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Forest to Agriculture: Based on The Lotka-Volterra Ecosystem Model

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Abstract

As people's demand for land continues to grow, large areas of land have been reclaimed for agricultural production. As forests recede and soils change, chemicals begin to appear on farmland, and the original ecological relationships in the forest gradually evolve into a food chain driven by human activity. In this article, we established an agricultural ecological model based on Lotka-Volterra to analyze the interactions between different biological populations.

First, We construct the Lotka-Volterra model based on the producer and multi-stage consumer model, determine how different species are related to each other. Second, we introduce decomposers and peregrine falcons (tertiary consumers) into the model to reflect the reappearance of species. We derive the corresponding equations and use the fourth-order Runge-Kutta method to calculate each population's rate of change. Third, we added bats to the food web model and considered their role in insect hunting and pollination to analyze their impact. Finally, we performed a sensitivity analysis of the model, changing four survival conditions. For a given range of data, the number of organism populations eventually plateaued. This validates the sensitivity of the model and confirms the stability of organic agro-ecology.

Keywords: Lotka-Volterra, Food web model, Runge-Kutta, LSTM

1. Introduction

Against the backdrop of sustained global population growth and increasingly severe environmental issues, traditional agricultural models are facing unprecedented sustainability challenges (Poslinski et al., 2025). The once complex forest ecological network is gradually being replaced by new ecosystems driven by human activities with agricultural production as the core.

Therefore, it is very important to establish a reasonable model for performance.The model should be able to comprehensively consider factors such as economic benefits, soil health, pest control, plant reproduction, biodiversity, and long-term sustainability to evaluate the impact of organic agriculture on agricultural ecosystems (Li et al., 2024). Helping decision-makers make agricultural production decisions through scientific and rational methods, thereby promoting the sustainable development of agricultural ecology, has profound significance.

2. Theories and Methods

The ecology of farmland is significantly different from that of forests, and many species struggle to adapt to the new environment. This disrupts the original food chain and vegetation structure, affecting population sizes. While the Lotka-Volterra model (Zheng and Chang, 2022) helps in understanding the predation and competition relationships between species (Cao et al., 2025), it has limitations in dealing with complex factors like seasonal changes and agricultural cycles.

In contrast, the LSTM (Long Short-Term Memory) model can better capture the long-term dependencies and nonlinear relationships within an ecosystem (Organic Agriculture Research and Extension Initiative (USDA), 2025). By analyzing historical population data, seasonal factors, and agricultural cycles, LSTM can reveal long-term trends brought about by ecosystem transitions and predict species changes under different environments. Combining the Lotka-Volterra model with the LSTM (Kiran Kumar et al., 2023) model allows for more accurate simulation and prediction of species composition changes during the forest-to-farmland transition, providing scientific support for agricultural practices and species conservation strategies.

2.1. Lotka-Volterra agro-ecosystem model

The Lotka-Volterra model is often used to describe the interactions between populations in ecosystems, especially predation, competition, etc. In this model, the growth or decline of a population depends not only on its own natural growth rate, but also on interactions with other populations (Seno, 2025). In this question producers are preferred weeds and crops, consumers have insects and birds.

Producers include weeds and crops, which are the basic energy sources in the system. Changes in the abundance of weeds and crops can be described by the following equations:

$$\frac{\mathrm{dN_1}}{\mathrm{dt}} = \alpha_1 \, \mathrm{N_1} - \beta_1 \, \mathrm{N_1} \, \mathrm{N_2} \tag{1}$$

Where: N_1 represents the number of producers (weeds and crops), α_1 is their natural growth rate, and β_1 is the strength of the relationship between weeds and crops and insects. The relevant parameters of equations 1 to 5 are shown in Table 1.

Natural growth rate (α_1): Based on historical ecological data (such as crop growth rate and insect reproduction rate in literature (Li et al., 2024; Seno, 2025) and field observation values, Lotka-Volterra equation is fitted to actual population dynamics data by least squares method.

