

Assessment of Farmland Ecosystem Transformation and Its Practical Impact

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Abstract. In the context of the constantly changing global agricultural environment, there is an urgent need to address pest issues, strengthen ecosystem stability, and drive the development of sustainable agriculture. This study emerges as a response to these challenges. Specifically, a comprehensive ecosystem model is developed, taking into account elements such as seasonality and agricultural cycles. The Lotka - Volterra equations are utilized to establish a mathematical model, with numerical methods employed to simulate the dynamic changes within the ecosystem. Additionally, a regional impact index system is constructed. During the research, it is discovered that the introduction of native species can significantly enhance biodiversity and ecosystem stability. For instance, bats have been proven to be highly effective in both pollination and pest control. Moreover, a sustainability index is calculated to quantitatively evaluate the performance of the agricultural ecosystem. In conclusion, this study innovatively integrates multiple factors, providing practical guidance for farmers to achieve a balance between ecological protection and economic benefits. Future research could focus on further refining the model under more complex real - world scenarios and promoting the wide - scale application of these findings in different agricultural regions globally.

Keywords: Lotka-Volterra Model; Ecological Stability; Euler Numerical Iteration; Organic Agriculture.

1. Introduction

Within the broad framework of the global ecological environment, human activities are like a double-edged sword, exerting profound and complex influences on the Earth's ecosystems. Among them, the impact of agricultural development is particularly significant, having severely affected forest ecosystems.

With the continuous growth of the global population, the demand for food and agricultural products has been rising exponentially ^[1]. This has greatly stimulated the continuous expansion of agricultural production scale. To obtain more arable land, large areas of forests have been brutally cut down. In many regions, vast tracts of virgin forests have been rapidly leveled to make way for farmland reclamation.

Such large-scale deforestation has caused countless wild animals to lose their habitats on which they depend for survival. Forest soil has accumulated rich humus during the long-term natural evolution process, forming a unique soil structure with extremely high fertility, which can provide sufficient nutrients for the growth of various plants. However, after the forest is transformed into farmland, frequent farming activities, such as deep plowing and the extensive use of chemical fertilizers, have damaged the original soil structure. The microbial community in the soil has also been imbalanced due to the change in the ecological environment, leading to a gradual decline in soil fertility. The originally fertile forest soil has become so barren that it is difficult to maintain the natural growth of forest vegetation.

Forests are like a natural ecological barrier in the ecosystem, playing a crucial role in maintaining ecological balance. Once the forests disappear, farmland is directly exposed to various ecological threats, among which the pest problem is particularly prominent. The rich biodiversity in the forest provides a wide variety of natural enemies of pests, which can naturally control the population of pests ^[2,3]. However, the farmland ecosystem is relatively simple, and the number of natural enemies of pests has decreased significantly. In the absence of effective constraints, pests are extremely likely to multiply in large numbers.

To deal with pests, farmers often rely too much on agricultural chemicals, such as insecticides and herbicides. However, the long-term and large-scale use of these chemicals not only leads to the development of pest resistance, making pest control increasingly difficult, but also causes serious pollution to the soil, water, and air, the balance of the ecosystem, trigger a series of chain reactions, and cause long-term and difficult-to-repair damage to the entire ecological environment^[4]. The complex and diverse food chains in the forest ecosystem have been simplified and reconstructed in the farmland ecosystem. The original food chain based on forest vegetation has been transformed into a new food chain centered around crops^[5,6]. In this process, some biological species gradually disappear due to their inability to adapt to the new ecological environment, while some species that adapt to the farmland environment thrive. After a long period of development and evolution, the farmland ecosystem has gradually formed its own unique ecological balance. Some native species may reappear in the mature farmland ecosystem after adapting to the new environment, which brings a glimmer of hope for the restoration and development of the ecosystem. In the in-depth exploration of this process of ecosystem transformation, the Lotka - Volterra model plays an important role. The Lotka - Volterra model was initially used to describe the dynamic changes of two interacting populations. In the study of farmland and forest ecosystems, it can be used to depict the relationships between different biological populations, such as pests and their natural enemies, and crops and weeds.

After the forest is transformed into farmland, weeds compete with crops for soil nutrients, water, and light resources^[7]. The model can quantify this competition relationship, helping researchers understand the change trends of the populations of crops and weeds under different conditions. For example, when the farmland ecosystem tends to be stable, different weeding measures can be evaluated through the model to analyze their impacts on the population dynamics of crops and weeds, so as to optimize farmland management strategies and increase crop yields.

