Research on Optimal crop planting strategy based on Mixed Integer Linear Programming

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Abstract. The food supply crisis and the sustainable development of agriculture in today's world have been continuously studied for decades and a lot of progress has been made, but there is still no detailed solution for the study of integrated planting strategies for specific planting environments as well as the complex planting requirements of crops. Therefore, in order to improve the efficiency of agricultural production and achieve the optimal allocation of resources, a mixed-integer linear programming model with the objective function of maximizing the total profit for the years 2023-2030 is established using the publicly available dataset of a village in the mountainous region of North China. The optimal crop planting scheme is also developed by considering two sales scenarios, i.e., the portion that exceeds the sales volume in 2023 is processed for stagnation and sold at a 50% price reduction, respectively. This research on optimal crop planting strategy solves the problem of crop planting in a specific planting environment, which greatly improves the productivity of agriculture under the premise of ensuring profit maximization and helps to promote the development of the agricultural planting industry.

Keywords: Crop Planting Strategies, Mixed Integer Linear Programming, Operations Research.

1. Introduction

With the increasing global population and accelerating urbanization, agriculture is facing serious challenges, especially in terms of food supply [1] and sustainable development [2]. With the great importance attached to agricultural development in various countries, many research results have been achieved in improving agricultural productivity. For example, in the area of crop planting risk factors, Kim-Net (2024) studied the analysis of crop seed planting risk factors and planting quality improvement strategies in Jilin Province, and studied the risk of crop seed production factors, both own and non-own, in order to build a multifaceted crop seed production and planting management model and to strengthen the management of seed planting technology [3]. In terms of crop planting technology, Zhao-Net (2023) analyzes the advantages and implementation status of green agricultural planting technology, and puts forward its own green agricultural planting technology promotion strategy on this basis [4]. In addition, Cao-Net (2022) also relies on the advantages of organic agriculture, and based on proposing and solving the problems of the current agricultural planting technology, it gives three aspects of organic agricultural planting technology measures, namely, weeding, selecting and planting land, and applying fertilizer [5]. Of course, in terms of crop planting countermeasures, Liu-Net (2021) has already put forward the general countermeasures of adjusting crop planting structure, strengthening crop field management, doing a good job in predicting and forecasting pests and diseases, emphasizing the quality and safety of agricultural products, and improving the quality of crop planting personnel in five aspects [6], which provides a large number of invaluable planting suggestions for the crop planting industry. However, scholars have only studied the intrinsic influencing factors affecting crop growth, the enhancement of crop planting technology, and generalized crop planting countermeasures, and have not considered the integrated planting strategy research on the complex planting requirements of crops under specific planting environments.

Therefore, based on the previous research results, this paper takes a village in the mountainous region of North China as the research object, and explores the optimal crop planting strategy under the influence of a specific environment and the constraints of crop planting requirements, aiming at improving agricultural production efficiency and realizing the optimal allocation of resources. By combining modern technology and traditional farming methods, this paper will use a mixed integer linear programming model to provide a scientific basis for sustainable agricultural development in this area.

The rest of this paper is organized as follows. Section 2 describes The basic funamental of Mixed Integer Linear Programming Model.Section 3 on the basis of data preprocessing and variable definition, establishes the mixed integer linear programming model. Section 3 establishes the Mixed Integer Linear Programming Model on the basis of data pre-processing and variable definition to formulate the results of optimal planting strategies for crops under two sales situations and analyze them, and finally conducts the rationality verification.Section 4 concludes the paper.

2. Relevant theory

The fundamentals of mixed integer linear programming [7]involve extensions of linear programming and integer constraints. The mixed integer linear programming problem combines the characteristics of linear programming and integer programming, i.e., in the planning problem, the objective function and constraints are linear, some of the decision variables take arbitrary real values, and some of the decision variables are restricted to integer values.

