Research on Solving Crop Planting Strategies Based on Particle Swarm Optimization Algorithm

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Abstract. In order to fully utilize the limited arable land resources in the rural area and improve the profits of the rural planting industry, this article mainly uses particle swarm optimization algorithm, and combines other models to determine the optimal strategy for crop planting in the rural area. Establish a mathematical programming model and use particle swarm optimization algorithm to solve for the planting strategy that maximizes the profit of the village under the given constraints. Firstly, write the objective function equation based on the given conditions. Subsequently, based on the constraints in the question, write down the constraints and add a penalty function to the objective function. Finally, the particle swarm algorithm is used to solve for the optimal planting strategy, and the crop planting area for each plot is allocated based on the obtained results. Using the planting strategy determined in this article, the annual profit of the village is approximately 6 million yuan; under another constraint, the annual profit of the village is approximately 8 million yuan.

Keywords: Particle Swarm Optimization Algorithm, Clustering Algorithm, Analytic Hierarchy Process, Multiple Linear Regression Model.

1. Introduction

A certain village is located in the mountainous area of North China and often faces many challenges due to the limitations of the natural environment. The village has 1201 acres of arable land, divided into four types: flat dry land, terraced land, hillside land, and irrigated land. The village hopes to choose suitable crops and optimize planting strategies to develop the organic planting industry, in order to achieve sustainable development and improve production efficiency. To further enhance agricultural efficiency, it is required to plant leguminous crops at least once per plot of land within three years, while avoiding continuous planting on the same plot. The planting plan also needs to consider the convenience of field management, avoid crop planting too scattered, and ensure that the planting area of a single plot is reasonable. This article mainly explores the optimal planting strategy for crops in the rural area, while also considering constraints such as replanting, planting legumes at least once every three years on all plots, and the convenience of farming operations and field management. This is an optimization problem where, based on the given conditions, the objective function expression is written, followed by the constraint condition expression. Furthermore, a penalty function is written to penalize feasible solutions that do not meet the constraint conditions. Ultimately, optimization algorithms can be used for solving.

2. Analysis of Cultivated Land Resources in the Mountainous Areas of North China

The cultivated land resources in the mountainous areas of North China are relatively limited, mainly distributed in Hebei, Shanxi, and northern Shaanxi. The terrain in this area is complex and suitable for planting crops such as wheat, corn, and millet. Although the soil conditions are good, water scarcity and soil erosion seriously affect agricultural development. In recent years, the promotion of agricultural technologies such as crop rotation and intercropping has improved the utilization rate of arable land [1-2]. At the same time, in order to promote agricultural development, the mountainous areas of North China actively use emerging technologies such as smart greenhouses to increase annual profits. As shown in Figure 1, it is a real picture of cultivated land in the mountainous areas of North China.

Figure 1. Farmland in the mountainous areas of North China

The village plot can be mainly divided into five categories: flat dry land, terraced fields, hillside land, irrigated land, and greenhouses. Among them, greenhouses can also be divided into two categories: ordinary greenhouses and smart greenhouses. The specific distribution is shown in Figure 2.

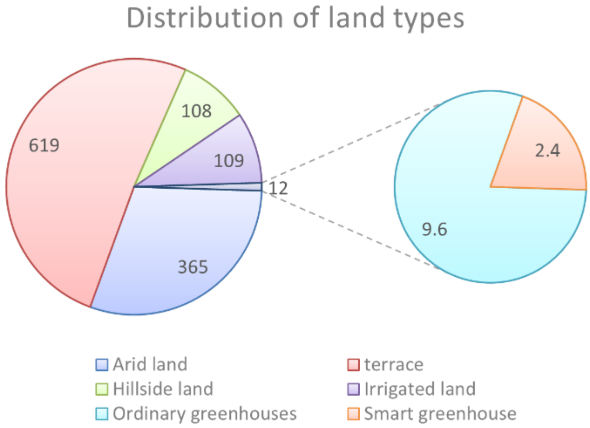

Figure 2. Pie chart of land parcel types distribution

From Figure 2, it can be seen that the area of terraced fields in the village is significantly larger than other types of land, at 619 acres, exceeding 50% of the total land area of all types, which is consistent with the true geographical location of the village in the mountainous area of North China. At the same time, the area of greenhouses is significantly smaller than other types of land, with the sum of the area of ordinary greenhouses and smart greenhouses being only 12 acres, accounting for only 10% of the total land area of all types.

