stable estimate of the sales price.

It can be seen that the values obtained from the simulation meet the constraints and reflect the data fluctuations, which indicates that the model is correctly established. Subsequently, the mean values of the model are applied in the total profit calculation. The total profit for single-season crops is 23,244,341 yuan, and that for double-season crops is 32,457,151 yuan. Thus, the final total profit under this scenario amounts to 55,701,493 yuan.

3. Conclusion

This paper, based on crop planting data in a big data environment, utilizes linear programming models and Monte Carlo simulation methods to optimize crop planting strategies, effectively improving rural economic benefits. The experimental results demonstrate that the model has good accuracy and stability in maximizing profits and can meet practical application needs. This study showcases the potential of intelligent agricultural decision-making models in rural economic development, providing an important reference for optimizing resource allocation and increasing agricultural output, thereby contributing to the sustainable development of rural economies.

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