Research on Ecological Balance of Agricultural Ecosystems Based on Dynamic Modeling and Numerical Simulation

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Abstract: This paper investigates the ecological balance of agricultural ecosystems through dynamic modeling and numerical simulation. As global population growth drives the conversion of natural forests into agricultural land, ecosystems face significant disruptions. Chemical agents like herbicides and pesticides, while boosting crop yields, often lead to soil degradation and loss of biodiversity. This study employs the Lotka-Volterra equations to model the dynamic interactions among crops, pests, and natural predators such as bats and birds, considering seasonal variations and the impact of chemical use. Key indexes including Ecosystem Stability Index (ESI), Species Diversity Index (SDI), Land Fertility Index (LFI), and Agricultural Output Index (AYI) are defined to quantify the system's health. Numerical simulations using the Runge-Kutta method reveal the long-term effects of reducing chemical inputs and introducing beneficial species like bats and bees on ecosystem stability and agricultural productivity. The results highlight the trade-offs between short-term yield gains from chemicals and long-term sustainability, emphasizing the importance of organic farming practices in restoring ecological balance. This research provides theoretical foundations and practical insights for sustainable agricultural development, offering a balanced approach to managing agro-ecosystems for both ecological health and economic viability.

1. Introduction

As the global population grows and agricultural demand increases, many natural forests and ecosystems have been cleared for agricultural use [1]. This transformation not only alters how land is used but also profoundly impacts the stability of ecosystems and biodiversity [2,]. The complex life networks in forests are disrupted, replaced by new ecological cycles driven by human agricultural activities. To address challenges in agricultural production, farmers increasingly rely on chemical agents such as herbicides and pesticides to boost crop yields and control pests [3]. However, this chemical dependence often disrupts ecological balance, leading to soil degradation and ecosystem imbalance. Previous studies have highlighted the negative long-term effects of chemical use on soil health and biodiversity. For instance, research has demonstrated that prolonged pesticide use can inhibit soil microbial activity, reducing the natural cycling of organic matter [4]. Similarly, it has been found that chemical-intensive agriculture leads to a decline in species diversity, affecting the resilience of ecosystems [5]. In contrast, the transition to organic farming methods, which reduce chemical use and enhance soil organic matter, has been shown to gradually restore species diversity and biodiversity in ecosystems. Studies have provided empirical evidence that organic farming practices can improve soil health and promote ecological balance [6, 7].

This article aims to explore the impact of the transition from forest to agriculture on ecosystem dynamics, species recovery, and organic farming practices, analyzing their long-term effects on

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ecological balance and agricultural production [8]. The study employs the Lotka-Volterra equations to model the dynamic interactions among crops, pests, and natural predators such as bats and birds, considering seasonal variations and the impact of chemical use [9, 10]. Key indexes including the Ecosystem Stability Index (ESI), Species Diversity Index (SDI), Land Fertility Index (LFI), and Agricultural Output Index (AYI) are defined to quantify the system's health. Numerical simulations using the Runge-Kutta method reveal the long-term effects of reducing chemical inputs and introducing beneficial species like bats and bees on ecosystem stability and agricultural productivity [11, 12, 13]. The results highlight the trade-offs between short-term yield gains from chemicals and long-term sustainability, emphasizing the importance of organic farming practices in restoring ecological balance. This research provides theoretical foundations and practical insights for sustainable agricultural development, offering a balanced approach to managing agro-ecosystems for both ecological health and economic viability. By providing a comprehensive analysis of the ecological and economic impacts of different agricultural practices, this study contributes to the growing body of literature on sustainable agriculture and ecosystem management, offering valuable references for policymakers, agricultural practitioners, and researchers [14, 15].

2. Data Preparation

Data collection is one of the key steps in modeling and analyzing agricultural ecosystem. Taking a prefecture-level city as an example, this paper describes in detail the process of data collection, including data source, indicator definition, collection method, data cleaning and processing.

2.1. Data Sources

The primary sources for data collection include the citys agricultural management department, statistical yearbooks, agricultural science research institutions, and geographic information system (GIS) platforms. By collaborating with local governments and agricultural research institutions, relevant data on agricultural production, ecological environment, and economic development have been collected. This data encompasses multiple indicators such as crop planting structure, yield, changes in land use, pest and disease control, and soil quality changes [16, 17].

2.2. Data Processing

In the process of data collection from diverse sources such as agricultural statistics yearbooks, agricultural technology research institutions, and GIS platforms, data cleaning and processing must be meticulously conducted to ensure the accuracy and consistency of the dataset. To achieve this objective, the Python pandas library was employed to implement a series of standardized procedures. Specifically, data filling techniques, including interpolation and mean filling, were applied to address missing values, thereby maintaining the integrity of the dataset. Additionally, outlier detection was performed through rigorous statistical analysis and machine learning algorithms to identify and rectify anomalies, ensuring the reliability and robustness of the data for subsequent analysis. These methodological steps are critical for establishing a high-quality dataset that supports valid and reproducible research outcomes in agricultural studies.