The problem model of mixed integer linear programming consists of the following three parts [8]:

(1) Establish a linear objective function: $\max(\min) Z = \sum_{i=1}^{n} c_i x_i$,where Z is the target variable, c_i is the correlation coefficient, and x_i is the decision variable.

(2) Establish linear constraints: $Ax \le b$, where A is the matrix of coefficients, b is a constant vector. These constraints limit the range of values for the decision variables.

(3) Restricted variable constraints: some of the decision variables are restricted to integer values; these are called integer variables. Other variables have no such constraints and are called continuous variables.

3. Experiment

In this section, a village in the mountainous region of North China is taken as the research object, and the optimal crop planting scheme based on the mixed-integer linear programming model is explored based on the data of Question C of the 2024 Gaojiaoshe Cup National College Students' Mathematical Modeling Competition to improve the efficiency of agricultural production and realize the optimal allocation of resources.The specific flow of the experiment is shown in Figure 1.

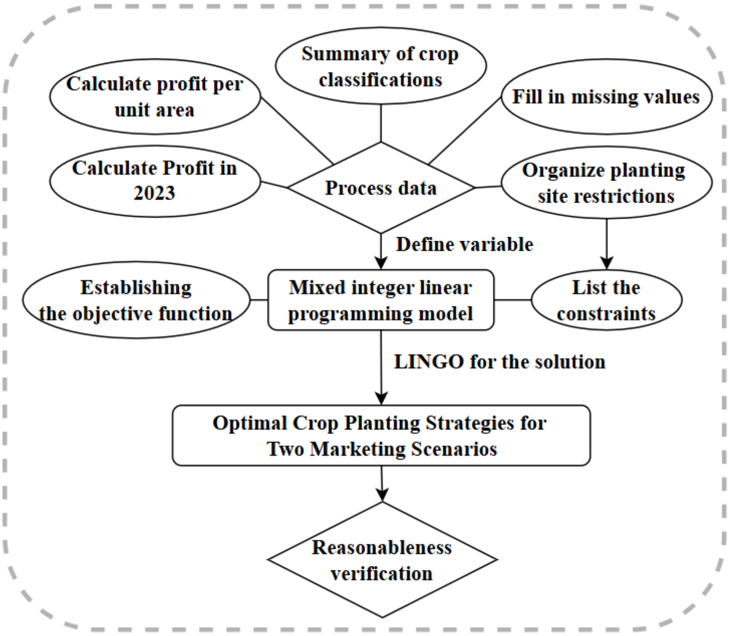

Figure 1. Flowchart of ideas

The village has 1,201 acres of existing open cultivated land, dispersed into 34 plots of different sizes, including four types of flat dry land, terraced land, hillside land and watered land, as well as 16 ordinary greenhouses and four intelligent greenhouses, each with a cultivated area of 0.6 acres. Afterwards, the open cultivated land and greenhouses are collectively referred to as planting land. Among them, flat and dry land, terraced land and hillside land are suitable for planting one season of grain crops per year; watered land is suitable for planting one season of rice or two seasons of vegetables per year. Ordinary greenhouses are suitable for growing one season of vegetables and one season of edible fungi per year, while intelligent greenhouses are suitable for growing two seasons of vegetables per year. Different crops can be combined on the same planting site.

According to the growth law of crops, each crop cannot be continuously planted with heavy crops in the same planting land, otherwise the yield will be reduced; because the soil containing legume crop rhizobium is favorable to the growth of other crops, all the land in each planting land will be planted with legume crops at least once in three years starting from 2023 [9]. At the same time, the planting scheme takes into account the convenience of farming operations and field management, such as: the planting plots for each crop per season should not be too scattered, and the area planted with each crop in a single planting plot should not be too small [10].

The data in the open dataset of the village was subjected to data cleaning and found to be free from outliers and missing values. The different crops were categorized and summarized according to category and type of planting land for subsequent analysis, modeling and solving, etc.