The same crop is planted on different types of land in this article, with different yields per mu. Based on common sense and relevant information, it is inferred that this may be related to different soil fertility. The more fertile the land, the higher the yield per mu, while the less fertile the land, the lower the yield per mu.

When observing the consequence from the Figure 3, we can conclude all cereal crops have the highest yield per mu in flat and dry land, and the lowest yield per mu in hillside land. It can be seen that in the mountainous areas of North China, flat dry land has the highest soil fertility compared to terraced fields and hillside land. Due to the fact that the planting cost of the same crop is the same on flat land, terraced land, and hillside land, the profit per mu on flat land should be the highest among these three types of land. Due to vegetable crops, the yield and planting cost per mu are different in irrigated land, ordinary greenhouses, and smart greenhouses, and the higher the planting cost, the generally higher the yield per mu. To explore which plot of land yields the highest planting income, formula (1) can be used to calculate the profit per mu.

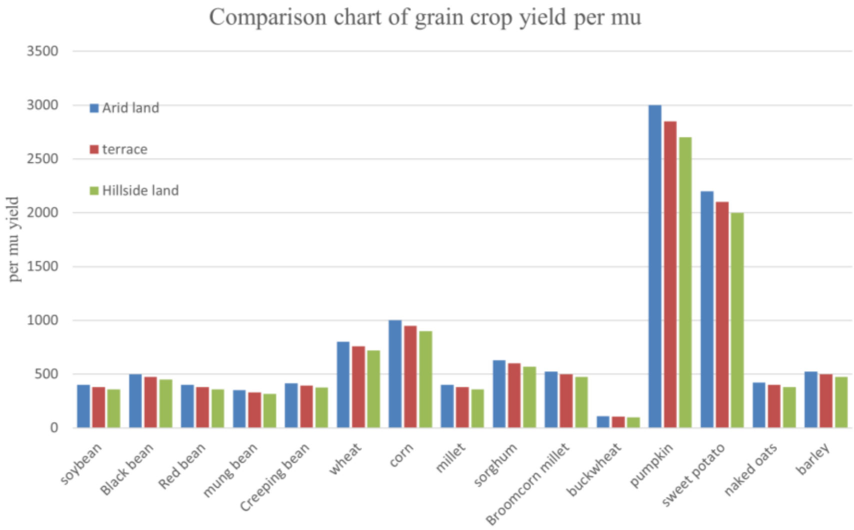

Figure 3. Comparison of yield per mu of grain crops

$$\text{Mu profit} = \text{per mu yield} \times \text{Sales unit price} - \text{Planting cost} \quad (1)$$

Use formula (1) to calculate the per acre profit obtained from planting each vegetable crop in irrigated land, ordinary greenhouses, and smart greenhouses, and visualize the results. Draw a bar chart as shown in Figure 4:

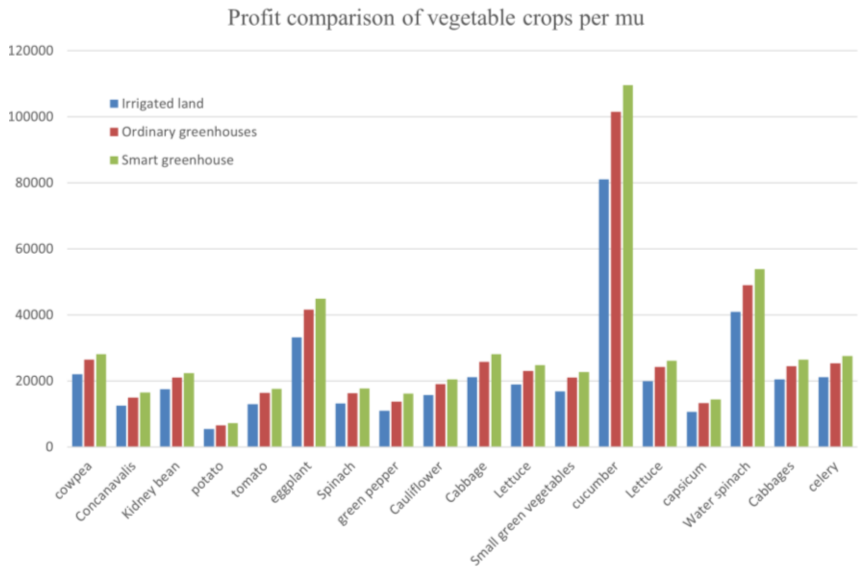

Figure 4. Comparison of Profit per Mu for Vegetable Crops

While observing the consequence from the Figure 4, compared to traditional irrigated land, planting in smart greenhouses can significantly increase the profit per mu even if the planting cost slightly increases.