3. Dynamic Modeling and Analysis of Agricultural Ecosystems

3.1. Establishment of the Lotka-Volterra Equations

We will employ the Lotka-Volterra equations to depict the dynamic relationship among crops, pests, and bats.

3.1.1. Crop Growth Model

Crop growth is affected by natural growth, pest infestation and chemical use, assuming that crops follow the Logistic growth model and consider the inhibiting effects of pest infestation and chemicals:

$$\frac{dP}{dt} = rP\left(1 - \frac{P}{K}\right) - \alpha PH - \sigma PC(t) \quad (1)$$

3.1.2. Pest Growth and Predation Model

The growth of pests is affected by the number of crops, and by predation by bats, birds (secondary consumers). According to Lotka-Volterra's predator-prey model, the growth rate of pests is both supported by crops and limited by predation by bats and birds:

$$\frac{dH}{dt} = \beta H\left(1 - \frac{H}{H_{\max}}\right) + \delta PH - \theta HC(t) - \gamma HB \quad (2)$$

3.1.3. Bat and Bird Population Equation

Bat and bird populations are affected by insect numbers and chemicals, and a similar population model can be used:

$$\frac{dB}{dt} = \gamma HB - \mu B \quad (3)$$

3.1.4. Consider Seasonal Variations

In the ecosystem, seasonal changes have significant effects on the growth of crops, the reproduction of pests, and the predation behavior of bats and birds. Therefore, we introduce seasonal factors to adjust the growth rate and predation rate, which are expressed by sine function.

Seasonal changes in crop growth rate:

$$r(t) = r_0\left(1 + a\sin\left(\frac{2\pi t}{T}\right)\right) \quad (4)$$

Seasonal changes in pest reproduction rates:

$$\beta(t) = \beta_0\left(1 + b\sin\left(\frac{2\pi t}{T}\right)\right) \quad (5)$$

Seasonal changes in bat feeding efficiency:

$$\gamma(t) = \gamma_0\left(1 + c\sin\left(\frac{2\pi t}{T}\right)\right) \quad (6)$$

Where T is the period (usually one year).

3.2. Definition of Key Indexes

3.2.1. Ecosystem Stability Index (ESI)

The Ecosystem Stability Index (ESI) can be used to measure the ability of an entire ecosystem to return to a state of equilibrium after disturbance, and can often be expressed by the interdependence of different species. The higher the stability, the stronger the resilience of the system in the face of external shocks. According to the hypothesis, the ecosystem will gradually become more stable over time, but in the presence of chemical interference, the stability may be affected.

$$ESI(t) = \frac{1}{1 + \alpha \cdot \exp(-\beta \cdot t)} \quad (7)$$

Where α and β are constants, which determine the rate and amplitude of stability change.

3.2.2. Species Diversity Index (SDI)

The Species Diversity Index (SDI) measures the diversity of species in a system. The higher the diversity, the more functional and adaptable the ecosystem. We use Shannon-Wiener Diversity

Index to define:

$$SDI = -\sum_{i=1}^{n} p_i \ln\left(p_i\right) \tag{8}$$

3.2.3. Land Fertility Index (LFI)

The Land Fertility Index (LFI) is used to measure the health of the soil and the potential for crop growth, and land fertility gradually declines with agricultural production.

$$LFI(t) = LFI_0 \cdot e^{-\delta \cdot t} \tag{9}$$

3.2.4. Agricultural Output Index (AYI)

Agricultural yield index is an important index to measure agricultural productivity and crop health. It is often used to reflect the productivity or yield of crops in a particular area. It is usually related to factors such as crop type, soil quality and pesticide use.

$$AYI(t) = Y_0 \cdot (1 - \alpha \cdot C(t)) \cdot e^{-\beta \cdot t} \tag{10}$$

3.3. Numerical Simulation and Analysis

By solving the above differential equations with the 4-step Runge-Kutta method, we can simulate the dynamics of agro-ecosystems under different scenarios (e.g. reducing chemical use, introducing bats, etc.). The formula is as follows:

$$k_1 = \Delta t \cdot f(P_t, H_t) \tag{11}$$

$$k_2 = \Delta t \cdot f\left(P_t + \frac{k_1}{2}, H_t + \frac{k_1}{2}\right) \tag{12}$$

$$k_3 = \Delta t \cdot f\left(P_t + \frac{k_2}{2}, H_t + \frac{k_2}{2}\right) \tag{13}$$

$$k_4 = \Delta t \cdot f\left(P_t + k_3, H_t + k_3\right) \tag{14}$$

Figure 1 shows the changing trend of area and yield over time. The broken line shows an increasing trend, indicating that both the area of agricultural land and crop yield have a steady growth over time.

