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Optimal crop planting strategies based on multi-objective planning and Monte Carlo algorithm

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Abstract: This paper solves the problem of how to plan the crop planting programme from 2024 to 2030 in order to get the highest total return, using dynamic planning as the basic method, applying the idea of greedy algorithm, each year based on the prediction of the previous year to formulate the decision of the current year, and constructing and solving the multi-stage planning model for the two treatments of the stagnant portion of the optimal decision-making for the period of 2024 to 2030 respectively. The optimal decision for 2024 to 2030 was obtained. At the same time, various potential planting risks such as past sales experience, expected sales volume of various crops, mu yield, planting cost and uncertainty of sales price were considered, and each parameter may be different at different times. In view of the above uncertainties, this paper adopts Monte Carlo algorithm and probabilistic statistical method to simulate the problem in different scenarios, and obtains the expected value of the problem through a large number of random samples sampling to enhance the planting programme's risk-resistant ability.

1. Introduction

As the global population continues to grow and the demand for food increases, the sustainable development of crop cultivation has become increasingly important. Rural areas usually face the problem of limited arable land resources, and how to improve the efficiency of land use is a real problem that still needs to be solved to achieve rural revitalisation. Most of the villages located in the mountainous areas of North China have complicated terrain and harsh climate conditions, and the phenomenon of dispersal of arable land resources is serious, and most of the areas can only grow one season of crops a year. Therefore, choosing suitable crops, optimising planting strategies, improving production efficiency and reducing planting risks caused by uncertainties are important issues for achieving rural economic development. Organic farming is a method of agricultural production that aims to grow crops through natural methods and sustainable practices, avoiding the use of synthetic fertilisers, pesticides and genetically modified organisms (GMOs). Organic characteristics, climatic conditions and soil types need to be taken into account when selecting suitable crops. Agricultural development should be tailored to the local conditions and suitable crops should be selected for large-scale cultivation based on different topographical features, such as flat dry land, terraced land, hillside land and irrigated land. In addition to this, various uncertainties such as climate change, market fluctuations, pests and diseases may have an impact on crop yields and returns. Optimising cropping strategies should increase yields while minimising the risks associated with uncertainties. Through scientific crop planting strategies, villages in North China and across the country are expected to realise higher production benefits with limited arable land resources, creating more economic value for local residents [1].

2. Planting Strategy Study

Inspired by the basic idea of greedy algorithm, if the optimal planting scheme of crops in the next seven years is obtained, i.e., the maximum crop yield in the next seven years, the optimal planting scheme should be obtained in each of the next seven years, i.e., the planting scheme in each year should obtain the local optimal solution. In each year's programme selection is based on the optimal solution of previous years to take the best choice in the current state, thus hoping to find the global optimal solution, that is, the optimal planting programme for the next seven years.

Hillside land, flat dry land and terraces are suitable for planting one season of grain crops, irrigated land is planted with one season of rice or two seasons of vegetables per year, ordinary greenhouses are planted with one season of vegetables and one season of edible fungi per year, and intelligent greenhouses are planted with two seasons of vegetables per year. Due to the above crops on the plot planting conditions of different requirements, planting time limitations and other factors to consider, this paper will be according to the different types of crops will be planting strategy is divided into two sub-problems to solve:

(1) Food crops can only be planted on hillside land, flat dry land and terraces, other plots can not be planted, so the first sub-problem can be divided into: food crops planning solution, planting plots for hillside land, flat dry land and terraces;

(2) Potatoes, tomatoes, aubergines, cuttle beans and other food crops can only be planted in the watered land with the first season of the ordinary greenhouses and the wisdom of the greenhouses, the ordinary rooks in the second season can only be planted shiitake mushroom morel mushrooms and other edible mushrooms. Rice can only be planted in a single season in watered land and only cabbage, carrot and white radish can be planted in the second season. It can be seen that a variety of restrictions make the subproblem greatly complicated, the second subproblem is divided into: rice and other crops planning solution [2].

