Study on Agricultural Land Planning Based on Sustainable Planting Strategies

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Abstract. With the increasing global demand for food and the environmental pressures of climate change, sustainable agricultural land planning has become a critical area of modern agricultural research. This study, based on sustainable planting strategies, constructs a multi-objective integer programming model aimed at optimizing planting schemes for various types of farmlands to maximize agricultural economic benefits and enhance land use efficiency while considering ecological sustainability. The model incorporates multiple constraints, including land area limitations, crop rotation requirements, the necessity of planting legumes, and greenhouse planting area restrictions. The results demonstrate that through rational crop allocation and planting pattern planning, limited land resources can be effectively utilized, leading to significant improvements in crop yield and economic returns. Additionally, the long-term ecological impacts of different planting strategies are evaluated, confirming the model's practical value in agricultural decision-making. This research provides a scientific decision-support tool for agricultural managers and policymakers, contributing to the sustainable development of agricultural production.

Keywords: Sustainable Planting Strategies, Agricultural Land Planning, Integer Programming, Crop Rotation.

1. Introduction

With the continuous growth of the global population and the intensification of climate change, agricultural production faces unprecedented challenges [1, 2]. On one hand, the demand for food is steadily increasing; on the other hand, arable land is limited, and environmental carrying capacities are gradually declining [3, 4]. Against this backdrop, sustainable agriculture has become a critical strategy for ensuring food security, improving ecological environments, and enhancing economic benefits [5, 6].

Traditional planting planning models often overlook factors such as soil fertility degradation, crop rotation requirements, and the optimal utilization of different land types, leading to inefficient land use, increased environmental pollution, and unsustainable long-term returns [7]. Therefore, scientifically planning agricultural land use and optimizing planting strategies to balance economic benefits and ecological sustainability has become a crucial issue in current agricultural production.

This study centers on sustainable planting strategies, introducing integer programming models and multi-objective optimization methods to explore optimal crop and land resource allocation under various land types and planting constraints. The research aims to maximize the utilization efficiency of agricultural land and economic profits while ensuring the long-term health of ecosystems. This study holds practical significance for increasing farmers' incomes and optimizing resource allocation, providing scientific support for governments and agricultural enterprises in formulating sustainable rural development policies.

2. Optimizing Agricultural Output Through Integer Programming

The data used in this paper originates from http://www.mcm.edu.cn. Considering that in real-life scenarios, the sales of crops may not always meet farmers' expectations in terms of the anticipated sales volume, this study sets up two scenarios [8, 9]. In the first scenario, when the total crop yield exceeds the expected sales volume, the surplus is assumed to remain unsold. In the second scenario, the surplus is sold at a 50% discount. The study will explore optimal planting strategies under both scenarios. The key lies in determining the fundamental objective function and the constraints on crop cultivation. A 0-1 integer programming analysis will be applied to the established model. A detailed explanation will be provided in the following sections.

2.1. Cultivation Situation and Set Definition

The crops are classified into three main categories: grains, legumes and non-legumes, vegetables, and edible fungi. These crops are represented by the set i = {1, 2, 3, ..., 41}. Grains, denoted as Gra, cover i = {1, 2, ..., 16}, with rice specifically identified as i = 16. Vegetables, called Veg, include i = {17, 18, ..., 37}, while edible fungi, labeled as Mus, correspond to i = {38, 39, 40, 41}.

Land plots are divided into six distinct types, each suitable for specific crops and cultivation patterns. Flat dry land (A) consists of plots A1 through A6, terraces (B) include B1 to B14, and sloping land (C) covers C1 to C6. Irrigated land (D) spans D1 to D8, while conventional greenhouses (E) are represented by E1 to E16, and smart greenhouses (F) are designated as F1 to F4.

The planting system allows for either single-season (k = 1) or two-season (k = 2) cultivation, with the time frame extending from 2024 to 2030, measured in annual units. Each type of land plot has specific rules regarding which crops and seasonal systems are permitted.

Flat dry land, terraces, and sloping land are restricted to single-season grain crops, excluding rice, meaning only crops i = {1, 2, ..., 15} can be grown on these plots. In contrast, rice (i = 16) is exclusive to irrigated land, and these D plots also support two-season vegetables, i = {17, 18, ..., 37}. However, some vegetable crops, namely i = {35, 36, 37}, are specifically limited to two-season cultivation on D plots.

Conventional greenhouses (E) present a unique flexibility. For single-season planting, they can accommodate a selection of vegetables (i = {17, 18, ..., 34}). However, for two-season planting, E plots are exclusively reserved for edible fungi (i = {38, 39, 40, 41}). Notably, edible fungi are confined to E plots under all conditions, reflecting their specific cultivation requirements. Meanwhile, smart greenhouses (F) are dedicated to two-season vegetable crops, allowing for the growth of i = {17, 18, ..., 34}.

This structured allocation ensures that each crop type is cultivated in the most suitable environment, optimizing both land use and crop productivity[10]. The planting framework is designed to balance the specific needs of different crops with the capabilities of each land plot, providing a comprehensive strategy for sustainable agriculture over the specified period.

2.2. Definition of Decision Variables

The decision variables are defined as follows:

X_{i,j,k,t} represents the planting area (in acres) of crop i on land plot j during season k in year t. Here:

- i ∈ I is the set of crop types (e.g., wheat, corn, legumes, vegetables, etc.).
- j ∈ J represents the set of land plots (including flat dry land, terraces, sloping land, irrigated land, conventional greenhouses, and smart greenhouses).
- t ∈ T = {2024, 2025, ..., 2030} is the set of planting years.
- k ∈ K denotes the set of seasons.