2.1. Model Establishment and Solution

This article lists the objective function and constraints, adds a penalty function to the iterative results, and uses particle swarm optimization algorithm to obtain the maximum profit [3].

There are a total of 55 plots in this rural area. To simplify the model and facilitate subsequent analysis, these 55 plots can be classified into 6 categories based on their different types, namely arid land, terraced fields, hillside land, irrigated land, ordinary greenhouses, and smart greenhouses. 15 types of seasonal grains can be planted in arid areas, terraced fields, and mountainous areas; In irrigated land, one season of rice or two seasons of vegetables can be planted, with 18 types of vegetables in the first season and a total of 3 types of vegetables in the second season; A regular greenhouse can grow 18 types of vegetables in the first season and 4 types of edible fungi in the second season; The smart greenhouse can grow two seasons of vegetables, and the types of vegetables in both seasons are 18 categories. For this purpose, the total area planted for each type of crop on each plot can be set as the decision variable xi (1≤i≤107), and solved using particle swarm optimization algorithm.

(1) Write the objective function equation

Using xi to represent the planting area of each crop, using si to represent the yield per mu of each crop on the corresponding plot, using mi to represent the selling unit price of each crop, and using ci to represent the planting cost of each crop on the corresponding plot, formula (2) can be used to calculate the maximum profit Profit obtained by planting crops in the rural area each year:

$$\text{Profit} = \sum x_i \times (s_i \times m_i - c_i) \tag{2}$$

Due to the fact that if the yield of each crop exceeds the expected sales volume, the excess will be unsold and result in losses. Therefore, if Li is used to represent the expected sales volume of each crop, the maximum annual profit Profit of the village is shown in formula (3):

$$\text{Profit} = \sum [x_i \times (s_i \times m_i - c_i) - m_i \times (s_i \times m_i - L_i)] \tag{3}$$

To make the objective function conform to the standard formula in mathematical programming models and facilitate the subsequent solution of particle swarm optimization algorithm, a negative sign can be added before formula (3) to transform the maximum value problem obtained in this paper into a minimum value problem [4]. The transformed objective function formula is shown in formula (4).

$$\text{Profit} = -\sum [x_i \times (s_i \times m_i - c_i) - m_i \times (s_i \times m_i - L_i)] \tag{4}$$

For the convenience of subsequent analysis, the profit Profit can be divided into six parts according to the type of land parcel, and represented by yi in sequence (1≤i≤6). For example, y1 represents the total profit obtained from arid land, y2 represents the total profit obtained from terraced fields, y3 represents the total profit obtained from hillside land, y4 represents the total profit obtained from irrigated land, y5 represents the total profit obtained from ordinary greenhouses, and y6 represents the total profit obtained from smart greenhouses. Therefore, the objective function Profit can also be represented by equation (5).

$$\text{Profit} = -(y_1 + y_2 + y_3 + y_4 + y_5 + y_6) \tag{5}$$

Since irrigated land can grow one season of rice or two seasons of vegetables, y4 can also be divided into three parts: the total profit obtained from planting one season of rice in irrigated land is set as y41, the profit obtained from planting the first season of vegetables in irrigated land is set as y42, and the profit obtained from planting the second season of vegetables in irrigated land is set as y43. Similarly, the total profit obtained from planting the first season of vegetables in a regular greenhouse is set as y51, and the total profit obtained from planting the second season of vegetables in a regular greenhouse is set as y52.