To better understand the changes in the process of forest-to-farmland transformation, constructing a model to track habitat changes is crucial for analyzing ecosystem evolution and evaluating the impacts of organic agriculture. Combining the analysis of biological population dynamics by the Lotka - Volterra model can provide a more comprehensive understanding of the complex changes in the ecosystem during the transformation from forest to farmland, providing strong support for promoting the development of sustainable agriculture.

2. Methods

To comprehensively elucidate the impact of agricultural development on forest ecosystems, the Lotka - Volterra model was applied across multiple ecological dimensions.

2.1. Constructing Species Interaction Models

Predator - Prey Relationships: In the context of forest - to - farmland transition, pests were designated as prey, and their natural enemies as predators. The Lotka - Volterra predator - prey model was utilized, where the temporal change in prey population (x) is characterized by $\frac{dx}{dt} = rx - axy$, and that of the predator population (y) is given by $\frac{dy}{dt} = -my + bxy$. Here, (r) denotes the intrinsic growth rate of the prey, (a) represents the predation efficiency of the predator on the prey, (m) signifies the mortality rate of the predator in the absence of prey, and (b) indicates the conversion efficiency of prey consumption into predator population augmentation. Through long - term field surveillance and data fitting, the trends of these parameters were determined as the environment was altered by forest reclamation. By forecasting the dynamic changes in pest and predator populations, the stability of the original predation relationship within the forest ecosystem could be evaluated. A continuous and substantial increase in pest populations far beyond the equilibrium point would imply a disruption of the stable predation relationship, potentially causing severe damage to forest vegetation over the long term.

Competition Relationships: The relationship between forest trees and invasive farmland weeds was modeled as a competitive interaction. The Lotka - Volterra competition model for the tree population $\frac{dx_1}{dt} = r_1x_1(1 - \frac{x_1}{K_1} - \alpha_{12}\frac{x_2}{K_1})$, and for the weed population (x_2) is $\frac{dx_2}{dt} = r_2x_2(1 - \frac{x_2}{K_2} - \alpha_{21}\frac{x_1}{K_2})$, where (r_1) and (r_2) are the intrinsic growth rates, (K_1) and (K_2) are the carrying capacities, and (α_{12}) and (α_{21}) are the competition coefficients. Agricultural practices such as fertilization and irrigation could induce alterations in these parameters. By analyzing the long - term variations in these parameters, the growth and decline of tree and weed populations were predicted, which could indicate potential shifts in the species composition and structure of the forest ecosystem.

2.2. Simulating Ecosystem Structure Changes

Food Chain Structure Changes: Considering the complex food chains in forest ecosystems that are simplified and restructured by agricultural development, a complex model was constructed based on the Lotka - Volterra model, which could be extended to a system of Lotka - Volterra equations for multiple interacting species. This enabled the simulation of population changes of different species within the food chain, including primary producers (forest vegetation or crops), primary consumers (pests or herbivores), and secondary consumers (natural enemies of pests or carnivores). By simulating the population dynamics at different stages of agricultural development, the long - term evolution of the food chain structure was predicted. A significant increase in primary consumers resulting from agricultural activities could lead to a reduction in primary producers, thereby affecting the stability of the entire food chain and the long - term health of the forest ecosystem.

Biodiversity Changes: The Lotka - Volterra model was integrated with species diversity indices. By predicting the population changes of different species using the model, indices such as species richness and evenness were calculated. As farmland expanded and forest habitats fragmented, the changes in species' living spaces and resources were manifested in the parameters of the Lotka - Volterra model. Over the long term, a continuous decline or even extinction of multiple species predicted by the model would lead to a reduction in species richness, a decline in biodiversity, and a subsequent impact on the stability and functionality of the forest ecosystem.

2.3. Considering Ecosystem Function Impacts

Soil Fertility and Nutrient Cycling: Although the Lotka - Volterra model is predominantly applied to biological population dynamics, its indirect impact on soil functions was considered. For example, soil microorganisms associated with nutrient cycling (such as nitrogen - fixing bacteria) were treated as a population, and an interaction model similar to the Lotka - Volterra model was constructed with other factors influencing soil nutrients (such as nutrient uptake by crops or weeds). By predicting the changes in the populations of soil microorganisms and nutrient - absorbing entities, the long - term changes in soil fertility were evaluated. A predicted decrease in beneficial soil microorganisms and excessive nutrient uptake by crops or weeds could lead to a decline in soil fertility, affecting the restoration of forest vegetation and the sustainability of the ecosystem.

