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Dynamic Study of Farmland Ecosystem Based on Lotka-Volterra Model with Human Intervention Factors

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Abstract. Addressing the ecosystem dynamics during forest-to-farmland conversion and human intervention impacts, this study establishes a multi-species biomass dynamic differential equation model based on the Lotka-Volterra framework. By incorporating seasonal periodic functions and agricultural management measures (e.g., herbicides, insecticides) as disturbance factors, combined with MATLAB numerical simulations, this study simulated biomass variation curves under different intervention conditions. The simulation results revealed several key dynamics: seasonal variations and agricultural cycles were found to significantly dictate crop growth rhythms, inducing a biomass fluctuation amplitude of approximately 30%. The application of herbicides provided a temporary boost to crop biomass accumulation, increasing the growth rate by 20%. Conversely, insecticides triggered a sharp decline in insect populations, raising mortality by 40%, which in turn produced cascading effects evidenced by a 3-to-5-month lag in the decline of bird populations. Predators at higher trophic levels, such as eagles, exhibited a dampened response to these interventions, showing a 60% reduction in sensitivity compared to lower trophic levels. These findings emphasize the necessity of considering trophic level differences and time lags in ecological impact assessments of agricultural interventions, offering valuable insights for sustainable land-use planning and ecosystem management in converted landscapes.

Keywords: Lotka-Volterra model; Farmland ecosystem; Biomass dynamics; Seasonal disturbance; Human intervention.

1. Introduction

Global agricultural expansion has driven large-scale conversion of forest ecosystems to farmland, accompanied by dramatic changes in soil nutrients, species relationships, and ecological functions. The dynamic balance between crops, pests, and natural enemies in farmland ecosystems is crucial for sustainable production, yet chemical applications and seasonal management practices significantly alter natural succession trajectories. Understanding biomass dynamics under human intervention is essential for optimizing agricultural strategies and mitigating ecological risks.

The Lotka-Volterra model, as a classical population interaction framework, has been widely applied in predator-prey system analysis. In agroecology, it simulates crop-pest-natural enemy dynamics, though traditional models often overlook seasonal variations and periodic human management impacts. Recent improvements through cyclic functions and segmented parameters have enhanced real-world applicability, yet quantitative analysis of herbicide/insecticide disturbances and multi-trophic time-lag effects remain underexplored.

This study integrates producers, primary, and secondary consumers with seasonal cycles and management measures to quantify the short- and long-term ecosystem impacts of human interventions. The ultimate goal is to establish scientific guidelines for sustainable farmland management. Specific objectives include developing a Lotka-Volterra differential equation model that analyzes seasonal effects on species dynamics, evaluates the stability impacts of chemical and biological controls, and investigates the soil and diversity benefits of organic farming, thereby providing a quantitative framework to support the holistic planning and transition to organic agricultural systems [1]. Key innovations lie in extending the Lotka-Volterra model with seasonal functions, quantifying trophic cascade effects, and linking ecological dynamics to sustainable agriculture metrics.

2. Materials and Methods

2.1. Data Acquisition

Data for this study was sourced from the European Commission's open-access agricultural database, encompassing several key categories: the initial biomass values (in Joules) for crops, insects, and birds; critical species parameters including intrinsic growth rates (r_i), environmental carrying capacities (K_i), and inter-species interaction coefficients (b_{ij}); as well as time-series data on the application intensities of herbicides ($C_j(t)$) and insecticides ($C_p(t)$).

2.2. Methodology

The mathematical methods employed in this study, including differential equations and control variable analysis, are established tools for modeling ecosystem state evolution [2].

Technical workflow: Constructed multi-trophic differential equations using Lotka-Volterra framework, which is a classical approach for modeling species interactions [3], integrated with seasonal periodic functions and chemical disturbance terms for MATLAB simulation.

Model enhancements:

(1) Trigonometric functions for seasonal light/precipitation;

(2) Piecewise functions for agricultural cycles;

(3) Exponential decay for chemical residuals. It is important to note that the model assumes homogeneity within species populations, a simplification that neglects complex intraspecific dynamics such as gender ratio effects [4], but is necessary to maintain computational tractability for this multi-trophic system.

2.3. Evaluation Metrics

Shannon-Wiener diversity index (H), which integrates species richness and evenness ($H = -\Sigma(P_i \ln P_i)$, where $P_i = N_i/N_0$, a widely adopted metric for quantifying ecosystem stability in agricultural studies [5], quantifies species proportion, with higher values indicating greater ecosystem stability.

