

A Study on Farmland Ecosystems Based on the Logistic Growth Model and XGBoost Algorithm

Haochen Liu^{1,*}, Mingzhe Liu²

¹ College of Computer and Information Science & College of Software, Southwest University, Chongqing, China

² College of Information Science and Engineering, Qingdao Huanghai University, Qingdao, China

* Corresponding Author Email: 1847914486@qq.com

Abstract. This study focuses on the issue of chemical pesticide dependency in the transformation of agricultural ecosystems, using the logistic growth model and XGBoost algorithm as core analytical tools to construct a multi-dimensional model revealing ecosystem dynamics and the feasibility of organic agriculture. The agricultural food web model constructed based on the logistic growth model uses bats and birds as top consumers, covering the complete food chain structure from producers to tertiary consumers. By expanding plant, insect, bird, and bat populations, as well as a soil nutrient model, to systematically analyse the impact of herbicides and insecticides on biological populations and the predation and competition relationships between species. The study found that the use of chemical pesticides leads to a decline in the populations of various biological species and soil nutrient content, triggering fluctuations in ecosystem stability. Following validation of ecological restoration potential through species regression models, the study employs the XGBoost algorithm to construct a multi-objective optimisation model, with economic profit and ecological sustainability as core objectives, combined with constraints such as budget and yield, to provide farmers with a framework for assessing the feasibility of organic agriculture. The study aims to form a complete research loop from ecological mechanism analysis to production practice decision-making, providing theoretical and methodological support for addressing imbalances in farmland ecosystems.

Keywords: Logistic Growth Model, XGBoost algorithm, farmland ecosystem, chemical agent.

1. Introduction

As human civilisation advances, the large-scale conversion of forests into farmland has triggered profound changes in ecosystems [1-2]. This situation not only threatens the stability of farmland ecosystems but also poses challenges to sustainable agricultural development. This study uses the Logistic Growth Model and XGBoost algorithm as core analytical tools to construct a multi-dimensional model that reveals ecosystem dynamics and the feasibility of organic agriculture [3].

This study employs the logistic growth model, expanding a five-dimensional analytical framework encompassing plant, insect, bird, bat populations, and soil nutrients. It systematically investigates the direct/indirect impacts of herbicides and pesticides on various populations, seasonal variations, and predation-competition relationships. The findings reveal that chemical pesticide use leads to declines in population sizes of various biological groups and soil nutrient content, triggering fluctuations in ecosystem stability [4]. Furthermore, a species regression model was introduced to explore feasible pathways for ecological restoration. Based on this, an organic agriculture decision-making model was constructed using the XGBoost algorithm, integrating economic profit and ecological sustainability objectives to provide farmers with a framework for assessing the feasibility of organic agriculture [5]. The final research recommendation is to promote sustainable agricultural development through biological pest control, planting beneficial plants, and policy support, thereby achieving a logical closed loop from ecological mechanism analysis to production decision support.

2. Farmland Food Web Model

Drawing on the principles of the logistic growth model, this paper developed a comprehensive food web model for the farmland ecosystem. In the model, this paper focused on bat and bird populations as the apex consumers, deliberately omitting consideration for any higher trophic levels. This method focuses on the direct interactions within the ecosystem that are most relevant to the research. Food chain from bottom to top: producers (wheat, weeds), primary consumers (caterpillar, aphid, leech), secondary consumers (ladybug, spider), and tertiary consumers (sparrow, bat).

2.1. Logistic Growth Model

Logistic growth model (LGM) is a mathematical model commonly used to describe the process of resource-constrained growth in areas such as population growth, ecosystem evolution, and disease transmission. It shows exponential growth at the beginning, then due to resource or environmental constraints, the growth gradually slows down and eventually stabilizes. It is often used in biology to describe biological population growth.

$$\frac{dO}{dt} = r_o \left(1 - \frac{O}{K} \right) \quad (1)$$

Where O is the population size

Based on the logistic growth model, this paper developed five models for assessing ecosystem stability, taking into account predatory and competitive relationships between populations and the effects of herbicides and pesticides.