Predation efficiency (β_1): Calibrated according to experimental data of predator-prey interaction (e.g. consumption of crops by insects per unit time) and statistical results of literature (Zhang, 2024).

$$\alpha_1(t) = \alpha_1 \cdot \mathrm{seasonal}(t) \tag{2}$$

Where: seasonal(t) is a sinusoidal function of periodic changes, which reflects the impact of seasonal changes (Genda et al., 2025) on the growth of producers, and adjusts the growth rate of plants according to factors such as temperature, light and precipitation.

$$\beta_1(t) = \beta_1 \cdot \ \mathrm{seasonal} \ (t) \tag{3}$$

Figure 1 to Figure 4 show the plant population curve, bird population curve, insect population curve and Euler equation solution of LV model respectively.

Table 1: Key parameter values

Parameters	definitions	values
α_1	Crop natural growth rate	0.15
β_1	insect predation efficiency	0.2
φ	bat pollination gain coefficient	0.01
γ_α	bat predation efficiency	0.3

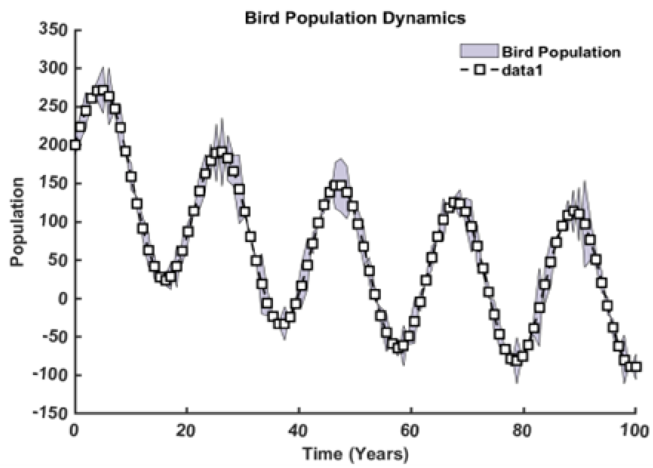

Figure 1: Plant population number curve

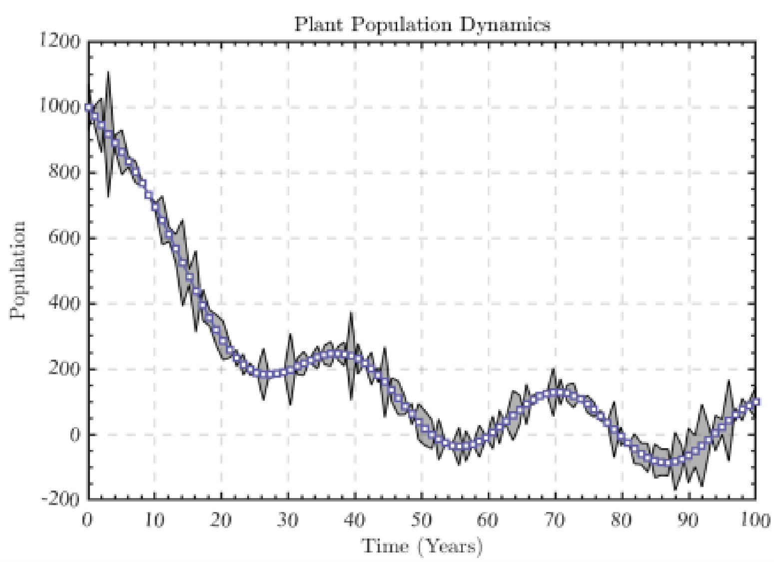

Figure 2: Bird population number curve

Producers, insects, and birds also show cyclical changes with seasonal cycles, and changes in predator populations lag behind those of producers.