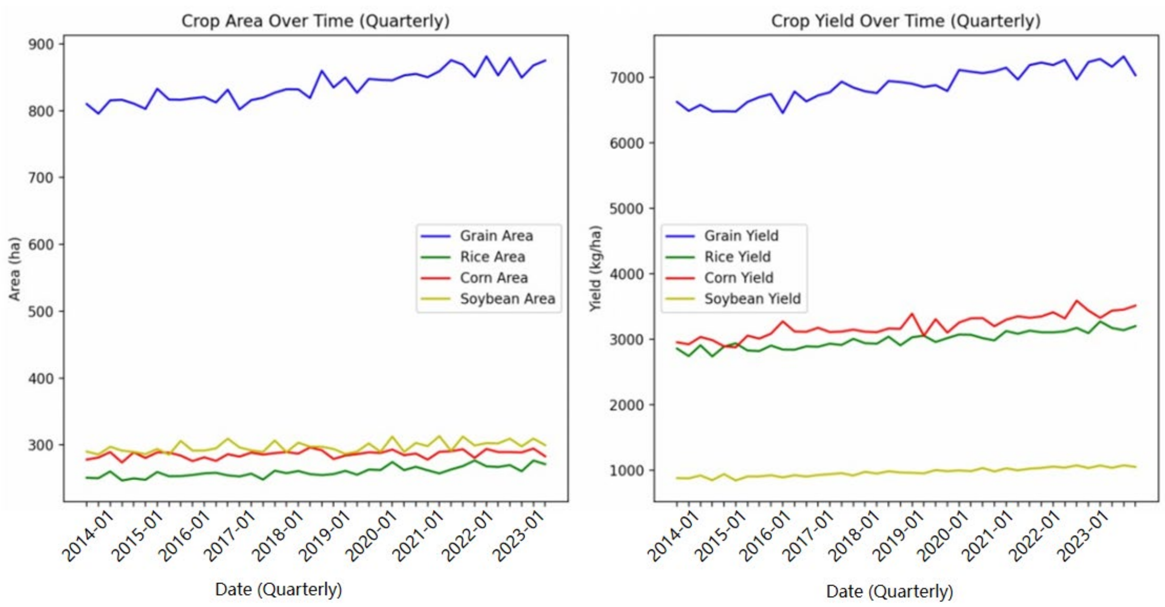

Figure 1 Changes of area and yield over time.

Figure 2 shows the increasing trend of the effects of pesticides on crop yield and soil organic matter over time. As the use of pesticides increased, crop yields gradually increased. This shows that pesticides can effectively reduce the impact of pests and diseases, thereby increasing crop yields. However, long-term pesticide use may bring about a gradual reduction in soil organic matter, affecting soil health. The figure shows that the declining trend of soil organic matter over time is accompanied by an increase in pesticide use, possibly because overuse of pesticides inhibits the activity of soil microorganisms and reduces the natural cycle of organic matter. This change reflects the dual impact of pesticides on agro-ecosystems, which may increase yields in the short term but may negatively impact soil quality in the long term.

Through experimental analysis, we observed a significant positive correlation between pesticide application costs and pest control efficacy. The measured data demonstrate that rising pesticide expenditures correspond to improved pest management outcomes, likely attributable to either the adoption of higher-efficacy formulations or adaptive responses to developing pest resistance patterns. These findings quantitatively validate the operational tradeoffs in modern agricultural pest control strategies. As pesticide application intensified, crop yields showed progressive improvement, demonstrating their efficacy in mitigating pest and disease damage. However, prolonged pesticide use was associated with a gradual reduction in SOM levels, suggesting adverse effects on soil health. The observed decline in SOM correlated with increased pesticide input, likely due to suppressed microbial activity and disrupted organic matter cycling. These findings highlight the dual role of pesticides in agroecosystems: while enhancing short-term productivity, they may compromise long-term soil quality.

Figure 2 shows a Lotka-Volterra model simulation of an agro-ecosystem. Crop, pest, bat and bird populations change dynamically over time. Crops are food for pests, more pests will reduce crops; Bats and birds prey on pests, which increase their numbers and then decrease as food decreases; Its predatory pests indirectly protect crops, and the three interact to maintain a relatively stable ecosystem.