2.1. Objective function

The objective function is to maximise the target profit function. In the following, i denotes the ith crop and j denotes the jth plot, where i =1, 2, 3, ..., 15, in turn, represents 15 food crops: soybean, black bean, red bean, mung bean, climbing bean, wheat, corn, grain, sorghum, millet, buckwheat, pumpkin, sweet potato, oat and barley; j =1, 2, ..., 26, in turn, represents A1 flat dry land, ..., A6 flat dry land, B1 terraced land, ..., B14 terraced land, ..., B14 terraced land, ..., B12 terraced land, ..., B12 terraced land. j = 1, 2, ..., 26, representing A1 flat dryland, ..., A6 flat dryland, B1 terrace, ..., B14 terrace, C1 hillside, ..., C6 hillside.)

x_{ij} is the acreage of crop i in plot j in acres. y_{ij} is whether or not crop i is planted in plot j.

$$y_{ij} = \begin{cases} 0, & indicates\ that\ crop\ i\ is\ not\ planted\ on\ plot\ j \\ 1, & indicates\ that\ crop\ i\ is\ planted\ on\ plot\ j \end{cases} \tag{1}$$

Let a_{ij} be the planting unit yield of the ith crop in the jth plot, in kg/mu. b_{ij} be the planting cost of the ith crop in the jth plot, in yuan/mu. c_i be the selling unit price of the ith crop, in yuan/jin. d_i be the predicted selling volume of the ith crop, and f_i be the total production of the ith crop in the current year, and it is easy to compute the expression of f_i.

$$f_i = \sum_{j=1}^{M} x_{ij} y_{ij} a_{ij} \tag{2}$$

Let g_i be the sales of crop i, g_i=f_i c_i, and the cost of cultivation m, be:

$$m = \sum_{i}^{N} \sum_{j}^{M} x_{ij} y_{ij} b_{ij} \tag{3}$$

Thus the profit function is easily obtained:

$$maxZ = \sum_{i}^{N} g_i - m = \sum_{i}^{N} [\sum_{j=1}^{M} x_{ij} y_{ij} a_{ij}] \cdot c_i - \sum_{i}^{N} \sum_{j}^{M} x_{ij} y_{ij} b_{ij} \tag{4}$$

2.2. Restrictive condition

(1) Crop production does not exceed expected sales per season

If the crop production exceeds the expected sales volume, it will result in a loss of profit, thus requiring that the crop production per set does not exceed the expected sales volume:

$$f_i = \sum_{j=1}^{M} x_{ij} y_{ij} a_{ij} \leqslant d_i, i = 1,2,\cdots,15 \tag{5}$$

(2) Crop planting does not exceed the size of the plot

Let e_j be the maximum planting area of the jth plot:

$$\sum_{i}^{N} x_{ij} y_{ij} \leqslant e_j, j = 1,2,\cdots,26 \tag{6}$$

(3) Planting plots should not be spread too thinly per crop per season

It is possible to combine different crops on the same plot, but a good planting programme should take into account the ease of field management and cultivation operations. According to the cultivation practice in 2023, only one crop is planted in A1 flat dryland, B1 terraced land and C5 hillside land, which is convenient for crop management. For the sake of appropriate crop combination, this paper stipulates that no more than three crops should be planted in the same plot, namely:

$$\sum_{i}^{N} y_{ij} \leqslant 3, j = 1,2,3,\cdots,26 \tag{7}$$

(4) Each crop should not be planted on too small an area in a single plot

According to the planting data in 2023, basically all the flat drylands are fully planted, and 35 acres are planted in the smallest A3 flat dryland, and there is no vacancy in other plots. Based on the above facts, it is assumed that not less than 35 acres of flat drylands, not less than 20 acres of flat terraces and not less than 13 acres of slopes will be planted with crops:

$$\begin{cases} x_{ij} \leqslant 35, j = 1,2,\cdots,6 \\ x_{ij} \leqslant 20, j = 7,8,\cdots,20 \\ x_{ij} \leqslant 13, j = 21,23,\cdots,26 \end{cases} \tag{8}$$

(5) Each crop cannot be planted in the same plot over and over again.

The indicator variable $z_{ij}(t)$ is introduced to denote the actual cultivation of crop i in year t in the jth plot.

$$z_{ij}(t) = \begin{cases} 0, & \textit{indicates that crop i is not planted on plot j in t year} \\ 1, & \textit{indicates that crop i is planted on plot j in t year} \end{cases} \tag{9}$$

Where t = 2023, 2024, ..., 2030.

The indicator variable $zz_{ij}(t)$ is also introduced to denote whether or not crop i can be planted in year c at the jth plot.

$$zz_{ij}(t) = \begin{cases} 0, & \textit{indicates that crop i can not be planted on plot j} \\ 1, & \textit{indicates that crop i can be planted on plot j} \end{cases} \tag{10}$$

Distinguish from the above equation, here t = 1, 2, ..., 15, denoting the years 2024, 2025, ..., 2030.

