Feasibility Analysis Study of Organic Agro-Ecosystems Based on Logistic Growth Models

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Abstract: With the increasing demand for agricultural land, large-scale forest conversion has significantly disrupted natural ecosystems. This study evaluates the ecological implications of converting forests into agricultural land and assesses the feasibility and sustainability of organic agriculture through a series of dynamic models. By constructing a logistic growth-based agro-ecosystem model incorporating producers, consumers, and chemical effects, we investigated the impacts of herbicides, pesticides, and seasonal cycles on ecosystem stability. The models were solved using the fourth-order Runge-Kutta method, revealing stable population dynamics and inter-species relationships. Further analysis included species regression modeling, demonstrating that reducing secondary consumers enhances stability. We then explored the effects of removing chemical inputs, which significantly restored insect populations and improved ecosystem resilience. Incorporating insectivorous bats and carnivorous birds into the food web showed effective pest control and further stabilized the system. Finally, we simulated an organic farming approach utilizing biological control agents such as probiotics and insecticidal bacteria, confirming increased biodiversity and reduced chemical dependency. This modeling framework supports informed decision-making for sustainable agriculture and highlights the ecological benefits of transitioning to organic practices.

1. Introduction

The rapid expansion of agricultural activities driven by increasing food demands has led to large-scale conversion of forest land into farmland. While this transformation addresses short-term economic and productivity needs, it simultaneously disrupts the ecological balance by reducing biodiversity, depleting soil fertility, and increasing the dependence on chemical fertilizers, herbicides, and pesticides [1]. These changes have raised concerns about the long-term sustainability of modern agricultural systems.

Forests, as one of the most important terrestrial ecosystems, play a crucial role in regulating climate, conserving biodiversity, and maintaining soil and water balance. Their destruction for agricultural purposes results in the loss of natural ecological services and disturbs the population dynamics of various species, especially producers, herbivores, and insect predators [2]. Additionally, excessive application of agrochemicals pollutes soil and water, degrades the land, and threatens beneficial species, thereby reducing the resilience and sustainability of the agro-ecosystem.

To address these challenges, ecological modeling combined with machine learning provides a promising solution for simulating complex ecosystem interactions and evaluating the feasibility of sustainable alternatives such as organic farming. In this study, we develop a set of dynamic models based on logistic growth and Runge-Kutta numerical methods to simulate population interactions under different ecological interventions [3]. We further extend our models by integrating biological control mechanisms—such as the introduction of insectivorous bats and probiotics—to assess the

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effectiveness of organic farming in enhancing ecosystem stability and biodiversity.

This paper presents the following key contributions:

- Ecosystem-Oriented Modeling Framework: We propose a comprehensive modeling framework for agro-ecosystems based on logistic growth dynamics, incorporating producers, primary and secondary consumers, and the impacts of chemical substances on population stability.
- Runge-Kutta-Based Simulation: The models are solved using a fourth-order Runge-Kutta method to simulate temporal population dynamics under various agricultural scenarios, ensuring high precision and convergence.
- Species Regression and Chemical-Free Scenarios: We construct species regression models and simulate the effect of eliminating herbicides and pesticides, demonstrating the ecological benefits of chemical reduction and restoration of insect populations.
- Biological Control via Machine Learning Insights: We extend the food web model by introducing bats and carnivorous birds to simulate biological pest control. The effectiveness of this approach is supported through data-driven modeling and ecological interpretation.
- Feasibility Analysis of Organic Agriculture: A biological alternative—based on probiotics and insecticidal bacteria—is proposed and evaluated, providing a machine learning-informed framework for supporting biodiversity, reducing chemical dependency, and guiding sustainable agricultural decision-making.

2. Methodology

2.1 Natural Model

In agroecosystems, producer growth receives seasonal variations, herbicides, and predation by herbivores and insects, which constitute primary consumers, and secondary consumers that feed on primary consumers and control the size of primary consumer populations [4].