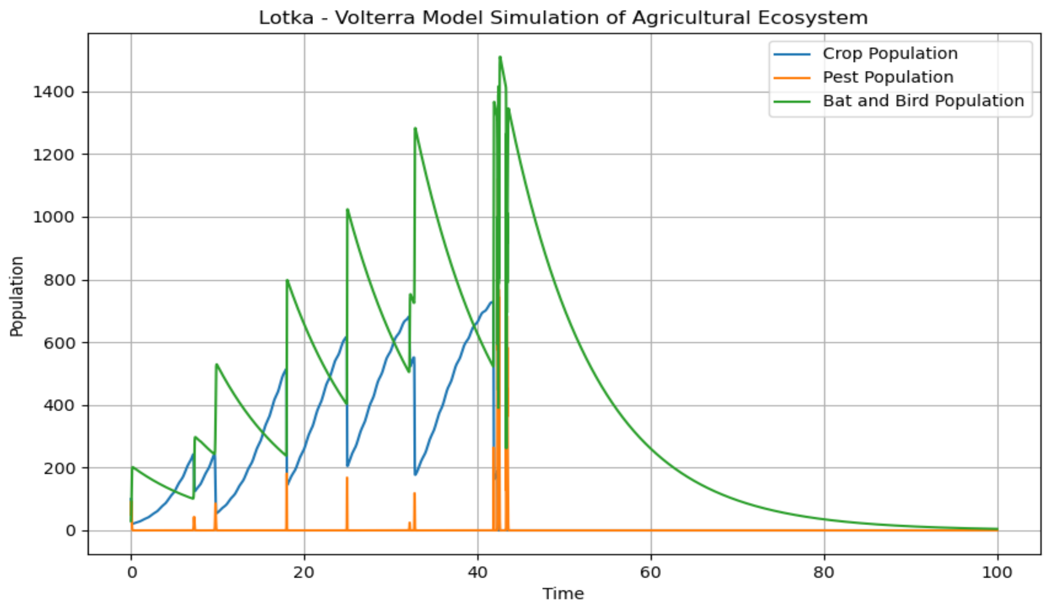

Figure 2 Dynamic population interactions in the agroecosystem simulated by the Lotka-Volterra model.

3.4. Lotka-Volterra Commercial Weight Analysis

The quotient weight method is based on the equilibrium point of the model and the stability of the system, helping us to understand how species interact with each other and ultimately reach an equilibrium state. In this problem, we can further analyze the stability of agro-ecosystem described by Lotka-Volterra equations through the method of commercial rights. The stability of the system near the equilibrium point is judged by analyzing the Jacobian matrix of the system. In the Lotka-

Volterra equations, the equilibrium point is the stable value of the population of all species, that is, the point at which the number of species no longer changes.

3.4.1. Defining the Balance Point

To simplify the equation (1) to (3), let $C(t)=0$, $\alpha(t),\beta(t),\gamma(t)$ and let:

$$\frac{dP}{dt}=0,\quad \frac{dH}{dt}=0,\quad \frac{dB}{dt}=0 \tag{15}$$

After that we can get equilibrium point:

$$(P^{*},H^{*},B^{*}) \tag{16}$$

3.4.2. Jacobian Matrix and Stability Analysis

After the equilibrium point is obtained, the next step is to judge the stability of the equilibrium point by calculating the Jacobian matrix. The Jacobian matrix is a linear approximation of the equations of the system, representing the effect of each equation on the other equations. For our system, the Jacobian matrix has the form:

$$J=\begin{pmatrix} \frac{\partial P^{*}}{\partial P} & \frac{\partial P^{*}}{\partial H} & \frac{\partial P^{*}}{\partial B} \\ \frac{\partial H^{*}}{\partial P} & \frac{\partial H^{*}}{\partial H} & \frac{\partial H^{*}}{\partial B} \\ \frac{\partial B^{*}}{\partial P} & \frac{\partial B^{*}}{\partial H} & \frac{\partial B^{*}}{\partial B} \end{pmatrix} \tag{17}$$

3.4.3. Stability Judgment and Analysis

By calculating the eigenvalues of the Jacobian matrix, we can judge the stability of the equilibrium point. If the real parts of all eigenvalues are negative, the system tends to be stable and the species reach a stable coexistence state. If there are positive eigenvalues, the system behaves as unstable, and species populations may explode or collapse.

4. Species Recolonization and Ecological Impact Assessment

4.1. The Biodiversity Restoration Model (BRM)

4.1.1. Number of species regression (R)

The number of returned species reflects the gradual reemergence of those native species in agro-ecosystems. Over time, the number of species returning will gradually increase, but the growth rate will be limited by the adaptability of the current environment.

$$\frac{dR}{dt}=\alpha R(t)\left(1-\frac{R}{R_{\max}}\right)\left(1+\left(\frac{R(t)}{K}\right)^{p}\right) \tag{18}$$

$$R(t)=R_0\cdot e^{at}\cdot\left(1-\frac{R(t)}{R_{\max}}\right)\left(1+\left(\frac{R(t)}{K}\right)^{\gamma}\right) \tag{19}$$

4.1.2. Changes in Ecosystem Stability (ES)

The return of species, species diversity and interactions between species increase ecosystem stability.