It is not difficult to show that $z_{ij}(t)$ and $zz_{ij}(t)$ have the following relationship:

$$\begin{cases} zz_{ij}(t+1) = 0, z_{ij}(t) = 1 \\ zz_{ij}(t+1) = 1, z_{ij}(t) = 0 \end{cases} \tag{11}$$

After adding the variable $zz_{ij}(t)$ again, the above objective function and constraints are modified and the yield is modified as:

$$f_i = \sum_{j=1}^{M} x_{ij} y_{ij} zz_{ij}(t) \cdot a_{ij}, i = 1,2,\cdots,15 \tag{12}$$

Planting costs are modified to:

$$m = \sum_{i}^{N} \sum_{j}^{M} x_{ij} y_{ij} zz_{ij}(t) \cdot b_{ij} \tag{13}$$

The objective profit function is:

$$maxZ = \sum_{i}^{N} f_i c_i - \text{cost} = \sum_{i}^{N} \left| \sum_{j=1}^{M} x_{ij} y_{ij} zz_{ij}(t) \cdot a_{ij} \right| \cdot c_i - \sum_{i}^{N} \sum_{j}^{M} x_{ij} y_{ij} zz_{ij}(t) \cdot b_{ij} \tag{14}$$

Constraint I is changed as follows:

$$f_i = \sum_{j=1}^{M} x_{ij} y_{ij} zz_{ij}(t) \cdot a_{ij} \leqslant d_i, i = 1,2,\cdots,15 \tag{15}$$

Constraint II is changed as follows:

$$\sum_{i}^{N} x_{ij} y_{ij} zz_{ij}(t) \leqslant e_j, j = 1,2,\cdots,26 \tag{16}$$

(6) Legumes to be planted at least once in three years starting in 2023

Since soil containing rhizobacteria of legume crops is favourable for crop growth, all plots were planted with legume crops at least once in three years from 2023 onwards. The legume crops are only numbered exactly i = 1, 2, 3, 4, 5 The five legumes, soybean, black bean, red bean, green bean, and climbing bean, are subject to the constraints V. Revealed, $qq_{ij}(t)$ and $q_{ij}(t)$ are introduced in a similar manner. where $q_{ij}(t)$ denotes the actual cultivation of the ith legume crop on plot j in year t.

$$q_{ij}(t) = \begin{cases} 0, & \textit{indicates that crop i is not planted on plot j in t year} \\ 1, & \textit{indicates that crop i is planted on plot j in t year} \end{cases} \tag{17}$$

where t = 2023, 2024, ..., 2030.

qqij(t) indicates whether legume crop i must be planted on plot j in year t, where

$$qq_{ij}(t) = \begin{cases} 0, & \textit{indicates that crop i must be planted on plot j} \\ 1, & \textit{indicates that crop i could not be planted on plot j} \end{cases} \tag{18}$$

Since all plots must be planted with legumes within three years, i.e., the planting interval is at least two years, and after an interval of two years without planting legumes, the third year must be planted, so that t = 2025, 2026, ..., 2030 is taken, where the condition that the planting of legumes in the years 2023 and 2024 affects the planting of legumes in the year 2025 is implicitly assumed.

There is a relationship equation between these two variables:

$$q_{ij}(t) + q_{ij}(t+1) = qq_{ij}(t+2) \tag{19}$$

If the legume crop is planted in 2023 and not in 2024, q_{ij} (2023) = 1 and q_{ij} (2024) = 0, then:

$$q_{ij}(2023) + q_{ij}(2024) = qq_{ij}(2025) = 1 \tag{20}$$

That is, there is no need to plant legume crop i on plot j in 2025. And then if no legume crop is planted in both 2023 and 2024:

$$q_{ij}(2023) + q_{ij}(2024) = qq_{ij}(2025) = 0 \tag{21}$$

i.e., legume crop i must be grown on plot j in 2025.

Since y_{ij} denotes the cultivation of the crop, thus $qq_{ij}(t)$ affects the value of y_{ij} to get the constraint VI:

$$y_{ij} = \begin{cases} 0, qq_{ij}(t) = 1 \text{ or } 2 \\ 1, qq_{ij}(t) = 0 \end{cases}, i = 1,2,3,4,5,6, j = 1,2,\cdots,26 \tag{22}$$

Combining the above analyses, we obtained the objective profit function, constraints, decision variables, and a multi-stage mathematical planning model with year t as the variable. Also based on the above discussion, the planting interval for the legume crop is at least two years, thus constraint six needs to be considered for 2025 and subsequent years.