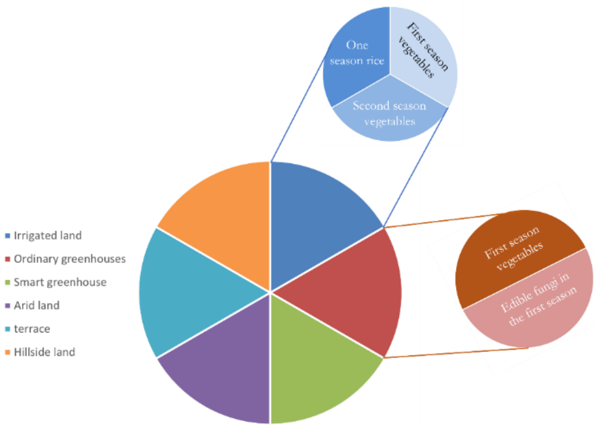

Figure 5. Composition of Total Profit

It can be seen from the observation in Figure 5, the composition of the total profit Profit can be clearly seen. In order to make the algorithm for this article more modular and facilitate the adjustment of its parameters in the future, we will now write formulas for yi in sequence for calculation. For the profit y1 of arid land, the land type is arid land, and a total of 15 types of seasonal crops can be planted. Therefore, the decision variable xi (1≤i≤15) is used to represent its corresponding planting area. The calculation formula for y1 is shown in equation (6) below.

$$y_1 = \sum_{i=1}^{15}[x_i \times (s_i \times m_i - c_i) - m_i \times (x_i \times s_i - L_i)] \quad (6)$$

Similarly, the calculation formulas for y2 and y3 are shown in equations (7) and (8) respectively:

$$y_2 = \sum_{i=16}^{30}[x_i \times (s_i \times m_i - c_i) - m_i \times (x_i \times s_i - L_i)] \quad (7)$$

$$y_3 = \sum_{i=31}^{45}[x_i \times (s_i \times m_i - c_i) - m_i \times (x_i \times s_i - L_i)] \quad (8)$$

Regarding the profit y4 of irrigated land, as there are a total of 109 acres of irrigated land for planting one season of rice or two seasons of vegetables, the decision variable x46 is used to represent the rice planting area, xi (47≤i≤64) represents the planting area corresponding to the first season of vegetables, and xi (65≤i≤67) represents the planting area corresponding to the second season of vegetables. Therefore, when planting in the first season, there exists an equation condition as shown in formula (9).

$$x_{46} = 109 - \sum_{i=47}^{64} x_i \quad (9)$$

Using mli to represent the profit per mu corresponding to planting different crops in different plots, and chao i to represent the loss amount caused by unsold sales exceeding expectations, the profit y4 of irrigated land can be calculated using the following formula (10).

$$ml_i = s_i \times m_i - c_i$$
$$chao_i = m_i \times (x_i \times s_i - L_i) \quad (10)$$
$$y_4 = x_{46} \times ml_{46} - \text{chao}_{46} + \sum_{i=47}^{67}[x_i \times ml_i - \text{chao}_i]$$

For the profit y5 of a regular greenhouse, the decision variable xi (68≤i≤85) is used to represent the planting area corresponding to the first season of vegetables, and xi (86≤i≤89) is used to represent the planting area corresponding to the second season of edible mushrooms. Therefore, the profit y5 of a regular greenhouse can be calculated using the following formula (11).

$$y_5 = \sum_{i=68}^{89}[x_i \times (s_i \times m_i - c_i) - m_i \times (x_i \times s_i - L_i)] \quad (11)$$

For the profit y6 of the smart greenhouse, assuming that the vegetables planted in two seasons are the same, the decision variable xi (90≤i≤107) is used to represent the planting area corresponding to the two seasons of vegetables. Therefore, the profit y6 of the smart greenhouse can be calculated using the following formula (12).

$$y_6 = \sum_{i=90}^{107}[x_i \times (s_i \times m_i - c_i) - m_i \times (x_i \times s_i - L_i)] \quad (12)$$

Finally, the objective function value can be calculated using formula (5).

(2) List constraint conditions

It is not advisable to continuously plant the same crops on the same plot (including greenhouses), as this can lead to soil nutrient depletion, the growth of pests and diseases, and other serious problems such as decreased crop yields and health damage. Therefore, it is necessary to list constraints to avoid the phenomenon of repeated planting. Due to the constraint conditions being in the extreme case, it is assumed that there exists a limit non repeating cropping scheme in the same plot, which can only plant one crop per year in this plot. However, due to the different planting positions of this crop in the plot each year, the phenomenon of repeated cropping can be eliminated [5-7], as shown in Figure 6.