Ecosystem Service Functions: Forests provide diverse ecosystem services, such as water conservation and climate regulation. The Lotka - Volterra model was employed to predict the impact of agricultural development on key species in the forest ecosystem and infer the long - term impact on ecosystem service functions. For instance, if the model predicted a decrease in the number of tree species crucial for water conservation due to agricultural development, it could lead to a decline in the forest's water - conservation capacity, thus affecting the stable supply of regional water resources and ecological balance over the long term.

3. Establishment and solution of agricultural ecosystem model

According to the requirements of Mathematical Contest in Modeling (MCM), the data source of this paper is hypothetical data. Based on the relevant literature, we need to construct a mathematical

model to simulate the changes in the ecosystem when forested areas are converted into farmlands. This model should take into account natural ecological processes, such as the interactions between species including predation and competition, as well as the impacts of human activities (such as the use of chemical agents) on the stability of the ecosystem^[8,9]. Seasonal changes and variations in the agricultural cycle are introduced to perfect the model. Our objective is to build a complete ecosystem model and analyze how this transformation affects the population dynamics of different species, as well as the overall health and sustainability of the ecosystem. Therefore, we choose to use the Lotka-Volterra equations and optimize them through a genetic algorithm, and then visualize the choices related to organic agriculture^[10].

$$\frac{dP}{dt} = r_p P \left(1 - \frac{P}{K_p} \right) - \alpha_{pI} IP - \beta_p S \quad (1)$$

where r_p is the natural growth rate of the crop, K_p is the environmental carrying capacity, α_{pI} is the predation rate of the pest on the crop, β_p is the effect of the herbicide on the crop, and S denotes the amount of herbicide used.

Pest growth equation:

$$\frac{dI}{dt} = r_i I \left(1 - \frac{I}{K_I} \right) - \alpha_{IB} BI - \alpha_{IN} NI - \delta_I D \quad (2)$$

where r_i is the natural growth rate of the pest, K_I is the environmental carrying capacity of the pest, α_{IB} is the predation rate of bats on the pest, δ_I is the effect of insecticides on the pest, and D is the amount of insecticide used.

Bat growth equation:

$$\frac{dB}{dt} = \gamma_B B \left(1 - \frac{B}{K_B} \right) + \alpha_{IB} BI - \mu_B B \quad (3)$$

γ_B is the natural growth rate of bats, K_B is the environmental carrying capacity of bats, μ_B is the mortality rate of bats.

Bird growth equation:

$$\frac{dN}{dt} = r_N N \left(1 - \frac{N}{K_N} \right) + \alpha_{IN} NI - \mu_N N \quad (4)$$

where K_N is the environmental carrying capacity of birds. α_{IN} is the predation rate of birds on pests μ_N is the mortality rate of birds.

To model the effects of seasonality and the effects of changes in the agricultural cycle on crop growth and insect reproductive rates, we introduce a seasonality factor into the Lotka-Volterra system of equations, and here we use a periodic equation to represent the effects of seasonality in the growth equations for crops, pests, bats, and birds after accounting for seasonal variation and the effects of chemicals^[11]:

Crop growth equation (accounting for seasonal variation):

$$r_{p0}(t) = r_p^0 \left(1 + A \sin \left(\frac{2\pi t}{T} + \phi \right) \right) \quad (5)$$

$$\frac{dP}{dt} = r_p(t) P \left(1 - \frac{P}{K_p} \right) - \alpha_{pI} IP - \beta_p S \quad (6)$$

r_{p0} basal crop growth rate. A factor for seasonal variation on crop amplitude. T period (one year). ϕ : phase difference, used to model the start of different seasons.

Pest growth equation (considering seasonal variations):

$$r_i(t) = r_i^0 \left(1 + B \sin \left(\frac{2\pi t}{T} + \phi \right) \right) \quad (7)$$

$$\frac{dI}{dt} = r_I(t)I \left(1 - \frac{I}{K_I}\right) - \alpha_{IB}BI - \alpha_{IN}NI - \delta_I D \quad (8)$$

r_I^0 reproduction rate of the pest. B factor of seasonal variation on the amplitude of the pest. T period (one year). ϕ : phase difference, used to model the start of different seasons.
 Bat growth equation (considering seasonal variations):

$$\gamma_B(t) = \gamma_B^0 \left(1 + C \sin\left(\frac{2\pi t}{T} + \phi_B\right)\right) \quad (9)$$

$$\frac{dB}{dt} = \gamma_B(t)B \left(1 - \frac{B}{K_B}\right) + \alpha_{IB}BI - \mu_B B \quad (10)$$

Where γ_B^0 is the natural growth rate of bats, and C is the amplitude of the effect of seasonal variation on the growth rate of bats. T period (one year) ϕ : phase difference, used to model the start of different seasons.