The planning model for 2024 crop is as follows:

$$maxZ = \sum_{i}^{N} \left[\sum_{j=1}^{M} x_{ij} y_{ij} zz_{ij}(2024) \cdot a_{ij} \right] \cdot c_i - \sum_{i}^{N} \sum_{j}^{M} x_{ij} y_{ij} zz_{ij}(2024) \cdot b_{ij} \tag{23}$$

$$\begin{cases} \sum_{i}^{N} x_{ij} y_{ij} zz_{ij}(2024) \leqslant e_j, j = 1,2,\cdots,26 \\ f_i = \sum_{j=1}^{M} x_{ij} y_{ij} zz_{ij}(2024) \cdot a_{ij} \leqslant d_i, i = 1,2,\cdots,15 \\ x_{ij} \leqslant 35, j = 1,2,\cdots,6 \\ x_{ij} \leqslant 20, j = 7,8,\cdots,20 \\ x_{ij} \leqslant 13, j = 21,23,\cdots,26 \\ \sum_{i}^{N} x_{ij} \leqslant 3, j = 1,2,3,\cdots,26 \\ zz_{ij}(2024) = 0, z_{ij}(2023) = 1 \\ zz_{ij}(2024) = 1, z_{ij}(2023) = 0 \end{cases} \tag{24}$$

The planning model for 2025 and subsequent years is shown below:

$$maxZ = \sum_{i}^{N} \left[\sum_{j=1}^{M} x_{ij} y_{ij} zz_{ij}(t) \cdot a_{ij} \right] \cdot c_i - \sum_{i}^{N} \sum_{j}^{M} x_{ij} y_{ij} zz_{ij}(t) \cdot b_{ij} \tag{25}$$

$$\begin{cases} \sum_{i}^{N} x_{ij} y_{ij} z_{ij}(t) \leqslant c_{ij}, j = 1,2,\cdots,26, t = 2025,\cdots,2030 \\ f_i(t) = \sum_{j=1}^{M} x_{ij} y_{ij} z_{ij}(t) \cdot a_{ij} \leqslant d_{ij}, i = 1,2,\cdots,15, t = 2025,\cdots,2030 \\ x_{ij} \leq 35, j = 1,2,\cdots,6 \\ x_{ij} \leqslant 20, j = 7,8,\cdots,20 \\ x_{ij} \leqslant 13, j = 21,23,\cdots,26 \\ \sum_{t}^{N} y_{ij} \leq 3, j = 1,2,3,\cdots,26 \\ \begin{cases} zz_{ij}(t) = 0, z_{ij}(t-1) = 1 \\ zz_{ij}(t) = 1, z_{ij}(t-1) = 0 \end{cases}, t = 2025,\cdots,2030 \\ q_{ij}(t-2) + q_{ij}(t-1) = qq_{ij}(t), t = 2025,\cdots,2030 \\ y_{ij} = \begin{cases} 0, qq_{ij}(t) = 1 \ or \ 2 \\ 1, qq_{ij}(t) = 0 \end{cases}, i = 1,2,3,4,5,6, j = 1,2,\cdots,26, t = 2025,\cdots,2030 \end{cases} \tag{26}$$

3. Optimisation of optimal planting strategies

Considering the uncertainty in the expected sales, cost of cultivation, selling price and yield of various crops and the possibility of unknown risks, it is necessary to give the optimal cropping plan for the village from 2024 to 2030. Therefore, the uncertainty and potential risk factors are added to the previous section and added to the model and the corresponding parameters are changed.

a_{ij} is the yield in pounds per acre of the ith crop on the jth cropland.

b_{ij} is the cost of planting the ith crop on the jth cropland in dollars per acre.

c_{ij} is the selling price of the ith crop in $/kg.

d_{ij} is the expected sales amount of the ith crop in dollars.

At the same time, it is assumed that if there is a surplus of the current year's crop, the surplus is sold at half the previous year's sales price.

The main factors affecting crop cultivation are the different market demand in each year as well as the climatic environment, based on the above considerations as above, Monte Carlo simulation is used to solve the problem.

Monte Carlo simulation is a method of applying digital simulation to realize random sampling, which was born in the mid-1940s, and was used to solve the series of problems arising in the process of random diffusion. With the promotion of information technology and digital technology, Monte Carlo simulation began to be applied to the field of economics, showing the unique advantages of solving high-dimensional problems, the core of which lies in solving a large number of computational problems by means of random numbers, and obtaining the final results infinitely close to the real situation by virtue of a certain number of simulations [3].