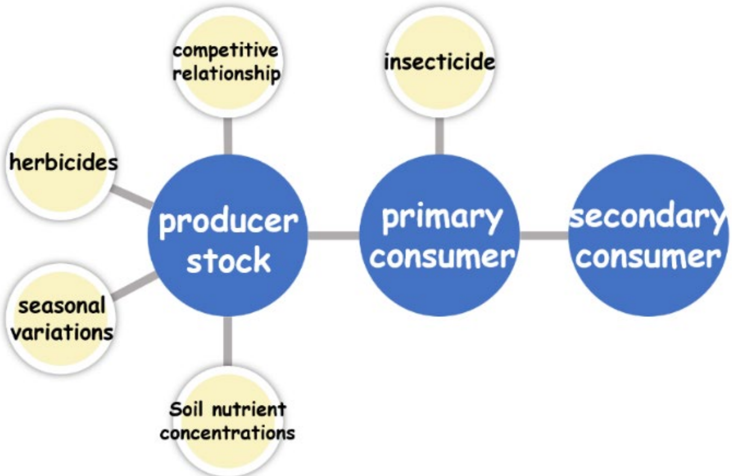


Figure 1 Natural model factor effects.

As shown in Figure 1, the three components mentioned above form a complete ecosystem, and the three are modeled to describe population changes in agro-ecosystems, taking into account the effects of seasonal variations, herbicides, pesticides, and other factors.

- Producers (weeds and crops)

Producers include weeds and crops whose population growth follows a logistic model and can be affected by seasonal variations and herbicides. Seasonal variations affect the growth cycle of plants, while herbicides negatively affect the growth of plants. In addition to this, producers are in competition with each other.

Population dynamics of weeds:

$$\frac{dF_1}{dt} = \eta_1 F_1 \left(1 - \frac{F_1 + \alpha_1 F_2}{M_1}\right) - \lambda_1 F_1 F_3 - \lambda_2 F_1 F_4 - \rho_1 F_1 + g(t) + \epsilon L F_1 \tag{1}$$

Population dynamics of crops:

$$\frac{dF_2}{dt} = \eta_2 F_2\left(1 - \frac{F_2+\alpha_2 F_1}{M_2}\right) - \lambda_1 F_2 F_3 - \lambda_2 F_2 F_4 - \rho_2 F_2 + g(t) + \epsilon L F_2 \quad (2)$$

Producer stock:

$$\frac{dF_{produce}}{dt} = \frac{dF_1}{dt} + \frac{dF_2}{dt} (3)$$

Where F_1, F_2 are the total amount of weeds and crops per unit area, η_1, η_2 are the growth rates of weeds and crops under ideal conditions, α_1, α_2 are the competition coefficients of crops to weeds and weeds to crops, M_1, M_2 are the environmental maximum carrying capacity of weeds and crops, λ_1, λ_2 are the consumption rates of herbivores and insects to plants, F_3 is the total amount of herbivores per unit area, F_4 is the total amount of insects per unit area, ρ_1, ρ_2 is the damage of herbicides to weeds and crops, and $g(t)$ is a seasonal variation factor, where L is the soil nutrient concentration, and ϵ is the rate at which plants consume soil nutrients.

The seasonal variation factor $g(t)$ can be modeled using the cosine function, and the purpose of studying seasonal variation is to obtain the cyclical variation over the year. We model the cosine function as follows:

$$g(t) = \mathrm{K}\cos\left(\frac{2\pi}{\mathrm{T}}\mathrm{t} + \theta\right) (4)$$

Where K denotes the magnitude of seasonal variation, T is the period of variation, t is the time, and θ is the phase.

For the degree of soil fertility, it is necessary to consider the depletion of its original fertility by plants, as well as the rate of replenishment of soil nutrient concentrations, and we use differential equations to describe the changes in soil fertility, the equations are as follows:

$$\frac{dL}{dt} = \delta - \epsilon L(F_1 + F_2) (5)$$

Where L is the soil nutrient concentration, δ is the rate of replenishment of soil nutrient concentration, and ϵ is the rate of plant consumption of soil nutrients.

- Primary consumer

The population of primary consumers is the sum of herbivores and insects, whose population growth is correlated with the plant population, and the adverse effects of pesticides on this population need to be considered.