Bird growth equation (considering seasonal variation):

$$r_N(t) = r_N^0 \left(1 + D \sin\left(\frac{2\pi t}{T} + \phi_N\right)\right) \quad (11)$$

$$\frac{dN}{dt} = r_N(t)N \left(1 - \frac{N}{K_N}\right) + \alpha_{IN}NI - \mu_N N \quad (12)$$

r_N^0 is the natural growth rate of birds, and D is the amplitude of the effect of seasonal variation on the growth rate of birds. μ_N is the bird mortality rate. α_{IN} is the predation rate of birds on pests.

During agro-ecosystem transformation, with marginal habitat succession and ecological corridor formation, some native species return via natural or artificial means and form stable populations^[12,13]. This ecological reconstruction changes the agro-ecosystem's structure and function in four aspects: ecosystem stability, soil fertility, species diversity, and agricultural yield. Native plants improve soil properties, and key insect species enhance biological control and optimize the food web structure^[13,14].

(1) Recolonization Rate, R

The species reappearance count reflects the number of native species gradually reappearing in the agricultural ecosystem. Over time, the species reappearance count tends to increase, but the rate of this growth is limited by the adaptability of the current environment.

$$\frac{dR}{dt} = \gamma R \left(1 - \frac{R}{R_{\max}}\right) \quad (17)$$

Here, γ is the growth rate of species reappearance, and R_{\max} is the maximum limit of species reappearance count.

$$R(t) = R_0 \cdot e^{\alpha t} \cdot \left(1 - \frac{R(t)}{K}\right) \quad (18)$$

Here, R_0 is the initial number of species reappearance, α is the species reappearance rate, and K is the maximum number of species that the ecosystem can support.

(2) Soil Fertility Recovery, SFR

The reappearance of species may promote soil restoration, especially through the return of plant species. These plants contribute to soil fertility restoration through nitrogen fixation and the decomposition of organic matter.

$$\frac{dSFR}{dt} = \delta SFR \cdot \left(1 - \frac{SFR}{SFR_{\max}}\right) \quad (19)$$

Here, δ is the soil restoration rate, and SFR_{\max} is the maximum value of soil fertility restoration.

$$SFR(t) = SFR_0 + \eta \cdot R(t) \tag{20}$$

Here, SFR_0 is the initial soil fertility, and η is the coefficient representing the impact of species reappearance on soil fertility restoration.

(3) Ecosystem Stability, ES

With the reappearance of species, the stability of the ecosystem may change. Species diversity and interactions between species can promote ecosystem restoration, leading to an increase in stability.

$$\frac{dES}{dt} = \beta \cdot \frac{R(t)}{K} \cdot (1 - ES) \tag{21}$$

Here, β is the coefficient representing the impact of species reappearance on ecosystem stability.

$$ES(t) = ES_0 + \frac{\beta \cdot R(t)}{K} \tag{22}$$

Here, ES_0 is the initial ecosystem stability, and β is the contribution of species reappearance to stability.

(4) Agricultural Yield, AY

Agricultural yield is typically related to factors such as crop types, soil quality, pesticide use, and other variables.

$$AYI(t) = Y_0 \cdot (1 - \mu \cdot SFR(t)) \cdot e^{-\rho \cdot t} \tag{23}$$

Here, Y_0 is the initial yield, and μ is the parameter influencing the yield.

Here, we assume that two different species, Species One and Species Two, return to the ecosystem. The reappearance of these two species will affect the restoration of soil fertility, which in turn influences changes in ecosystem stability and agricultural yield.