Suppose that s_i denotes the first planting site,in which $i = 1, 2, ..., 54$ .Divide the numbering of the planting sites as in equation (1):

$$i = \begin{cases} 1 \sim 6, arid - area \\ 7 \sim 20, terraced - field \\ 21 \sim 26, hilly - land \\ 27 \sim 34, irrigable - land \\ 35 \sim 50, common - greenhouse \\ 51 \sim 54, \text{int}\, elligent - greenhouse \end{cases} \tag{1}$$

In this case, the numbering of crops is divided as in Equation (2), where 1~15,17~19 are legumes:

$$j=\begin{cases}1\sim 16, grain\\17\sim 37, vegetable\\38\sim 41, \ fungus\end{cases}\tag{2}$$

Suppose that $n=1,2,\cdots,8$ represent the years 2023 to 2030 in sequence. k is the crop planting season number, i.e., the first season of 2023 is recorded as $k=1$,the second quarter of 2023 is recorded as $k=2$,the research in this paper numbers the quarters from 2023 to 2030 in the order in which they are listed.In the following functions (3) to (11), the $k=2n-1$ denotes the first quarter of the year. $k=2n$ Indicates the second quarter of the year.

x_{ikj} is the area of the ith plantation planted with the jth crop in the kth season,in which $j=1,2,...,41$. y_{ikj} is the acre yield (in pounds) of the jth crop planted in the kth season at the ith planting site. z_{ikj} is the unit sales price ($/pound) of the jth crop grown in the kth season at the ith planting site. c_{ikj} is the cost of planting the jth crop in the kth season at the ith planting site ($/acre).

F for seven years total profit ($), $T_{ikj}=x_{ikj}\times y_{ikj}$ is the total production (in pounds) of the jth crop grown in the kth season at the ith planting site. P_{ikj} is the expected sales volume (in pounds) of the jth crop planted in the kth season at the ith planting site.

Season k crop j is planted in planting plot i, $w_{ikj}=1$; Season k crop j is not planted in planting plot i, $w_{ikj}=0$.

When no rice planted on planting plot i in season k, $v_{ik16}=0$; When rice planted on planting plot i in season k, $v_{ik16}=1$.

(1) Establishment of the objective function in the case of more than partial demurrage treatment: When $\sum_i T_{ikj}\le\sum_i P_{ikj}$,sold at normal price;When $\sum_i T_{ikj}>\sum_i P_{ikj}$,The excess cannot be sold.

Setting the objective function to maximize the total profit, equation (3) can be set:

$$\max F=\begin{cases}\sum_i\sum_k\sum_j(T_{ikj}\times z_{ikj}-x_{ikj}\times c_{ikj})\times w_{ikj},\sum_i T_{ikj}\le\sum_i P_{ikj}\\\sum_i\sum_k\sum_j(P_{ikj}\times z_{ikjj}-x_{ikj}\times c_{ikj})\times w_{ikj},\sum_i T_{ikj}>\sum_i P_{ikj}\end{cases}\tag{3}$$

(2) The objective function is established for the case where the excess is sold at 50% of the 2023 price:

When $\sum_i T_{ikj}\le\sum_i P_{ikj}$,sold at normal price;When $\sum_i T_{ikj}>\sum_i P_{ikj}$,The excess is sold at 50% of the 2023 price, at which point the total profit is:

$$\max F=\begin{cases}\sum_i\sum_k\sum_j(T_{ikj}\times z_{ikj}-x_{ikj}\times c_{ikj})\times w_{ikj},\sum_i T_{ikj}\le\sum_i P_{ikj}\\\sum_i\sum_k\sum_j(P_{ikj}\times z_{ikj}+0.5\times(T_{ikj}-P_{ikj})\times z_{ikj}-x_{ikj}\times c_{ikj})\times w_{ikj},\sum_i T_{ikj}>\sum_i P_{ikj}\end{cases}\tag{4}$$

The constraints on the objective function for both of these cases satisfy the following definition.