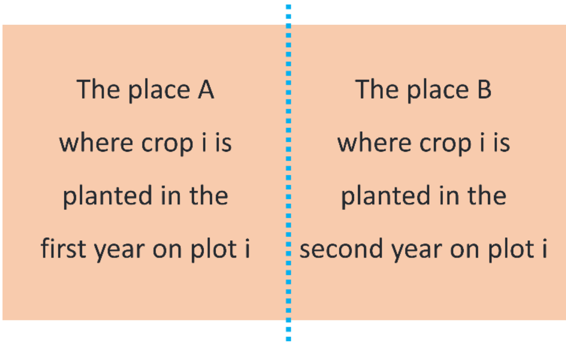

Figure 6. Schematic diagram of extreme non repetitive cropping scheme

As shown in Figure 6 above, suppose that plot (i) can be perfectly divided into two places, A and B, with no shared soil between them. If the same crop (i) is planted in place A of plot (i) in the first year, and then in the second year it is planted in place B, which has no overlapping soil with place A, this scenario represents the extreme case of non-replanting. Due to the fact that in practice, if only one piece of land is divided into two parts, there must be adjacent areas where the same crops are planted for two consecutive years. Even if strictly speaking, it does not belong to the phenomenon of continuous cropping, it will inevitably suffer serious consequences similar to continuous cropping near the boundary between the two pieces of land. To avoid this situation, each type of plot in the attachment can be evenly divided into three equal parts, that is, the area of each crop planted on the same plot should not exceed one-third of the current plot area. This upper limit constraint on decision variables can effectively avoid the phenomenon of repeated cropping. Based on the above analysis, the upper limit constraint condition is shown in formula (13):

$$x_i \leq \frac{area_j}{3}, 1 \leq i \leq 107 \tag{13}$$

Since the planting area of each crop must be a natural number, meaning that the lower limit of all decision variables is 0, the above constraint conditions can be changed to the following equation (14).

$$s.t. \quad 0 \leq x_i \leq \frac{area_j}{3}, 1 \leq i \leq 107 \tag{14}$$

(3) Add a penalty function to the iteration results

In order to maintain the nitrogen content in the soil and keep the soil fertility at a relatively high level, starting from 2023, all land in each plot (including greenhouses) will be planted with leguminous crops at least once within three years. After consulting relevant literature and daily knowledge, it is found that only when the planting area of leguminous crops in each plot exceeds 30%, can leguminous crops have nitrogen fixation effect on the current plot. To simplify the model, two planting schemes can be set. Scheme one does not consider the constraint that the planting area of leguminous crops must exceed 30%, while Scheme two considers the constraint that the planting area of leguminous crops must exceed 30%. Since 2023, all land on each plot (including greenhouses) in the village has been planted with beans at least once within three years [8-9].

Due to the similarity of crops, Scheme One and Scheme Two can be used alternately by year: for example, choosing Scheme One in the first year, Scheme Two in the second year, Scheme One again in the third year, and Scheme Two again in the fourth year, repeating the cycle in sequence. This not only effectively considers the planting issues of leguminous crops. Also, because the planting plan chosen each year is different, it can effectively avoid the problem of repeated cropping.

In the subsequent optimization iteration process of the particle swarm algorithm, each optimization result may not necessarily meet the constraint of bean planting area exceeding 30%. Therefore, a penalty function needs to be added to first determine whether the feasible solution obtained from the iteration meets this constraint, and then penalize the feasible solutions that do not meet the feasible region. The added penalty function is shown in formula (15).

$$\begin{cases} \text{if } \sum x_j < (\text{ area }_i \times 0.3) \\ \quad \text{then let } y_i = 0 \end{cases} \tag{15}$$

In formula (15), area represents the total area of a certain plot type, and xj represents the planting area of leguminous crops that can be planted in the corresponding plot type. For feasible solutions that do not meet the constraints of planting legumes, their profit is directly reduced to 0. In addition to the restrictions on planting legumes mentioned above, there is also a limit on the total planting area of each plot, which means that the total area of crops planted on each plot cannot exceed the area of that plot. Now it is possible to first determine whether the feasible solution obtained through iteration meets this constraint condition, and then add a penalty function to the feasible solution that does not meet this constraint condition as shown in formula (16).

$$\begin{cases} \text{if } \sum x_j > \text{area }_i \\ \text{then let } y_i = y_i \times \exp\left(-\frac{\sum x_j - \text{ area }_i}{\text{area }_i}\right) \end{cases} \tag{16}$$

In the above formula (16), the more $\sum x_i$ exceeds $area_i$, the more the relative value of y_i will decrease. Therefore, in the subsequent iteration process, if there is a feasible solution that does not satisfy this constraint condition, under the penalty of this penalty function, the subsequent iteration process will gradually approach this constraint condition until it is satisfied.