Herbivore population dynamics:

$$\frac{dF_3}{dt} = \eta_3 F_3\left(1 - \frac{F_3}{M_3}\right) - \lambda_3 F_3 F_5 - \mu_1 F_3 - \nu_1 F_3 (6)$$

Insect population dynamics:

$$\frac{dF_4}{dt} = \eta_4 F_4\left(1 - \frac{F_4}{M_4}\right) - \lambda_4 F_4 F_5 - \mu_2 F_4 - \nu_2 F_4 (7)$$

Primary consumer population dynamics:

$$\frac{dF_{primary}}{dt} = \frac{dF_3}{dt} + \frac{dF_4}{dt} (8)$$

Where F_3, F_4 is the total number of herbivores and insects per unit area, η_3, η_4 is the reproduction rate of herbivores and insects in an ideal state, M_3, M_4 is the maximum carrying capacity of the environment for herbivores and insects, respectively, λ_3, λ_4 is the rate of consumption of herbivores and insects by carnivores, F_4 is the total number of carnivores per unit area, μ_1, μ_2 is the insecticides' herbivore and insect damage, ν_1, ν_2 is the natural mortality rate of herbivores and insects.

- Secondary consumers (carnivores)

Sub-consumer population growth is influenced by their food resources:

$$\frac{dF_5}{dt} = \eta_5 F_5\left(1 - \frac{F_5}{M_5}\right) - \nu_3 F_5 (9)$$

Where, F_5 is the total number of carnivorous animals per unit area, η_5 is the ideal reproduction rate of carnivorous animals, M_5 is the maximum carrying capacity of the environment for carnivorous animals, and ν_3 is the natural mortality rate of carnivorous animals.

The model is an ordinary differential equation model containing the population dynamics equations for producers, primary consumers and secondary consumers. In this paper, we use the method of considering the right end term of the equation as $f(t,y)$ and solve it by the fourth order Runge-Kutta method:

For ordinary differential equations:

$$\frac{dy}{dt} = f(t,y)(10)$$

The update formula for the fourth-order Runge-Kutta method is:

▪ Calculate the four slopes:

$$\begin{cases} k_1 = h * f(t_n, y_n) \\ k_2 = h * f(t_n + \frac{h}{2}, y_n + \frac{h}{2}) \\ k_3 = h * f(t_n + \frac{h}{2}, y_n + \frac{h}{2}) \\ k_4 = h * f(t_n + h, y_n + h) \end{cases} (11)$$

▪ Update the solution by weighted average:

$$y_{n+1} = y_n + \frac{1}{6}(\varphi_1 + 2\varphi_2 + 2\varphi_3 + \varphi_4)(12)$$

In this paper, considering that temperature, rainfall and other conditions have a large impact on plant growth, we assume that the amplitude of seasonal fluctuations is 2, which represents the impact of different seasons on plant growth, with a period of 365 days and a phase shift of 0 (i.e., the change starts from January 1), then the seasonal variation function is:

$$g(t) = -2\cos(\frac{2\pi t}{365})(13)$$

By borrowing this function, it is possible to model the seasonal variation of the producer's growth cycle, in which peaks can be reached in the summer, followed by troughs in the winter, and a smoother period in the spring and fall.

2.2 Species Regression Models

In the ecosystem, there is a species return phenomenon, the species return phenomenon refers to the activity of a species to establish a new population in an endangered existing distribution area or an extinct historical distribution area, the phenomenon will cause an increase in the population size of the species, and at the same time, rewilding is also widely regarded as an important means of ecological conservation and restoration, so the study is important for ecological conservation and restoration [5]. In this paper, we assume that species regression exists for primary and secondary consumers, while producers are not considered for their species regression. In addition, we assume that the species regression function can be described by a linear function.

After considering the conditions for species regression, we make improvements to the original model. Primary consumer populations gradually return as habitats mature.