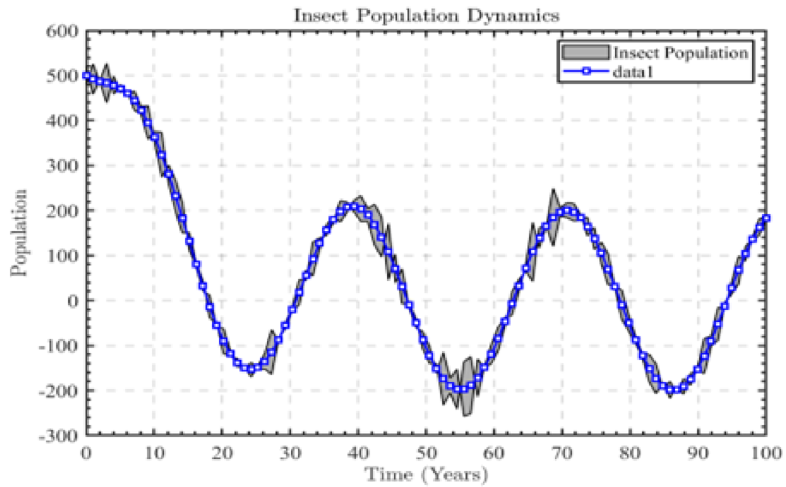

Figure 3: Insect population number curve

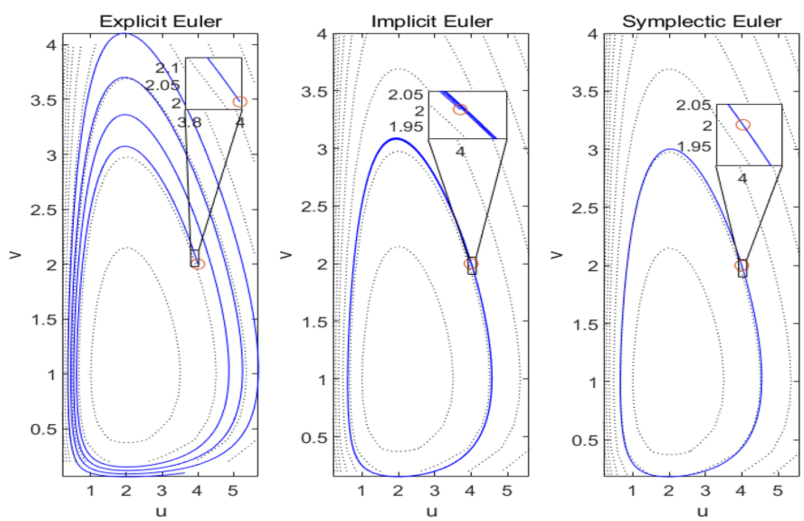

Figure 4: Solution of Euler equation for LV model

The changes in the number of producers and insect populations before and after the introduction of pesticides are as shown in Figure 5.

2.2. LSTM agroecosystem model

In the LSTM model (Zhang, 2024), the long-term impact of pesticide use P(t) on ecosystems can be captured by using pesticide use as an external input. The predicted results of population changes are shown in Figure 6.

The input layer of the LSTM contains:

1.Population data: $N_1(t)$, $N_2(t)$, $N_3(t)$, which are the populations of weeds, crops, birds, and insects, respectively.

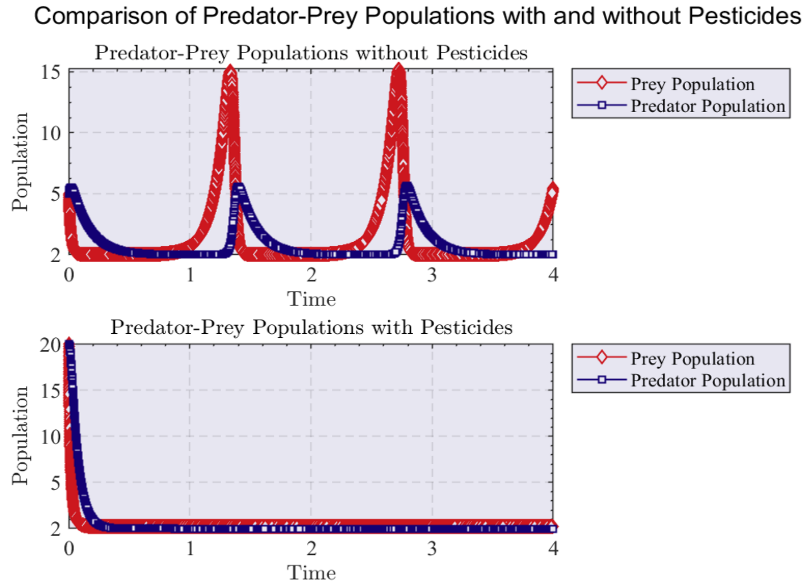

Figure 5: Comparison of vegetation and insects before and after pesticide application

2.Pesticide dosage: P(t).

3.Seasonal factors: temperature, humidity, precipitation and other environments.

4.Agricultural cycle: characteristics of the agricultural cycle such as sowing and harvesting.

LSTM layer:

Learn about dependencies in time series data to capture the complex relationships between pesticide application rates and population changes.