(3) Definition of constraints:

The same parcel of land may be planted with a combination of different crops each season, and the sum of the acres occupied by the crops planted on each planting site is equal to the total number of acres on the site:

$$\sum_k\sum_j x_{ikj}\le s_i, i=1,2,\cdots,54\tag{5}$$

Water-consumed land is suitable for growing one season of rice or two seasons of vegetables per year; if the first season of water-consumed land is planted with vegetables other than cabbage, white radish and carrot, the second season of planting can only be planted with cabbage, white radish and carrot:

$$\begin{cases} \sum_{i=27}^{34} x_{ik16} \le \sum_{i=27}^{34} s_i \times v_{ik16}, k = 2n-1 \\ \sum_{i=27}^{34} x_{ikj} \le \sum_{i=27}^{34} s_i \times (1-v_{ik16}), k = 2n-1, j = 17, 18, \cdots, 34 \\ \sum_{i=27}^{34} x_{i(k+1)j} \le \sum_{i=27}^{34} s_i \times (1-v_{ik16}), k = 2n, j = 35, 36, 37 \end{cases} \tag{6}$$

Ordinary greenhouses grow vegetables other than cabbage, white radish and carrot in the first season and only edible mushrooms in the second season:

$$\begin{cases} \sum_{i=35}^{50} x_{ikj} \le \sum_{i=35}^{50} s_i, k = 2n-1, j = 17, 18, \cdots, 34 \\ \sum_{i=35}^{50} x_{i(k+1)j} \le \sum_{i=35}^{50} s_i, k = 2n-1, j = 38, 39, 40, 41 \end{cases} \tag{7}$$

Smart greenhouses are suitable for growing two seasons of vegetables per year except cabbage, white radish and carrot:

$$\begin{cases} \sum_{i=51}^{54} x_{ikj} \le \sum_{i=51}^{54} s_i, k = 2n-1, j = 17, 18, \cdots, 34 \\ \sum_{i=51}^{54} x_{i(k+1)j} \le \sum_{i=51}^{54} s_i, k = 2n-1, j = 17, 18, \cdots, 34 \end{cases} \tag{8}$$

Flat drylands, terraces and hillsides are suitable for growing one season of food crops (other than rice) per year:

$$\sum_{i=1}^{26} x_{ikj} \le \sum_{i=1}^{26} s_i, k = 2n-1, j = 1, 2, \cdots, 15 \tag{9}$$

Each crop cannot be planted consecutively in the same plot:

$$\begin{cases} w_{ikj} + w_{i(k+1)j} \le 1, k = 2n-1, i = 27, 28, \cdots, 54, j = 17, 18, \cdots, 34 \\ w_{ikj} + w_{i(k+2)j} \le 1, k = 2n-3, i = 1, 2, \cdots, 26, j = 1, 2, \cdots, 5 \\ w_{ikj} + w_{i(k+2)j} \le 1, k = 2n-2, i = 1, 2, \cdots, 26, j = 6, 7, \cdots, 15 \\ v_{ikj} + v_{i(k+2)j} \le 1, k = 2n-3, i = 27, 28, \cdots, 34, j = 16 \end{cases} \tag{10}$$

Each plot has been planted with legumes at least once in three years. Of these, planting plots 4, 5, 8, 9, 10, 11, 17, 23, 26, 31, 32, 35, 41, 42, 43, 44, 45, 53, 54 have been planted with beans in 2023. If the plot has not been planted with pulses in 2023, then pulses will be planted in 2024.

$$\sum_{i} \sum_{k} \sum_{i \in Beans} x_{ikj} \ge 1, i = 1, 2, 3, 4, 5, 17, 18, 19 \tag{11}$$

k for any three consecutive years between 2023-2030.