In order to effectively avoid getting trapped in the local optimal solution when searching for the optimal value in particle swarm optimization, an adaptive neighborhood mode can also be used for search. Using neighborhood mode in the early stage of search can divide the particle swarm into multiple different subgroups, which is beneficial for searching in multiple regions simultaneously and avoids the search results of the particle swarm falling into local optima. In the later stage of the search, global mode is used to treat all other particles as neighboring particles, in order to accelerate the information exchange speed within the particle swarm and ultimately make the particle swarm algorithm have a faster convergence speed. In addition, if the fitness starts to stop.

Lag time, particle swarm search will transition from neighborhood mode to global mode, and once fitness begins to decline, it will revert back to neighborhood mode to avoid falling into local optima. When the number of pauses in fitness is large enough, the inertia coefficient gradually decreases, which facilitates local search.

In the process of solving the particle swarm algorithm in this article, the planting area of different types of crops on each type of plot is sequentially set as the decision variable, with a total of 107 decision variables. The number of particles is set to 1500, and the inertia weight setting range is [0.1, 1.1]. Adaptive measures are taken during the iteration process, and adjustments are continuously made as the iteration process progresses. According to the theory of compression factor, the individual learning factor c1 and the social learning factor c2 are both set to 1.49 [10-14].

Based on the above constraints and parameter settings, the objective function (5) is solved to obtain a planting strategy that comprehensively considers various influencing factors and achieves the maximum profit. The annual maximum profit of Scheme 1 is about 6 million yuan, and the annual maximum profit of Scheme 2 is about 5.9 million yuan.

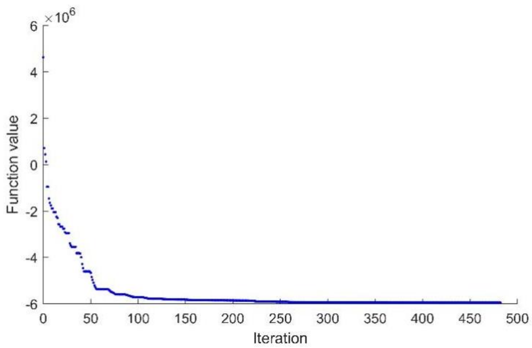

Figure 7. Scatter plot of the optimal objective function value as a function of iteration times

From Figure 9, it can be seen that after approximately 200 iterations, the maximum profit obtained by the particle swarm algorithm has stabilized. After about 270 more iterations, the optimal objective function value obtained by the particle swarm algorithm no longer changes. Therefore, it can be considered that the result has converged and automatically jumped out of the loop to obtain the optimal solution.

3. Conclusion

This article's model considers a comprehensive approach, taking into account most common factors such as crop rotation, planting leguminous crops at least once every three years on all land, ease of farming operations (planting sites cannot be too scattered), market uncertainty, planting risks, and the substitutability and complementarity between crops. The model considers a comprehensive approach and makes planting decisions more scientific; taking into account the time and space complexity of the algorithms used, the model was simplified to a certain extent without significantly affecting the accuracy of the results. This greatly improved the simplicity of the model, not only greatly reducing the subsequent code computation time, but also making it easier to promote and apply; Simultaneously using particle swarm algorithm for solving, compared with traditional mathematical programming algorithms, particle swarm algorithm has strong global search ability, as well as advantages such as simple implementation, strong adaptability, fast convergence, good parallelism, and fewer parameter adjustments. The crop planting decision studied in this paper is a common and practical planning issue encountered in real life. In the future, the reasonable planning of plots for planting different varieties of crops will remain an important problem that needs to be addressed. There may be even more uncertain factors and constraints in real crop planting scenarios. Therefore, the model presented in this paper will become more rational and practical through continuous use and refinement in the future, facilitating better solutions to crop planting planning problems.

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