4. Results

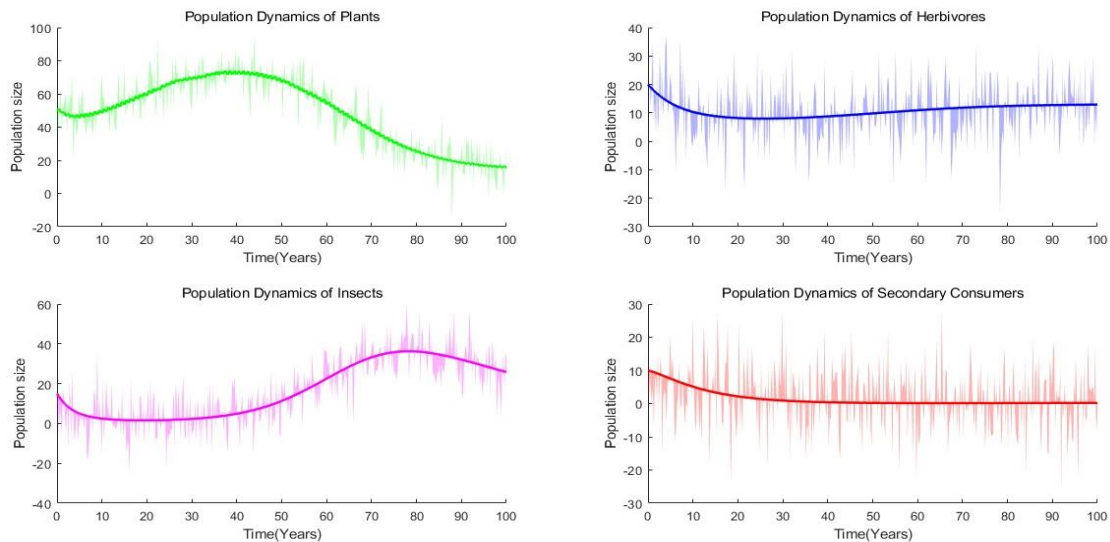


Figure 1 Seasonal Impact Diagram

This analysis, based on visual charts, reveals that seasonality differentially impacts various ecological components, with complex interrelationships among consumers at different trophic levels. As shown in Figure 1.

Producer crops, depicted in the upper left chart, exhibit pronounced periodic population fluctuations. Seasonal changes significantly influence their growth and decline, making them highly sensitive. Additionally, herbivore populations directly affect producer crops; increased herbivore numbers lead to higher grazing pressure and reduced crop populations, while lower herbivore numbers promote crop growth.

Herbivores in the upper right chart are also subject to seasonal effects, though with moderate fluctuations around a stable trend line. Their population dynamics are influenced not only by seasonality but also by the availability of producer crops as a food source. Furthermore, insects and secondary consumers impact herbivores indirectly and directly, respectively. Insects, shown in the lower left chart, display complex and highly volatile responses to seasonality, being strongly affected by factors like temperature, humidity, and food availability. Their roles as pollinators or pests of producer crops and as a food source for other consumers create intricate ecological interactions.

The lower right chart shows that secondary consumers, as top predators, are the least affected by seasonality, with relatively smooth population curves. However, their predation behavior significantly influences herbivore and insect populations, contributing to ecosystem stability.

In summary, while all four groups—producer crops, herbivores, insects, and secondary consumers—are impacted by seasonality to varying degrees, insects and producer crops are the most sensitive, and secondary consumers the least. The complex web of interactions among these components is crucial for maintaining ecosystem balance.