Then new herbivore population dynamics:

$$\frac{dF_3}{dt} = \eta_3 F_3 \left(1 - \frac{F_3}{M_3}\right) - \lambda_3 F_3 F_5 - \mu_1 F_3 - \nu_1 F_3 + R_3(t) + E(t)(14)$$

New insect population dynamics:

$$\frac{dF_4}{dt} = \eta_4 F_4 \left(1 - \frac{F_4}{M_4}\right) - \lambda_4 F_4 F_5 - \mu_2 F_4 - \nu_2 F_4 + R_4(t) + E(t)(15)$$

New primary consumer population dynamics:

$$\frac{dF_{primary}}{dt} = \frac{dF_3}{dt} + \frac{dF_4}{dt} \quad (16)$$

Where $E(t)$ is the marginal habitat benefit.

The relevant equation for $E(t)$ is:

$$\frac{dE(t)}{dt} = r(E_0 - E(t)) - d * E(t) \quad (17)$$

Where r is the efficiency of habitat restoration or expansion, E_0 is the maximum marginal benefit of the habitat, and d is the rate of decline in marginal benefit caused by external factors.

New sub-consumer population dynamics:

$$\frac{dF_5}{dt} = \eta_5 F_5 \left(1 - \frac{F_5}{M_5}\right) - \nu_3 F_5 + R_5(t) + E(t) \quad (18)$$

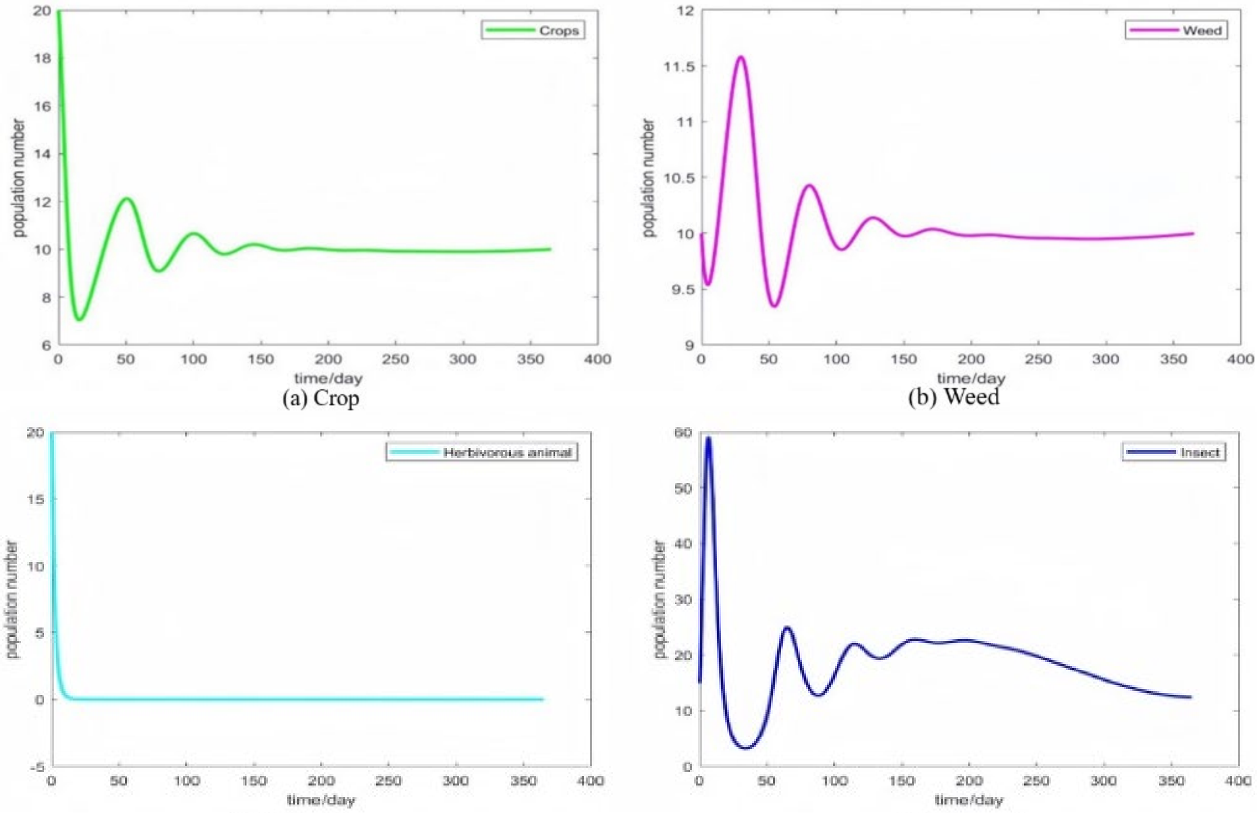
In this paper, considering that species reappearance rates are usually correlated with the degree of maturity of edge habitats, which is correlated with time, we assumed that the reappearance rate of species is linearly related to time for each species:

$$R_i(t) = \eta_i * F_i \ (i = 3,4,5) \quad (19)$$

By modeling the re-emergence of species as described above, we can study the changes in the populations of organisms in the ecosystem under the conditions of species regression under consideration.

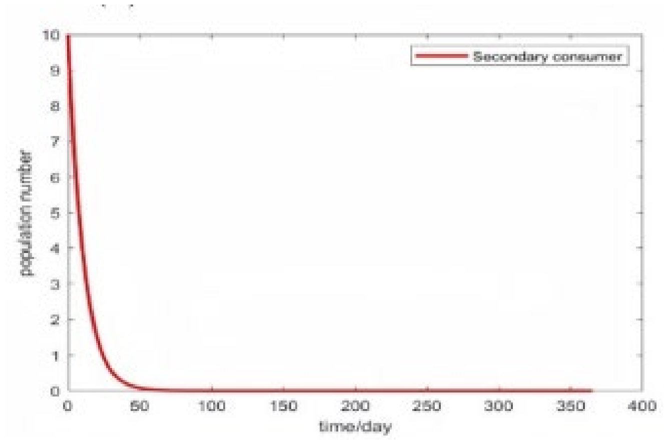
3. Results

For the other parameters in the model, we set each initial parameter in our model according to the relevant data of our selected area, and according to the calculation of the model, we get the Figure 2:



(a) Crop (b) Weed

(c) Herbivore (d) Insect



(e) Sub-consume

Figure 2 All population dynamics.

The crop population will decrease rapidly at the initial stage and will reach the lowest value of about 7.04 in about 14 days, this is due to the fact that our model takes into account the effect of seasonal factors, which leads to the decrease of the crop population. However, when the crop population decreases to a certain limit, there is an excess of resources, which leads to an increase in the crop population and finally to equilibrium.

Weed population also decreases in the initial period and it minimizes to about 9.68 in about 4 days. However, its decrease is less compared to the crop population and it starts to grow immediately afterward, which is because the weed population is more adapted to the conditions of low temperature and lack of water. Meanwhile, since our model takes into account the competitive relationship between weed populations and crop populations, an increase in weed populations will further lead to a decrease in crop populations. Finally, the weed population will also tend to equilibrate to about 9.99 or so, remaining relatively stable with the crop population.

Herbivores will show a large decrease in the initial period, which is due to the fact that our model takes into account the predatory relationship between the herbivore population and the crop population, and the weed population, and the large decrease in the latter leads to a lack of food. Eventually, the herbivores will be maintained at a low and stable level, reaching equilibrium at around 31 days, maintained at around 0.001.

The insect population will have a surge in the initial period, peaking at around 6 days, at around 59.00 or so, due to the relatively low demand of insects for food and their greater ability to acquire resources compared to herbivores. However, when the insect population grows, the amount of resources is insufficient, resulting in a decrease in the number of insect populations, reaching a minimum value of 3.27 in about 34 days, and eventually converging to a moderate level.

The secondary consumer population also shows a decrease in the initial period, but its decrease is slower than that of the herbivore population. The reason is that the decrease of herbivore population leads to the lack of food for the secondary consumer population, which leads to the decrease of the secondary consumer population. Eventually, the secondary consumer population maintains a low level, dropping to about 0.01 and equilibrating in about 70 days. The final stabilization of the population also represents a dynamic equilibrium in the predation relationship between the secondary consumers, herbivores and insects.