2.3. Establishment of the Objective Function

To achieve optimal utilization of arable land and maximize the economic benefits of crop production, a profit maximization model is constructed based on historical data. The objective function for this study is expressed as:

$$TP = \sum_{t=2024}^{2030} \sum_j \sum_k \left(P_i \times \min\left\{C_i \times X_{i,j,k,t}, Q_i\right\} + \delta \times P_i \times \max\left\{C_i \times X_{i,j,k,t} - Q_i, 0\right\}\right) - \sum_t \sum_k \sum_j PC_i \times X_{i,j,k,t} \quad (1)$$

Where: X_(i,j,k,t) is the planting area of crop i on plot j during season k in year t. P_i is the selling price of crop i. C_i is the yield per acre of crop i. δ is the discount rate applied to surplus sales (Scenario 1: δ = 0; Scenario 2: δ = 0.5).

2.4. Construction of Constraints

2.4.1. Land Area Constraints

To avoid the negative impact of limited land on crop yields and to maximize the benefits from available land, the total planting area for all crops on a given plot must not exceed the total area of that plot. Let A_j represent the total area of land plot j. The constraint can be expressed as:

$$A_i \geq \sum_i X_{i,j,k,t}, \forall_{i,j,k,t} \quad (2)$$

2.4.2. Necessity of Planting Legumes Within Three Years

Since legume crops enrich the soil with beneficial nitrogen-fixing bacteria, which improve the productivity of subsequent crops, it is required that every plot (including greenhouses) plant legumes at least once every three years starting from 2023. Let t represent the time in years, and i ∈ legumes. The constraint is formulated as:

$$\sum_{t\leq 3} \sum_{i\in \text{legumes}} X_{i,j,k,t} \geq 1, \forall i \quad (3)$$

2.4.3. Crop Rotation Constraints

To maintain soil fertility and prevent the depletion of nutrients, continuous planting of the same crop on the same plot across consecutive years is not allowed. Thus, if crop i is planted on a plot in year t, it cannot be planted on the same plot in year t+1. This can be expressed as:

$$i_t \neq i_{t+1}, \ \forall i, \ t \quad (4)$$

Where I is crop grown; t is time (years).

2.4.4. Minimization of fragmentation of planted areas

According to the question, each crop can not be too dispersed in each season, and each crop in a single plot (including greenhouses) planting area should not be too small, the need to avoid each crop planting area being too dispersed, you can add constraints to limit the planting area of the same crop in adjacent plots, assuming that more than 50% of the area of a plot are planted with crop i, to achieve the result of the aggregation of crop i, so that the result can be obtained constraints are:

$$X_{i,j,k,t} \geq 50\% \quad (5)$$

Where $X_{i,j,k,t}$ is the area planted to each crop i in the kth season of plot j, in the tth year.

2.4.5. Greenhouse Planting Area Restrictions

After observing the crops grown in greenhouses in 2023 (Annexure 2), it was found that each crop occupied either only 0.3 acres or 0.6 acres of the planting area, and therefore, the planting area of the crops grown in greenhouses was required to be only 0.3 acres or 0.6 acres:

$$X_{greenhourse} = 0.3 \text{ or } X_{greenhourse} = 0.6 \quad (6)$$

2.5. Maximum profit model based on 0-1 integer programming

Based on satisfying the full utilization of arable land resources, the reduction of planting risk and the selection of suitable crops, providing the maximum profit with the smallest plot possible, combining the known conditions and materials, the maximum profit model based on 0-1 integer planning can be:

$$TP = \sum_{t=2024}^{2030} \sum_{j} \sum_{k} \left(P_i \times \min\{C_i \times X_{i,j,k,t}, Q_i\} + \delta \times P_i \times \max\{C_i \times X_{i,j,k,t} - Q_i, 0\}\right) - \sum_{t} \sum_{k} \sum_{j} PC_i \times X_{i,j,k,t} \tag{7}$$

$$S.t \begin{cases} A_i \geq \sum_i X_{i,j,k,t}, \forall_{i,j,k,t} \\ \sum_{t\leq 3} \sum_{i\in legumes} X_{i,j,k,t} \geq 1, \forall i \\ i_t \neq i_{t+1}, \ \forall i, \ t \\ X_{i,j,k,t} \geq 50\% \\ X_{greenhourse} = 0.3 \text{ or } X_{greenhourse} = 0.6 \end{cases}$$

The planting schedule obtained through the solution is shown in Table 1. Due to space limitations, only partial results are presented here.

Table 1. Solution results (partial)

Plot	Soy	Black bean	Red bean	Green bean	Pea	wheat
A1	0	0	0	0	0	0
A2	0	0	27.5	0	0	0
A3	0	0	0	0	0	0
A4	0	0	0	0	0	0
A5	0	0	0	0	34	0
A6	0	0	0	0	0	27.5

3. Conclusion

This study developed an optimal crop planting strategy using a 0-1 integer programming model, addressing two realistic scenarios of crop sales. The first scenario assumes that surplus yields remain unsold, while the second allows for surplus sales at a 50% discount. Through a comprehensive analysis of land utilization, crop classification, and cultivation constraints, the model effectively maximizes economic benefits by determining optimal planting arrangements across different land types and seasons from 2024 to 2030.

The findings highlight the importance of crop rotation, the necessity of planting legumes to maintain soil fertility, and the strategic allocation of crops to specific land types, including conventional and smart greenhouses. By adhering to constraints such as land area limits, minimum planting areas, and greenhouse-specific requirements, the proposed model ensures sustainable land use while maximizing profitability.

This study provides valuable insights for farmers and agricultural planners, offering a robust framework for balancing economic gains and sustainable farming practices. Future research could extend this work by incorporating additional factors such as climate variability, water resource constraints, and dynamic market conditions to further refine the planting strategy.

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