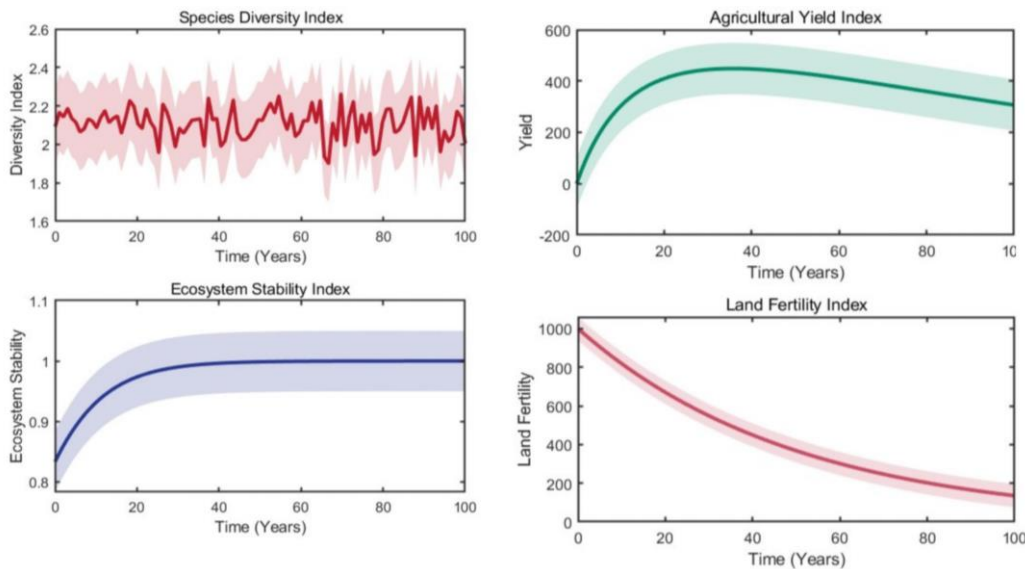


Figure 2 various indicators of the regional ecosystem

In Figure 2, the dynamic changes of the ecosystem stability index, species diversity index, soil fertility index, and agricultural yield index are studied, and an ecosystem model system is constructed. The shaded area represents the potential fluctuation range of the indices, helping us understand the stability or uncertainty of the data.

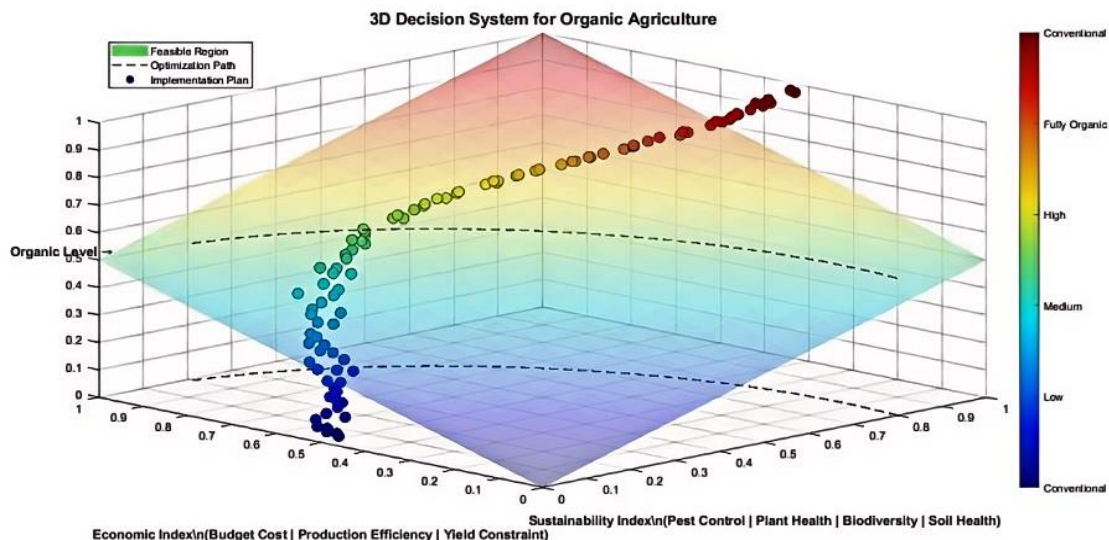


Figure 3 Establishment of green agricultural ecological model

The above model constructs a decision-making system for organic agriculture by means of mathematical modeling and 3D visualization techniques such as Figure 3, which demonstrates the relationship between sustainability index, economy index and organic level. The intuitive visualization results provide important reference information for decision makers to help them find the best balance between sustainability and economy and find the best implementation path.

5. Conclusions

In the present investigation, a green agricultural sustainability model was constructed through the integration of multifarious factors encompassing ecological, economic, and social dimensions. Seasonal variations and agricultural cyclicities were incorporated into the model framework.

This methodological approach facilitated a comprehensive analysis of the intricate factors impinging upon agricultural development and enabled an accurate portrayal of the interrelationships among diverse elements. As a consequence, practical guidelines were formulated to assist farmers in attaining a balance between ecological conservation and economic viability, thereby effectively augmenting the comprehensiveness and adaptability of the model. The novelty of this research resides in its holistic integration of a broad spectrum of factors, rendering it more congruent with the real-world complexities inherent in agricultural production compared to antecedent models.

For prospective research endeavors, it is recommended to persistently incorporate emerging factors and advanced technological modalities. This may involve the utilization of more refined real-time data sources associated with environmental surveillance and socio-economic fluctuations. Such efforts will further fortify the efficacy and adaptability of the model across diverse agricultural scenarios, thereby propelling the sustainable development of global agriculture.

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