Output layer:

Predicted population numbers at future time steps: $N_1(t+1)$, $N_2(t+1)$, $N_3(t+1)$.

Solving the LSTM model can obtain the trend curve of population number change:

2.3. Comparative analysis of the effects of bees and bats

When the agroecosystem matures and the use of pesticides is stopped, the impact of pesticides received by insects (primary consumers) gradually decreases, and the mortality rate decreases, while the predation efficiency of birds and bats (secondary consumers) increases, and bats not only affect the number of insects, but also play a role in spreading pollen, helping plants to reproduce and providing support for plants. Therefore, in the original model, the pesticide factor was removed, and the role of bats was added to form a complete food chain. Figure 7 shows the analysis process for introducing bats into the model.

Bats: The insectivorous and pollinating effects of bats are more complex and may be more extensive, especially in the pelagic middle of the food chain. Bats can maintain ecologicalbalance by controlling pests and promoting plant reproduction.

$$\frac{dN_a}{dt} = \gamma_a N_2 N_a - d_a N_a - \zeta P N_a + \phi N_1 N_a \tag{4}$$

Where: N_1 is the number of plant populations, and φ is the contribution of bat pollination to plants.

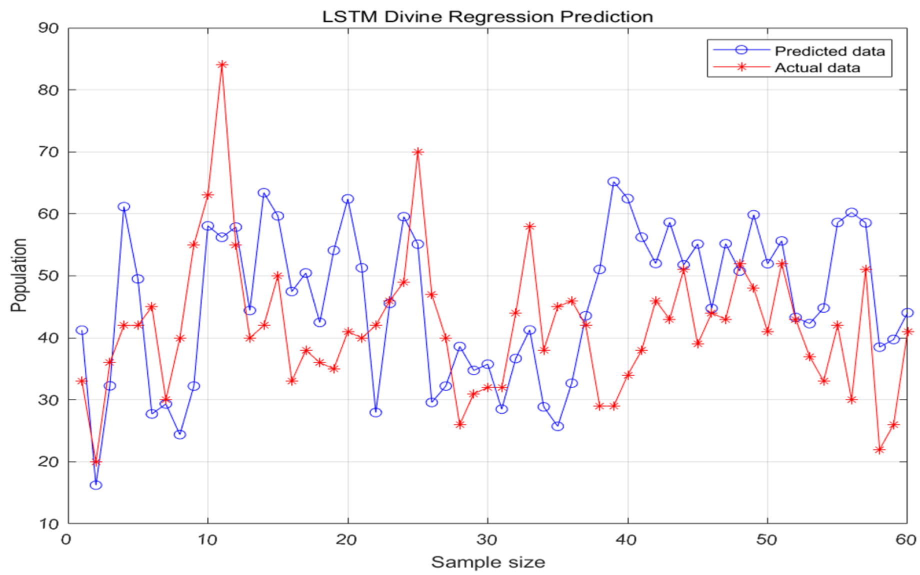

Figure 6: Prediction of the change trend of biological population number

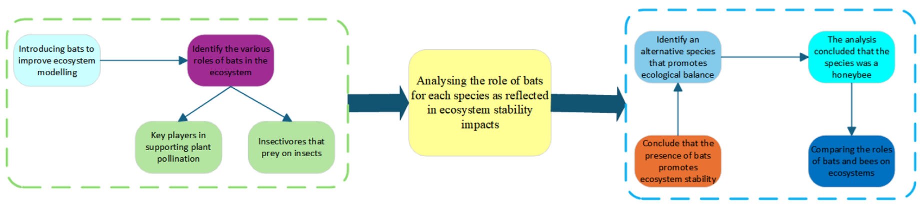

Figure 7: Introduction of bats, search for alternative biological flow charts

Consider bees as an alternative species, not only as an insectivore to control the number of insects, but also to pollinate like bats. So the role of bees is similar to that of bats, and the impact on plants is mainly reflected in pollination.

Bees: Bees mainly affect ecosystems through pollination and controlling small pest populations, which may be relatively small in scope and depth, but bees have a more direct and efficient role in promoting plant reproduction.

$$\frac{dN_e}{dt} = \gamma_e N_2 N_e - d_e N_e - \zeta P N_e + \phi_1 N_1 N_e \tag{5}$$

Where: N_e is the number of bee populations. The result of that population change of the two species are shown in figure 8.