2.2. Five Extension Models Based on Logistic Model

2.2.1. Plant populations model

Due to the need to consider the impact of chemicals such as pesticides and herbicides, the Logistic growth model was modified in this paper. For plants, herbicides will kill weeds, so the corresponding plant populations will decline, so this paper have to subtract the effect of herbicides from the Logistic growth model. And insecticides will kill insects, but insects include beneficial insects and pests. As it is an agroecosystem, people will surely choose the insecticides that mainly kill pest. Therefore, this paper thinks that insecticides kill mainly pests, which make the number of plant populations go up, so this paper adds it on top of subtracting the effect of herbicides earlier. Considering that insects prey on plants, this paper is going to subtract the portion of the plant population that decreases due to insect pre- dation. And plant populations are cyclical and seasonal, so this paper has to add a seasonal change factor. Finally, the plant population model is expressed as:

$$\Delta P = \frac{dP}{dt} = r_p \left(1 - \frac{P}{K_p} \right) - \alpha_p PC_h + \beta_p \beta_I PC_p - \gamma_I I + S(t) \quad (2)$$

Where P is plant populations, r_p is natural growth rate of plants, which reflects the growth rate of plants under ideal conditions, K_p is environmental capacity of plants, which indicates the maximum carrying capacity of plants in a given environment, α_p is the coefficient of effect of herbicides on plants, β_p is indirect effect coefficient of insecticides on plants, γ_I is insect predation rate on plants. $S(t)$ is a seasonal variation factor.

$S(t)$ depicts a plant's periodic fluctuations (such as the distinct traits of the spring, summer, fall, and winter seasons), can be used to simulate the seasonal variation factor. The expression for a basic sine function is:

$$S(t) = A \sin \left(\frac{2\pi t}{T} + \varphi \right) \quad (3)$$

Where A is amplitude of seasonal fluctuations, indicating the intensity of seasonal variation, T is period, φ is phase offset, which determines the timing of seasonal fluctuations.

2.2.2. Insect populations

$$\Delta I = \frac{dI}{dt} = r_I \left(1 - \frac{I}{K_I} \right) - \alpha_I \alpha_P I C_h - \beta_I I C_p - \gamma_B B - \gamma_V V, \quad (4)$$

Where I represents the insect biomass, indicating the total number of insects per unit area; r_I is the natural growth rate of insects, reflecting their reproduction rate under ideal conditions; K_I is the environmental capacity of insects, representing the maximum carrying capacity of insects in a given environment; α_P is the direct effect coefficient of herbicides on plants; α_I is the indirect effect coefficient of herbicides on insects; β_I is the coefficient representing the impact of insecticides on insects; γ_B is the predation rate of birds on insects; and γ_V is the predation rate of bats on insects.

2.2.3. Bird populations

$$\Delta B = \frac{dB}{dt} = r_B \left(1 - \frac{B}{K_B} \right) - \alpha_B \alpha_I \alpha_P B C_h - \beta_B \beta_I B C_p - \varepsilon V, \quad (5)$$

Where B is bird biomass, which indicates the total number of birds per unit area, r_B is natural growth rate of birds, which reflects the rate at which birds reproduce under ideal conditions, K_B is environmental carrying capacity of insects, indicating the maximum carrying capacity of insects in a given environment, α_B is indirect impact factor of herbicides on birds, β_B is indirect effect coefficient of insecticides on birds.

2.2.4. Bat populations

$$\Delta V = \frac{dV}{dt} = r_V \left(1 - \frac{V}{K_V} \right) - \alpha_V \alpha_I \alpha_P V C_h - \beta_V \beta_I V C_p - \varepsilon B \quad (6)$$

Where V is bat biomass, which represents the total amount of bat species per unit area r_B is natural growth rate of bats, reflecting the rate of reproduction of bats under ideal conditions K_B is environmental carrying capacity of bats, indicating the maximum carrying capacity of bats in a given environment α_V is indirect impact factor of herbicides on bats β_V is indirect effect coefficient of insecticides on bats.

2.2.5. Solid nutrient

Soil nutrition is also an important part of assessing the stability of agroecosystems. For soil nutrition, both herbicides and pesticides have a direct impact on soil nutrition. The soil nutrition model can be expressed as:

$$\Delta S = \frac{dS}{dt} = r_S S - \alpha_S S C_h + \beta_S S C_p \quad (7)$$

Where S is soil area, r_S is soil nutrient natural recovery rate, α_S is herbicide impact factor on soil, β_S is insecticide impact factor on soil.