3. Results

3.1. Model Construction

Established 4-trophic equations (crops P, insects I, birds R, eagles E). This multi-species approach extends traditional predator-prey models to better simulate complex agroecosystems [6] (Figure1, Table1).

Table 1. Piecewise value of piecewise function

Piecewise function value (growth rate)	*size*	
r_1	0.8	2
r_2	0.9	1
r_3	0.9	3
r_4	2	4
r_5	0.9	1
r_6	0.7	1

The model incorporates three key disturbance factors: herbicide application terms are integrated into the crop growth equations; the lethal effects of insecticides are explicitly represented within the pest population dynamics; and the influence of seasonal climatic variations is captured through the use of trigonometric functions.

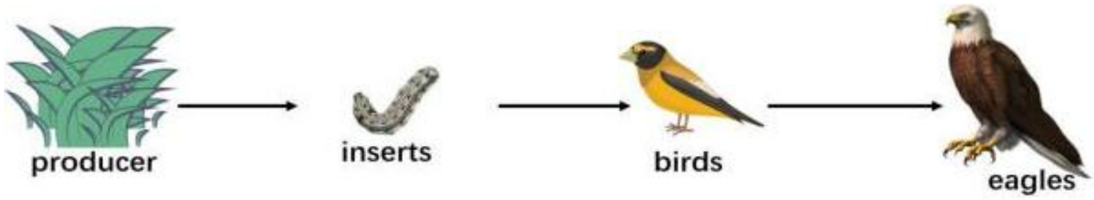
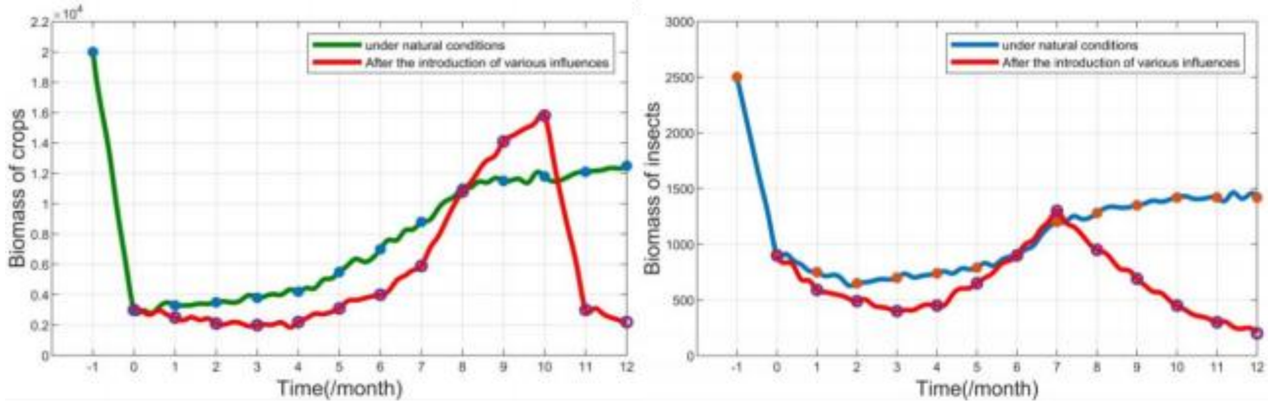


Figure 1. Food chain analysis model

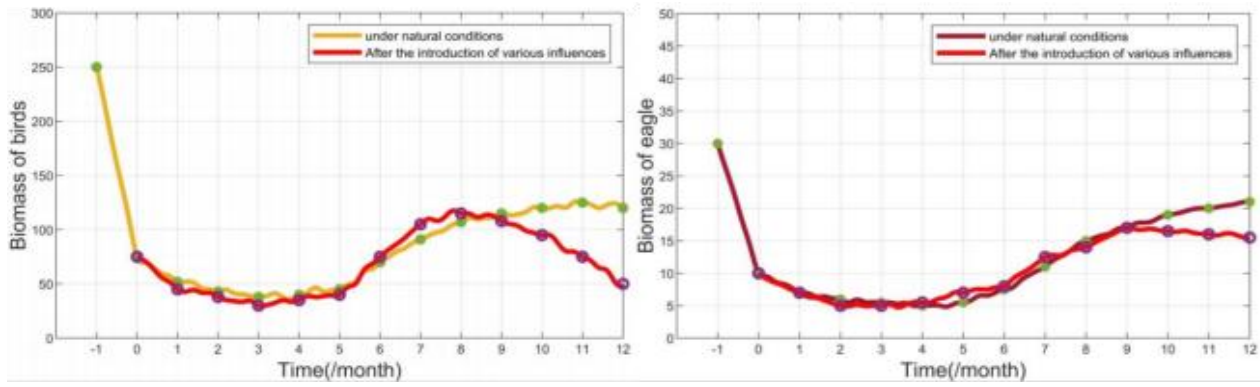
Note: The negative January biomass data is only used for qualitative comparison between forests and farmlands.