$$\frac{dES}{dt} = \beta \cdot \frac{R(t)}{K} \cdot (1 - ES) \quad (20)$$

$$ES(t) = ES_0 + \frac{\beta \cdot R(t)}{K} \quad (21)$$

4.1.3. Land Fertility Recovery (SFR)

One of the returning species is the nitrogen-fixing plant, which helps to restore soil fertility by nitrogen fixing and decomposition of organic matter.

$$\frac{d\mathrm{SFR}}{dt} = \delta \mathrm{SFR} \cdot \left(1 - \frac{\mathrm{SFR}}{\mathrm{SFR}_{\max}}\right) \quad (22)$$

$$\mathrm{SFR}(t) = \mathrm{SFR}_0 + \eta \cdot R(t) \quad (23)$$

4.2. Numerical Simulation and Analysis

The odeint function based on Runge-Kutta method is used to solve the initial value problem of ordinary differential equations, and its internal default is LSODA algorithm, which integrates a variety of numerical methods.

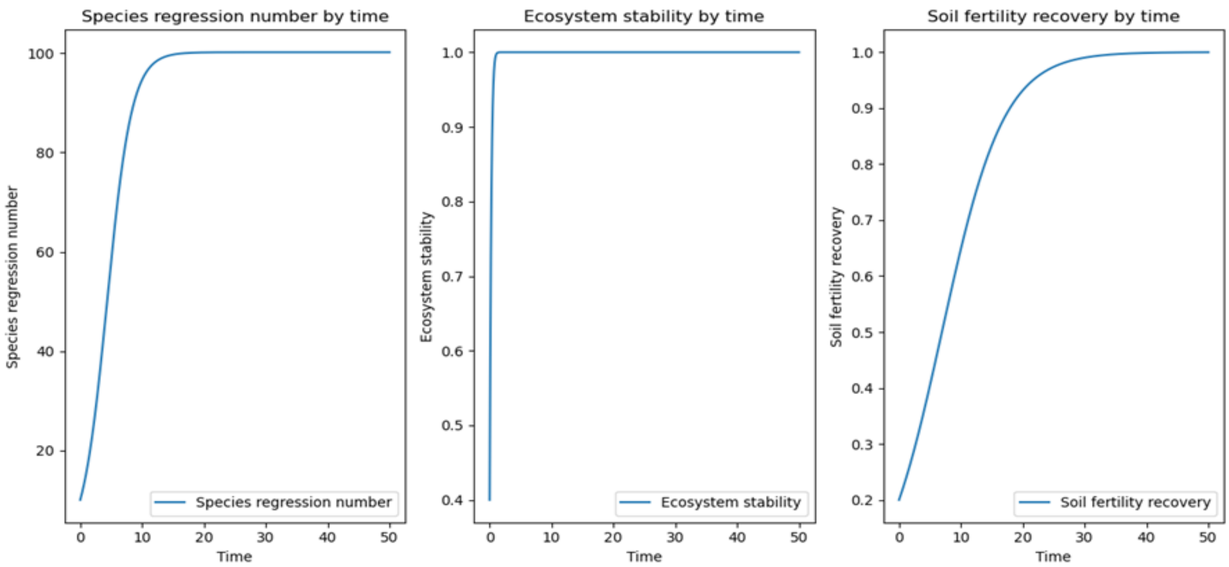

Figure 3 Temporal Dynamics of Species Regeneration, Ecosystem Stability, and Soil Fertility Recovery.

Figure 3 illustrates the temporal dynamics of species regeneration, ecosystem stability, and soil fertility recovery as simulated by our model. As shown, the number of species regenerated reaches a plateau after approximately 10 time units, indicating a saturation point in species diversity. Ecosystem stability quickly approaches 1 within about 5 time units, signifying that the ecosystem has achieved a stable state. Soil fertility recovery shows a more gradual increase, stabilizing near 1 after about 15 time units, which suggests that the soil's fertility has been largely restored.

4.2.1. Number of Species Regression

As can be seen from the numerical simulation results, with the increase of time, the number of species regression gradually increases, and finally approaches $R_{\max} = 100$, which is in line with the actual situation, because the environmental capacity limits the number of species regression. The existence of regulatory parameters makes the growth rate of species regression gradually slow down when the number approaches the maximum limit.

4.2.2. Ecosystem Stability

With the increase in the number of species returning, ecosystem stability will gradually improve. This indicates that species regression has a positive effect on the stability of the ecosystem, and the rate of stability growth gradually decreases over time, because the difficulty of improving the stability of the ecosystem gradually increases as the ecosystem stability gradually approaches the maximum value.

4.2.3. Land Fertility Recovery

Land fertility recovery shows a logical growth trend, the growth rate is fast at the beginning, and gradually slows down 1.0 as it gets closer. This shows that the recovery of soil fertility is also restricted by its own maximum recovery limit.