For equations (4)~(11), $w_{ijk} = 0/1, v_{ijk} = 0/1, n = 1, 2, 3, 5, 6, 7, x_{ijk} \ge 0, s_i > 0$

Combining Eqs. (3) ~(11), have successfully established an optimal crop planting model based on mixed integer linear programming. Then will use this model in combination with a publicly available dataset of a village in the mountainous region of North China to develop an optimal crop planting program for the years 2024-2030 under two sales scenarios.

4. Results

The above mixed integer linear programming equations are used to formulate the optimal crop planting scheme that maximizes the total profit of seven years crop planting for both sales scenarios. Some of the planting schemes are shown in Table.1. and Table.2.

Table.1. The optimal planting scheme in the case of excess unsalable is omitted

Season	Land	2024		…	2027		…	2030	
		Crop	Area/acres	…	Crop	Area/acres	…	Crop	Area/acres
First season	A1	millet	56	…	sweet potato	50	…	proso millet	10
		buckweat	24	…	buckweat	20	…	sweet potato	50
		/	/	…	/	/	…	buckweat	20
	A2	millet	55	…	sorghum	25	…	proso millet	20
		/	/	…	proso millet	20	…	sweet potato	25
		/	/	…	buckweat	10	…	buckweat	10
…	…	…	…	…	…	…	…	…	…
Second season	F3	eggplant	0.6	…	cucumber	0.6	…	cucumber	0.6
		/	/	…	/	/	…	/	/
		/	/	…	/	/	…	/	/
	F4	eggplant	0.6	…	eggplant	0.3	…	eggplant	0.2
		/	/	…	water spinach	0.3	…	cucumber	0.4
		/	/	…	/	/	…	/	/

Table.2. The optimal planting plan in the case of the excess is sold at 50% of the price

Season	Land	2024		…	2027		…	2030	
		Crop	Area/acres	…	Crop	Area/acres	…	Crop	Area/acres
First season	A1	soybean	45	…	Sweet potato	55	…	soybean	80
		ormosia	10	…	naked oat	25	…	/	/
		buckweat	25	…	/	/	…	/	/
	A2	ormosia	41	…	barley	55	…	soybean	55
		Sword bean	14	…	/	/	…	/	/

		/	/	…	/	/	…	/	/
…	…	…	…	…	…	…	…	…	…
Second season	F3	elm mushroom	0.6	…	bailing mushroom	0.6	…	elm mushroom	0.6
		/	/	…	/	/	…	/	/
	F4	/	/	…	/	/	…	/	/
		elm mushroom	0.6	…	lentinula edodes	0.6	…	elm mushroom	0.6
		/	/	…	/	/	…	/	/

Based on the specific planting scenarios for each year, the total profit per year (in millions) can be calculated for the two sales scenarios, see Figure 2.

The blue color represents the case where more than the portion is sold at a stagnant price and the orange color represents the case where more than the portion is sold at 50% of the original price.

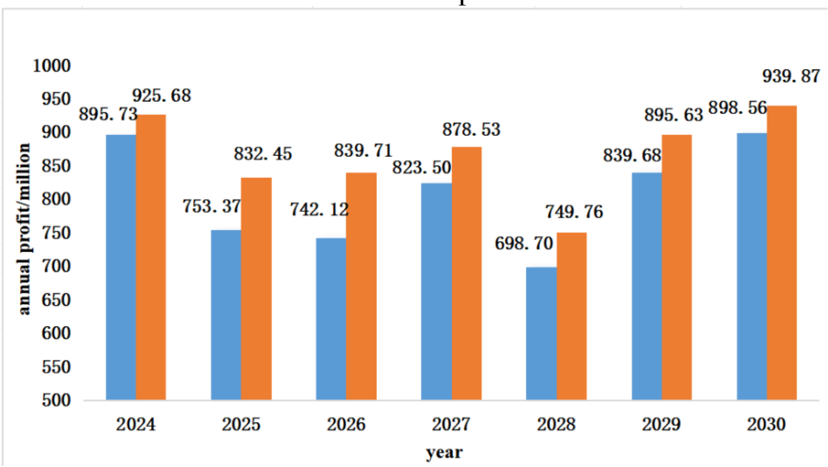

Figure 2. Line graph of total profit per year for two sales scenarios

From the data and Figure 2. the following conclusions can be drawn:

(1) A comprehensive analysis of the crops grown on various types of planting sites each year reveals that sweet potatoes and buckwheat are the main crops grown in the grain category, cucumbers and eggplants in the vegetable category, and elm mushrooms in the edible fungi catego

(2) The profit range stabilizes between \$6 and \$10 million per year under both the excess lag disposal and the excess sale at 50% of the 2023 price.