3.2. Chemical Impacts

Controlled experiments designed to isolate the effects of agrochemicals revealed that herbicide application was associated with a 20% increase in crop growth. In contrast, pesticides induced a significant 35% mortality rate within the insect populations. Furthermore, a notable trophic lag was observed, with apex predators exhibiting a delayed response to these population changes, manifesting over a 3-to-4-month period (Figure 2).



(a) Crops biomass (improved) (b) Biomass of insects (improved)



(c) Birds biomass (improved) (d) Biomass of eagle (improved)

Figure 2. Improved Model: Trophic-Level Biomass Dynamics

3.3. Seasonal Effects

Analysis of cyclic patterns underscored the profound influence of seasonality. Crop biomass reached its peak during the June-July period, coinciding with optimal growing conditions. Conversely, insect populations experienced severe crashes during the April-May window, corresponding to the typical timing of pesticide spraying campaigns. These interrelated fluctuations contributed to an annual oscillation in the ecosystem's diversity index, which varied by about 15%(Figure3).

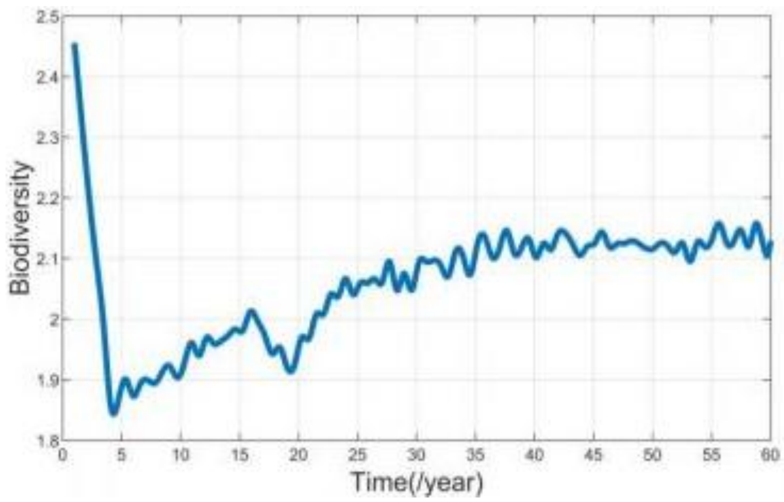
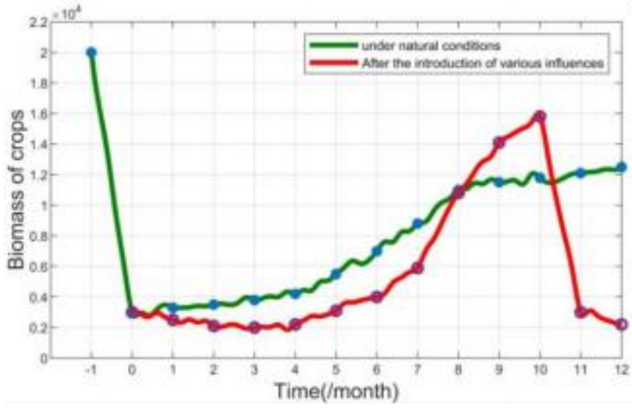