5. Herbicide Removal and Species Introduction

5.1. Removal of Herbicide

As the ecosystem matures, removing some chemicals can reduce planting costs and reduce negative impacts on crops, bats, and birds. In the ecosystem without herbicides, we established the following model based on model of Chapter 3 to analyze the stability of the the ecosystem.

5.1.1. Crop Growth Model

After the herbicide is not used, σ and $C(t)$ change, and it is also affected by weed competition, modifying the logistic growth model.

$$\frac{dP}{dt} = r(t)P\left(1 - \frac{P}{K} - s_1\frac{W}{W_{\max}}\right) - \alpha PH - \sigma PC(t) \tag{24}$$

Where W is the number of weeds, $W_{\max}$ is the maximum tolerance of the environment for weeds, s_1 is the factor affecting the crop value-added rate when W reaches $W_{\max}$.

5.1.2. Weed Growth Model

The number and variety of weeds began to increase. We build a logistic model that is affected by its natural growth, pest infestation, pesticides, seasonal variation, and crop competition.

$$\frac{dW}{dt} = \lambda_T(t)W\left(1 - \frac{W}{W_{\max}} - s_2\frac{P}{K}\right) - \alpha WH - \sigma PC(t) \tag{25}$$

Where s_2 is the factor affecting the weed value-added rate when P reaches K, λ is the discount factor for weed growth relative to crop growth.

Combined with the formula, we solve the above-differential equation. As depicted in Figure 4, which illustrates the simulated dynamics of plant, weed, and bat populations following the removal of herbicides, we observe distinct trends. From the producer's perspective, the number of plants initially decreases in the short term. However, over the long term, the plant population begins to recover, albeit remaining lower than in previous years when herbicides were utilized. From the consumer's perspective, the number of pests will increase in the short term, and the number of pests will begin to decrease in the long term, and the number of bats will gradually increase and stabilize.

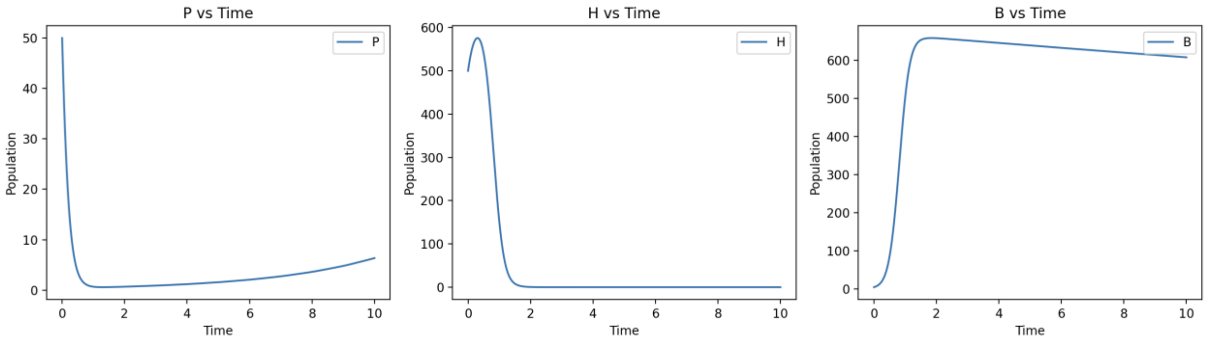

Figure 4 This caption has one line so it is centred.

So far, we have concluded that not using herbicides will affect crop yields in the short term, but in the long term, although crop yields are still lower than before to a certain extent, not using herbicides can not only reduce the impact of chemicals on the health of animals and plants, but also be conducive to the development of system biodiversity and stability, which has long-term benefits.

5.2. Introduction of Bats

After the herbicide is not used, the reduction of chemicals promotes the return of species to a certain extent. We need to consider bats, as secondary consumers, can not only promote the pollination of crops, increasing the number and competitiveness of crops, but also prey on pests and reduce the negative impact of pests on crop growth. We adjust the previous model.

5.2.1. Crop Growth Model

After the introduction of bats, crop growth was also affected by bat pollination. The model was modified to:

$$\frac{dP}{dt}=r(t)P\left(1-\frac{P}{K}-s_1\frac{W}{W_{\max}}\right)-\alpha PH-\sigma PC(t)+\omega PB_{\text{bat}} \tag{26}$$

Where ω is the contribution of bat pollination, B_{bat} is the number of bats.

5.2.2. Bat Growth and Predation Model

$$\frac{dB_{\text{bat}}}{dt}=\gamma(t)B_{\text{bat}}\left(1-\frac{B_{\text{bat}}}{B_{\max}}\right)-\mu B_{\text{bat}}-\varepsilon AB_{\text{bat}} \tag{27}$$

Where A is the number of predators of bats and birds, ε the predation rate of birds and bats by predators, $B_{\max}$ is the maximum density of bat populations.