(3) The annual profit is about \$500,000 higher in the case where the excess is sold at 50% of the 2023 price compared to the case where the excess is disposed of in demurrage.

(4) For 2028, a significant downward trend in profits was found for both marketing scenarios. This is due to the fact that in order to meet the constraint of having to grow one legume crop per plot for three consecutive years, more plots in 2028 were chosen to grow a relatively less profitable legume crop per unit area.

In order to test the reasonableness of the seven-year total profit under the two sales scenarios, the research in this paper again sells the part of the sales volume that exceeds the expected sales volume at the price of 2023 for the calculation of the seven-year total profit, resulting in Figure 3.

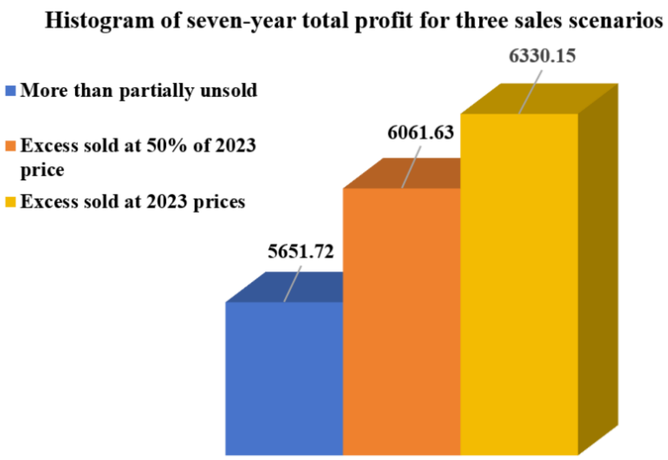

Figure 3. Histogram of seven-year total profit for three sales scenarios

It is found that the seven-year total profit under the two sales scenarios is lower than the original price of the sale, which can validate the reasonableness of the calculation of the mixed-integer linear programming model described above.

After the above research and analysis, it is found that this research on the optimal planting strategy of crops based on mixed integer linear programming achieves the goals of profit maximization and planting strategy optimization in practical use. It is fully proved that the model has high practical use value in improving agricultural production efficiency and realizing the optimal allocation of resources.

5. Conclusions

In this paper, in response to the world's food supply crisis and the sustainable development of agriculture, with the help of the data of Question C of the 2024 Gaoxueshe Cup National College Students' Mathematical Modeling Competition, a large amount of data preprocessing is carried out to fill in the missing values, summarize the classification of crops, sort out the limitations of the planting land, calculate the profit per unit area and the profit of the year 2023, and sort out specific constraints on the planting of crops. Based on the above, the optimal crop planting strategy model based on mixed integer linear programming is formulated. In this way, the crop planting scheme is given in two cases: the part of a village in the mountainous region of North China that exceeds the sales volume in 2023 is processed for stagnant sales and sold at a 50% price reduction. Finally, the reliability and feasibility of this study are proved in the rationality analysis.

On the basis of this model of optimal crop planting strategy, future research can further deepen the universality and practicability of the model, and strive to incorporate external factors affecting crop planting, such as economic factors, political factors, weather factors, etc., into the scope of research on crop planting strategy, so as to make it flexibly applied to crop planting decision-making in different regions, so as to improve the yield and quality of crops, to To cope with the globalized food supply crisis and the sustainable development of agriculture.

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