This paper considers the effects of species regression of primary and secondary consumers on the ecosystem. We follow the fourth-order Runge-Kutta method to solve the differential equations and obtain the Figure 3:

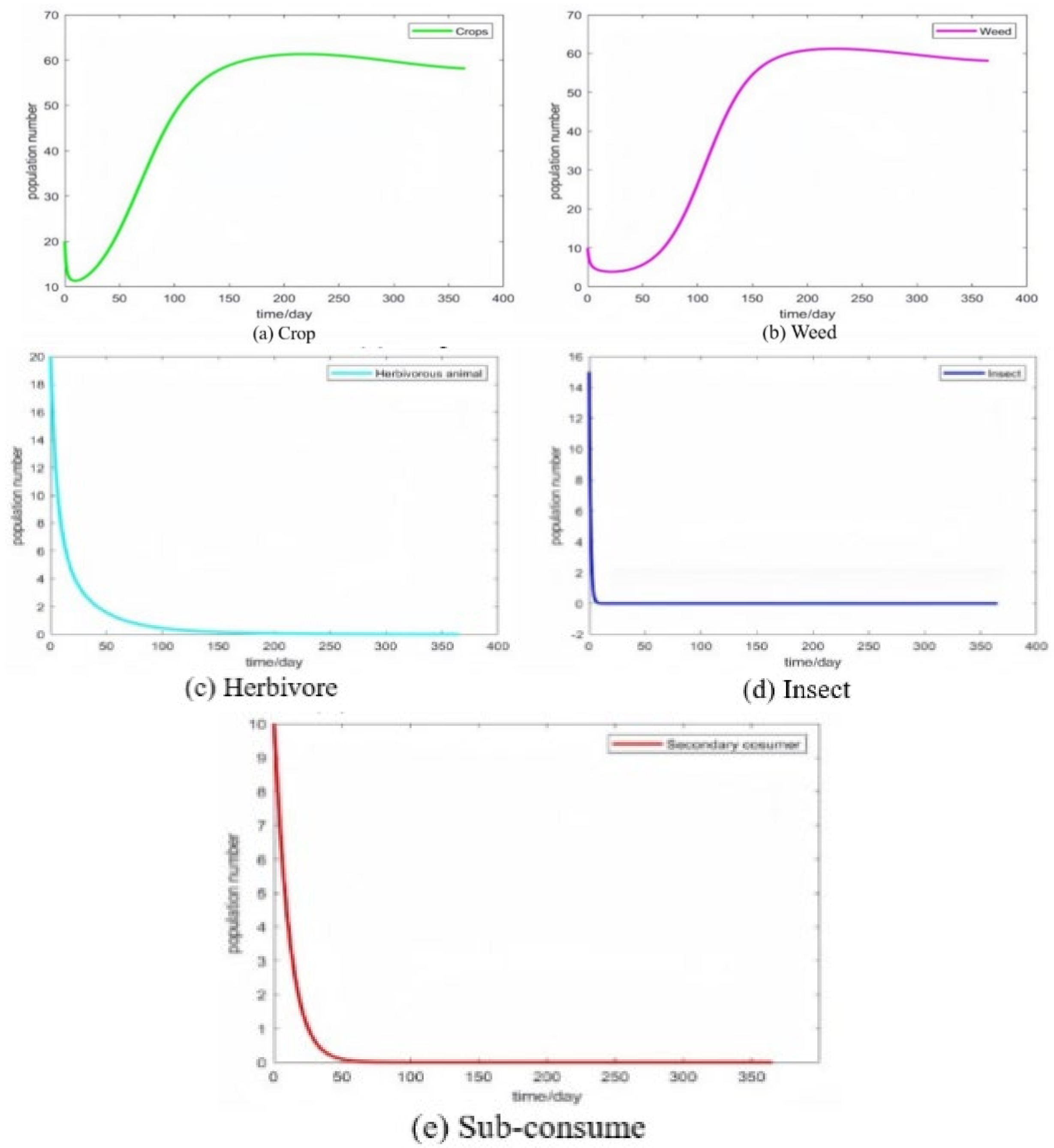


Figure 3 All population dynamics.