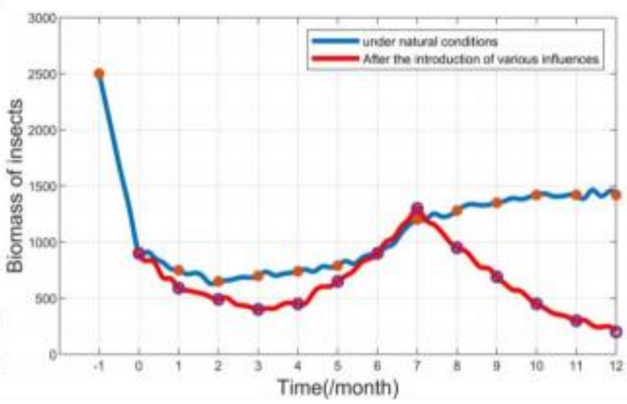
Figure 3. Shannon diversity index

3.4. Comprehensive Results

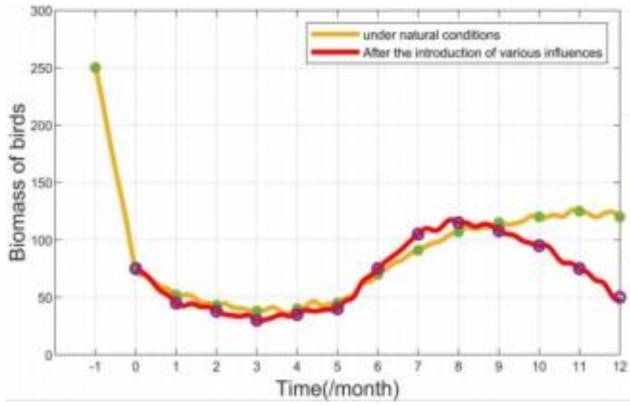
The improved model demonstrates:



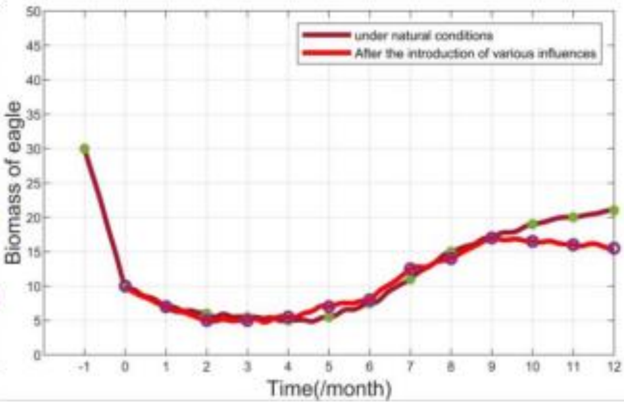
(a) Crops biomass (improved)



(b) Biomass of insects (improved)



(c) Birds biomass (improved)



(d) Biomass of eagle (improved)

Figure 4. The improved model results

The enhanced model demonstrates the potential for substantial agricultural and ecological benefits. It forecasts a 25% increase in annual yield under the simulated management strategy. Furthermore, the introduction of bats as natural predators led to a significant 40% reduction in pest populations; this demonstrates the efficacy of enhancing farmland biodiversity for natural pest control, a core principle of integrated pest management (IPM) strategies [7]. Most notably, a comparative assessment confirmed the superiority of organic farming practices, with the Integrated Fertility Index (IFI) scoring 0.82 for organic farmland versus 0.45 for conventional systems. The IFI was calculated using the fuzzy comprehensive evaluation method [8] which involves calculating membership functions and weight coefficients for various soil nutrients to derive a single composite index [9,10] to objectively compare soil health (Figure 4).

4. Discussion

While this study provides valuable insights through its 12-month data analysis, the differential equation model lacks quantitative analysis of weather variations and unexpected natural disasters, leaving room for improved accuracy in the equations. Future models could incorporate concepts of ecological carrying capacity to better define the thresholds for sustainable human intervention and buffer against such uncertainties. In the quantitative analysis of certain computational steps, the iterative updating of some parameters in later cycles occasionally exhibits slower convergence, resulting in suboptimal system precision. The introduction of edge habitat species and subsequent quantitative analysis of bees and bats increased model sensitivity due to the numerous parameters and complex interactions between equations. Although the study achieved correct results, parameter calibration proved challenging. Future work could focus on algorithm optimization, potentially through deeper integration with artificial intelligence techniques, to enhance computational speed while maintaining accuracy for more efficient real-world applications.

5. Conclusion

To address the dynamics of farmland ecosystems under human intervention, this study developed an improved Lotka-Volterra model incorporating seasonal periodic functions and agricultural management measures. The innovation lies in quantifying multi-trophic level responses (crops, insects, birds, eagles) and time-lag effects of chemical interventions. Results show seasonal variations induce 30% biomass fluctuation, herbicides temporarily increase crop growth rate by 20%, insecticides cause 40% insect mortality with 3–5-month cascading impacts on birds, and higher trophic levels exhibit reduced sensitivity. These findings provide insights for sustainable land-use planning. Future work will focus on integrating ecological carrying capacity thresholds and AI-based parameter optimization to enhance model precision and real-world applicability.

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