Monte Carlo simulations deal with uncertainties in acreage, expected sales, sales prices and growing costs. For different years, the above parameters fluctuate within a certain range, e.g., the sales growth rate of corn and wheat is in the range of 5% ~ 10%, the annual sales volume of the rest of the crops may vary in the range of ±5%, the annual yield per acre varies in the range of ±10%, etc. The Monte Carlo simulation takes these parameters into account. Monte Carlo simulation treats all of these covariates as random variables, and the optimal planting plan for each year is derived from multiple simulations [4].

(1) Initialisation parameters

First set the initial acre yield, sales volume, sales price, and cost of planting based on empirical values and ranges of variability for each type of uncertainty.

Specify the range of variation of the parameters, e.g., the growth rate of sales of maize and wheat is at 5 ~ 10 per cent, and the variation of annual sales of the remaining crops may be at ± 5 per cent, etc.

(2) Monte Carlo method specific process

● Generate stochastic parameters: for each year and crop, within a reasonable range, generate the rate of change of mu yield, sales growth rate, planting cost growth rate and sales price fluctuations with stochasticity.

● Model Calculation: Under these hyperparameters with randomness, run the optimal planting model to calculate the total crop yield of the year.

● Repeat simulation: Simulate each year's planting several times (e.g., 1000 times) to obtain different possible outcomes [5].

(3) Results statistics

The optimal crop planting strategy is shown in Table 1.

Table 1: Planting programme 2024-2030.

Year	Parcel Name	Barley	Sorghum	Millet	Sorghum vulgare	Broomcorn millet	Buckw heat	Cucurbit	Sweet potato	Hordeum vulgare
2024	A	46.3	65.7	0	20.8	36.4	0	65.1	126.2	0
	B	104.3	93.5	17	38.4	124.2	0	36.9	184	5.8
	C	11	12.9	13.6	0	6.8	18.3	0	0	17.8
2025	A	37.5	65.1	5	37.5	55.1	30.5	49.9	17.6	15
	B	44.5	36.9	47	40.3	26.8	109.2	121.2	16.6	30
	C	0	0	0	0	0	13.6	28.3	13.6	0
2026	A	25.5	35.2	0	22.6	31.4	5	85.9	138.8	0
	B	45.2	42.3	13	40	48.6	19.1	93.1	251.3	5.8
	C	0	0	14.9	0	0	27.5	3.9	15.5	18.4
2027	A	34.9	35.8	10	33.4	38.7	5	65.1	65.1	5
	B	42.3	41.6	35.7	41.6	43.8	78.9	36.9	36.9	16.4
	C	0	0	3.9	0	0	27.8	0	0	14.9
2028	A	79.7	69.5	0	23.7	44.9	0	49.9	49.9	0
	B	85.6	112.8	20.6	41.5	33	2.9	110.7	110.6	17.3
	C	15.5	15.4	13.1	0	0	16.2	11.5	15.5	11.5
2029	A	43.1	35.8	10	46.3	59.5	10	65.1	90.5	5
	B	52.9	37.2	12.9	103.4	88.6	28	36.9	36.9	15.1
	C	0	0	13.3	15.5	15.5	30.3	0	0	12.1
2030	A	43.1	35.8	10	46.3	59.4	10	65	90.4	5
	B	52.9	37.2	12.9	103.5	88.8	28	36.9	36.8	15.1
	C	0	0	13.3	15.5	15.5	30.3	0	0	12.2

4. Conclusions

The model predicts crop planting strategies for a total of seven years, from 2024 to 2030, and is able to provide growers with longer-term scenarios and plan for the following year based on each year, which is better able to deal with unforeseen situations that actually occur. Such long-term planning is important for sustainable agricultural development.

In addition, this paper considers more realistic scenarios, such as future growth in sales of wheat and maize, the effects of climate change, the impact of markets, and changes in future projections for each crop, etc. Considering multiple scenarios will help to develop more robust strategies in the future.

Although this paper has considered multiple influencing factors, it has ignored the low occurrence of natural disasters such as droughts, floods and pests, which cause huge losses despite the low probability of outbreaks. Moreover, with the rapid development of science and technology, perhaps new seeds or new planting techniques will be developed, which will have a greater impact on yield.

Climate, market conditions, and land resources are different in different regions. The model can be used not only for agricultural production planning in the region, but can also be extended to all parts of the country, in all regions, to achieve higher yields and higher returns by allocating limited land resources through the substitutability and complementarity of different crops. The model mentions only crops such as wheat, maize, vegetables, mushrooms, etc. It can also be used for fruits, groundnuts and cash crops, etc. By increasing the variety of crops, the variety of substitutes and complementarities will also increase, thus optimising the cropping strategy for higher yields.

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