The crop population reaches its maximum value in 204 days, while the weed population reaches its maximum value in 212 days, and finally both of them decrease slowly, and both of them reach 57.88 and 58.17 in 362 days, respectively. This is because our model takes into account the species regression, and the decrease of herbivore population becomes slower, which leads to the decrease of the producer population.

Compared to the results of the first model, the insect population showed a significant decrease because our model considered the regression of species, which led to a slower decrease in herbivore and secondary consumer populations. On the 10th day, the insect population decreased to 0.007, and the decrease in the insect population also led to a food shortage in the secondary consumers, which also started to decrease.

After considering the maturation of marginal habitats over time after the return of species, which led to a greater stability of the ecosystem itself in our study, the populations of each species ended up staying within a stable range, where crop populations and weed populations were maintained in a relatively stable interval after 200 days, while herbivore populations, insect populations, and sub-consumer populations, respectively, were These data indicate that the ecosystem has reached a state of equilibrium, as the herbivore population, insect population, and secondary consumer population reached a steady state at 150, 7, and 55 days, respectively.

4. Conclusions and Future Work

This paper presents a comprehensive modeling-based investigation into the ecological implications of converting forest land into agricultural land and the potential of organic agriculture to restore and stabilize agro-ecosystems. By constructing a series of logistic-based models and applying the fourth-order Runge-Kutta numerical method, we simulated the dynamic interactions among producers, consumers, and environmental factors within various agricultural contexts. The results reveal that chemical inputs such as herbicides and pesticides significantly destabilize species populations, reduce biodiversity, and weaken the resilience of the agro-ecosystem. In contrast, scenarios involving the removal of chemical substances and the introduction of biological control mechanisms—such as bats, carnivorous birds, probiotics, and insecticidal bacteria—demonstrated marked improvements in ecosystem stability, restoration of insect populations, and enhanced biodiversity. Furthermore, the modeling framework effectively captures the influence of seasonal changes, population competition, and predator-prey dynamics, offering valuable insights into ecological outcomes under different agricultural strategies. These findings strongly support the feasibility of organic agriculture as a sustainable alternative that balances crop productivity with ecological integrity, and provide a data-driven basis for guiding agricultural planning and policy development.

Despite the robustness of our current modeling framework, there remain several avenues for future research to enhance its precision and applicability. One key direction is the incorporation of additional ecological and environmental variables such as soil nutrient cycles, decomposer dynamics, and the influence of extreme weather events, which could make the model more reflective of real-world agro-ecosystems. Integrating machine learning techniques, such as neural networks or reinforcement learning, could enable adaptive prediction and dynamic optimization based on empirical data streams. Moreover, validating the model against field data and expanding its scope to include economic and policy constraints would increase its utility in practical decision-making. Future studies may also extend the model to simulate regional or global agro-ecosystems under climate change scenarios, providing insights into large-scale ecological sustainability. By addressing these enhancements, the model can evolve into a powerful tool for supporting intelligent and sustainable agricultural development.

References

[1] Montemurro F, Persiani A, Diacono M. Organic vegetable crops managed with agro-ecological practices: Environmental sustainability assessment by DEXi-met decision support system[J]. Applied Sciences, 2019, 9(19): 4148.

[2] Rana R S. Agro-Ecosystems: An Assessment[J]. Indian Journal of Plant Genetic Resources, 2002, 15(1): 1-16.

[3] Kropff M J, Bouma J, Jones J W. Systems approaches for the design of sustainable agro-ecosystems[J]. Agricultural systems, 2001, 70(2-3): 369-393.

[4] Ukraintseva I V, Skvortsov V P, Dolzhikov V V, et al. Prospects and feasibility of involvement of fallow lands in organic agricultural production[C]//BIO Web of Conferences. EDP Sciences, 2025, 161: 00051.

[5] Panwar A S, Ansari M A, Ravisankar N, et al. Effect of organic farming on the restoration of soil quality, ecosystem services, and productivity in rice–wheat agro-ecosystems[J]. Frontiers in Environmental Science, 2022, 10: 972394.