5.2.3. Bird Growth and Predation Model

$$\frac{dN}{dt}=\gamma(t)N\left(1-\frac{N}{N_{\max}}\right)-\mu N-\varepsilon AN \tag{28}$$

Where N is the number of birds, $N_{\max}$ is the maximum density of bird populations.

5.2.4. Predator of Bats and Birds Growth Model

$$\frac{dA}{dt}=o(t)PA-\xi A \tag{29}$$

Where $o(t)$ is the seasonal variation in predator of bats and birds growth rates, ξ is the natural mortality rate of predators of bats and birds.

5.2.5. Seasonal Variation

$$o(t) = o_0 \left(1 + d \sin\left(\frac{2\pi t}{T}\right)\right) \quad (30)$$

Where o_0 is the initial growth rate of bees.

The simulation results (Figure 5) show that the return of bats has a rapid impact on pests, the number of pests and weeds gradually decreases, and the number of plants gradually increases until it reaches a relatively stable state. The entire system is moving towards a more stable and economically efficient direction.

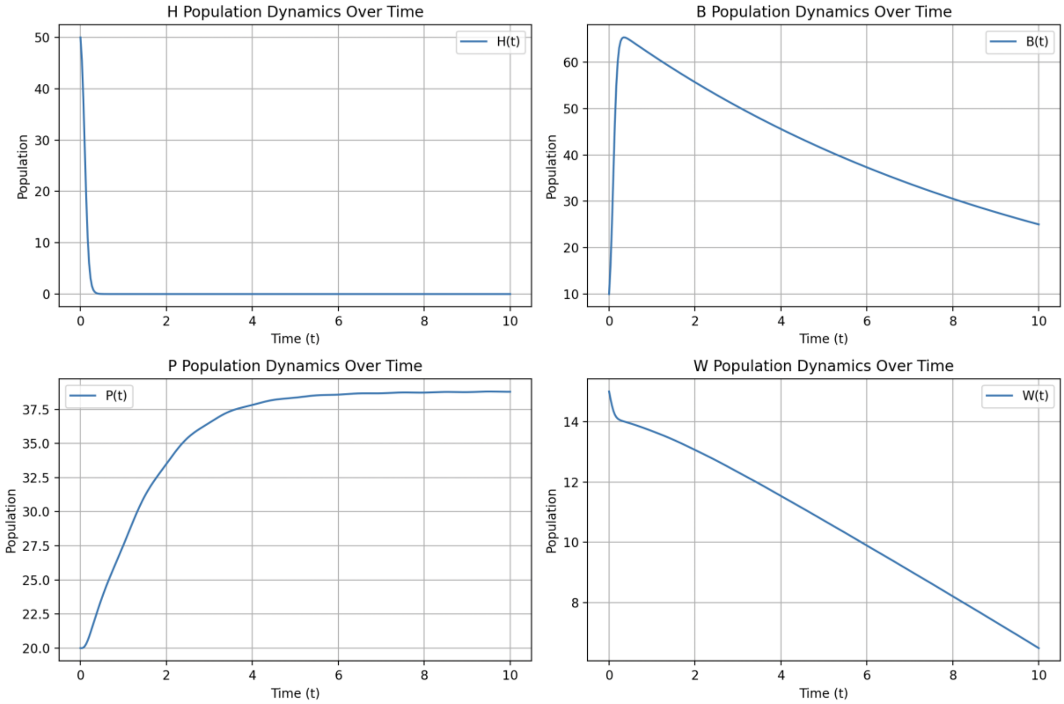

Figure 5 Population Dynamics of Plants, Weeds, and Pests Post-Bat Introduction.

5.3. Introduction of Bees

Considering a new species that is beneficial to the restoration of the balance of the ecosystem, we chose bees. In the current food web, bees are secondary consumers with almost no natural enemies. Moreover, bees have a positive effect on crop pollination and have the advantages of low cost and easy management. Below, we model the introduction of bees and analyze its impact.

5.3.1. Crop Growth Model

After the introduction of bees, crop growth was affected by bee pollination. The model was modified to:

$$\frac{dP}{dt} = r(t)P\left(1 - \frac{P}{K} - s_1 \frac{W}{W_{\max}}\right) - \alpha PH - \sigma PC(t) + \varphi PB_{\text{bee}} \quad (31)$$

Where φ is the contribution of bee pollination, B_{bee} is the number of bees.

5.3.2. BeeGrowth Model

$$\frac{dB_{\text{bee}}}{dt} = \tau(t)PB_{\text{bee}} - \nu B_{\text{bee}} \quad (32)$$

Where $\tau(t)$ is the seasonal variation in bee growth rates, ν is the natural mortality rate of bees.

5.3.3. Seasonal Variation

$$\tau(t) = \tau_0\left(1 + e\sin\left(\frac{2\pi t}{T}\right)\right) \tag{33}$$

Where τ_0 is the initial growth rate of predators of bats and birds.