3. Sensitivity Analysis

In real life, statistics are often inaccurate and there may be some biases in our model inputs. These biases may affect the results of our model, so in order to test the robustness of the model, we changed the four conditions of the carrying capacity of the prey population,the rate of prey consumption by predators, the rate of reproduction by predators due to prey consumption, and the natural mortality

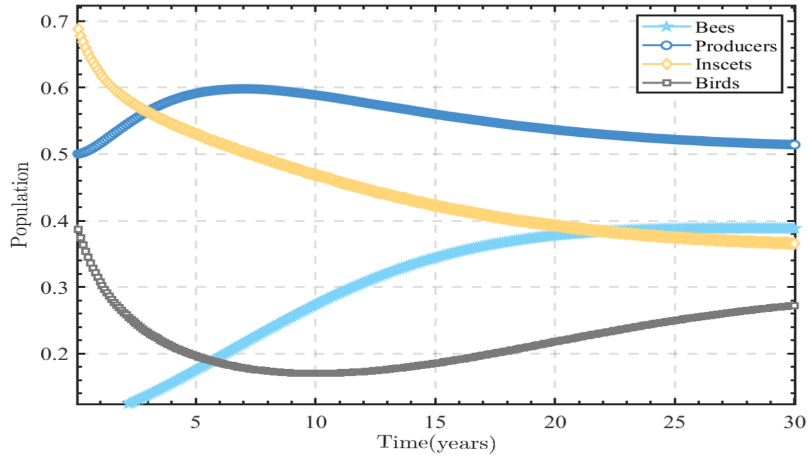

Figure 8: Comparison of population changes of bats and bees

rate of predators, and plotted the sensitivity analyses of the number of different organisms' populations from the basic survival conditions to a small range of fluctuations, Figure 9 can be seen that the predators and the producers end up changing very little, and changes in survival conditions cause changes in the number of organisms' populations, but the fluctuations are small, and the overall convergence and eventual stabilisation at roughly the same level show that our model is robust.

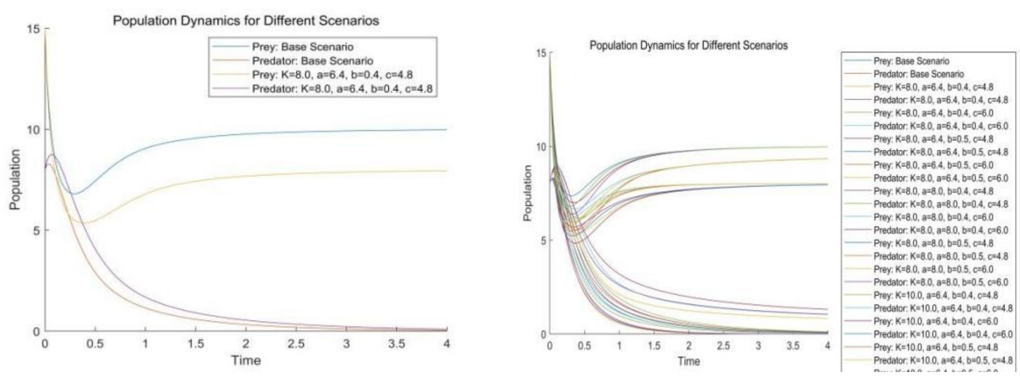

Figure 9: Sensitivity analysis of Prey&Predator

4. Conclusion

Around the world, it is not uncommon for forests to be cleared for agriculture. When forests give way to agriculture, the intricate web of life that thrives in the forests is disrupted and a new, human-driven agro-cycle takes its place, creating new food webs on top of agro-ecosystems, and what we want to do is to track how the various environmental factors, new species introductions, and the use of chemicals in the transformed agro-ecosystem (Cao et al., 2020). The effects of pesticide use on the ecosystem and the impact of the addition of bats and other species to the ecosystem will be analysed and solved using Lotka-Volterra and LSTM conformal models!We obtained a series of predictions and proved that our model is stable and effective through sensitivity analyses. While solving the problem, we also helped the farmers to analyse some agricultural strategies, and our research makes a valuable contribution to the long-term sustainability of organic agriculture (Ren et al., 2020) and advocates for today's policies to support and protect the development of organic agriculture.

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