As shown in Figure 6, we can find that the number of pests and weeds gradually decreased, the number of bats gradually increased, and the number of plants gradually increased and fluctuated within a certain range after the introduction of bees.

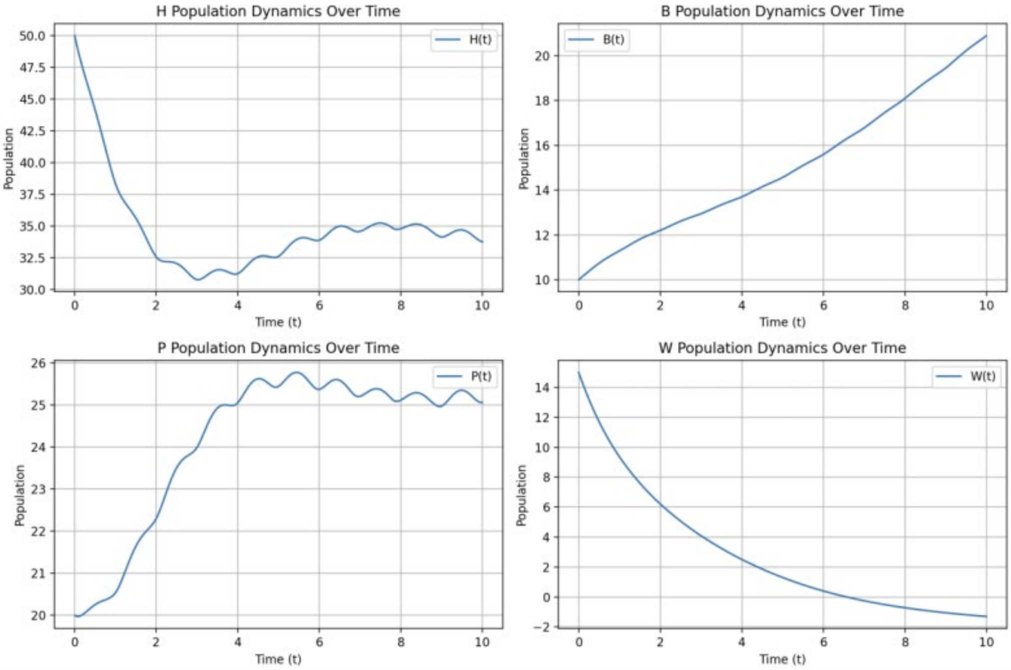

Figure 6 Population Dynamics Following Bee Introduction: Fluctuations and Trends.

Compared with the impact of bats, the peak number of crops in the system was lower, and it took longer to restore stability. But both bats and bees play an important role in the recovery of the system.

6. Conclusion

The research presented in this paper offers valuable insights into the ecological balance of agricultural ecosystems through dynamic modeling and numerical simulation. The use of the Lotka-Volterra equations, combined with the Runge-Kutta method for numerical simulation, provides a robust framework for analyzing the complex interactions among crops, pests, and natural predators such as bats and birds. The introduction of key indexes like the Ecosystem Stability Index (ESI), Species Diversity Index (SDI), Land Fertility Index (LFI), and Agricultural Output Index (AYI) further enhances the comprehensiveness of the study by quantifying various aspects of the agro-ecosystem's health. The model effectively captures the dynamic nature of the agro-ecosystem, highlighting the trade-offs between short-term yield gains from chemical use and long-term sustainability. The results underscore the importance of organic farming practices in restoring ecological balance and promoting biodiversity. The numerical simulations reveal that reducing chemical inputs and introducing beneficial species like bats and bees can significantly enhance ecosystem stability and agricultural productivity over time. However, the model is not without its limitations. One significant limitation is the simplification of the ecosystem dynamics. While the Lotka-Volterra equations provide a foundational framework, they may not fully capture the complexity of real-world agro-ecosystems, which involve multiple interacting species and environmental factors. Additionally, the model assumes a certain level of homogeneity in the ecosystem, which may not reflect the spatial and temporal heterogeneity observed in actual agricultural landscapes.

Future work should focus on refining the model to incorporate more realistic ecological interactions and environmental variables. This could include the development of more sophisticated predator-prey models that account for multiple trophic levels and the inclusion of additional factors such as climate change, soil type, and water availability. Moreover, integrating spatial dynamics through the use of spatially explicit models, such as agent-based models or cellular automata, could provide a more nuanced understanding of the spatial distribution of species and ecosystem services.

In conclusion, this study provides a solid foundation for understanding the ecological balance of agricultural ecosystems and the potential benefits of sustainable farming practices. By addressing the limitations and building on the strengths of the current model, future research can contribute to the development of more effective strategies for managing agro-ecosystems in a way that balances ecological health and economic viability.

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