2.3. Solution of Differential Equations

Based on the initialized data, this paper calculated and drew images of their respective corresponding changes over a five-year period. As can be seen from Fig. 1, plant populations, insect populations, bird populations, bat populations, and soil nutrients are in decline after the use of chemicals such as herbicides and pesticides. That is, chemical use has a negative effect on plant health, insect populations, bat and bird populations. The use of chemicals affects the number of populations in the food web, and fluctuations in population size led to fluctuations in the stability of the ecosystem, so the use of chemicals can lead to ecosystem instability.

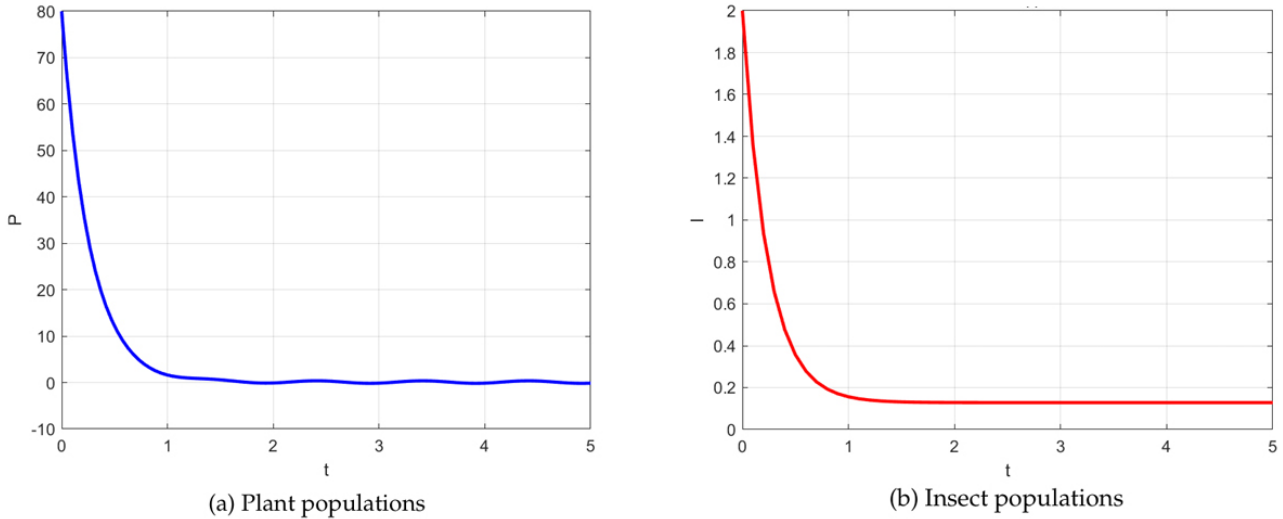


Fig. 1 Various ecological figures (using plants and insects as examples)

3. Species Regression Model

3.1. Model Construction

Species re-emergence rate functions are usually time dependent and in this paper are expressed as simple linear functions, i.e.:

$$R_i(t) = \delta_i \times N_i, \tag{8}$$

Where δ_i is species regression rate, N_i is number of species.

This paper chose two organisms to regress, microorganisms in the soil and birds. The regression of these two organisms leads to a change in the model this paper has developed above, as shown by the regression of the birds being a change in the rate of predation by birds on insects, which in turn leads to a change in the rate of predation by insects on plants, a change in the rate of competition between bird and bat populations, and a change in the rate of reversion of soil nutrients. The models are represented below after the change:

$$\begin{aligned} \Delta P &= \frac{dP}{dt} = r_p \left(1 - \frac{P}{K_p} \right) - \alpha_p P C_h + \beta_p \beta_I P C_p - \gamma'_I I + S(t) \\ \Delta I &= \frac{dI}{dt} = r_I \left(1 - \frac{I}{K_I} \right) - \alpha_I \alpha_p I C_h - \beta_I I C_p - \gamma'_B B - \gamma'_V V \\ \Delta V &= \frac{dV}{dt} = r_V \left(1 - \frac{V}{K_V} \right) - \alpha_V \alpha_I \alpha_p V C_h - \beta_V \beta_I V C_p - \varepsilon_B B \\ \Delta B &= \frac{dB}{dt} = r_B \left(1 - \frac{B}{K_B} \right) - \alpha_B \alpha_I \alpha_p B C_h - \beta_B \beta_I B C_p - \varepsilon_V V + R_B(t) \\ \Delta S &= \frac{dS}{dt} = r'_S S - \alpha'_S S C_h + \beta_S S C_p + R_S(t) \end{aligned} \tag{9}$$

This paper compares obtained results with those of the species not regressed as shown in Fig. 2:

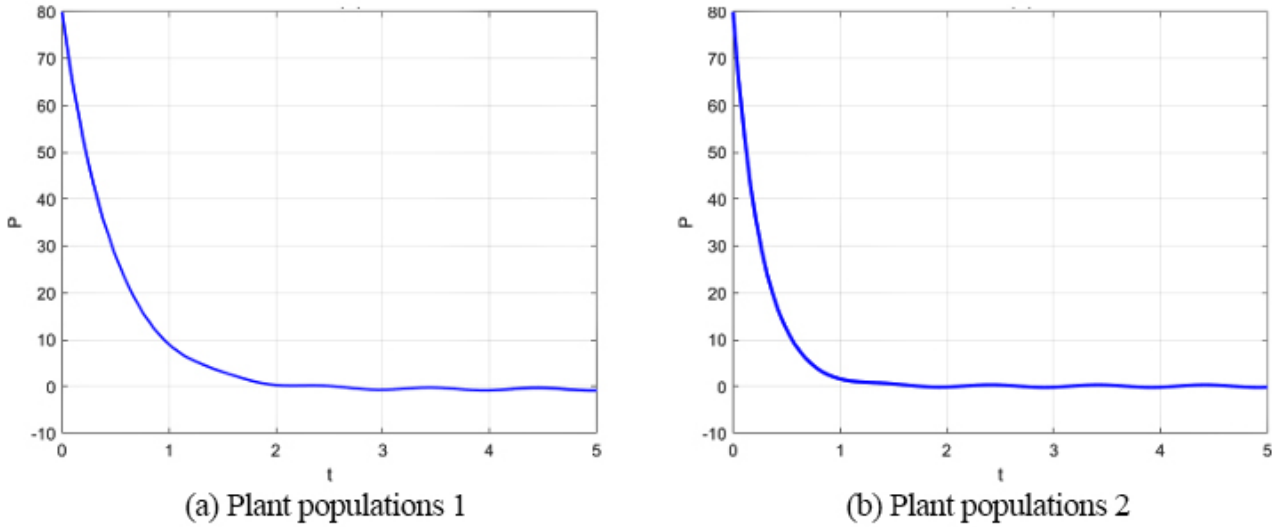


Fig. 2 The species regression-containing image and regression- free image (using plants as examples)

The species regression-containing image is at the front, while the species regression- free image is at the rear. The ecosystem is more stable following species regression, as evidenced by the slower declining trend of the image following species regression and the larger vertical coordinates of the stabilized points compared to the points without species regression.

3.2. Removal of Herbicide Effects

This paper has already discussed the effects of herbicides and pesticides on each population in detail in the models of the five populations established above, so here this paper only needs to delete the part about the effects of herbicides in the models of each population, and do not consider the nutrition of the soil samples in the models of the five populations this paper has established. The model changes are represented as follows:

$$\begin{aligned}
 \Delta P &= \frac{dP}{dt} = r_p \left(1 - \frac{P}{K_p} \right) + \beta_p \beta_I P C_p - \gamma_I I + S(t) \\
 \Delta I &= \frac{dI}{dt} = r_I \left(1 - \frac{I}{K_I} \right) - \beta_I I C_p - \gamma_B B - \gamma_V V \\
 \Delta B &= \frac{dB}{dt} = r_B \left(1 - \frac{B}{K_B} \right) - \beta_B \beta_I B C_p - \varepsilon V \\
 \Delta V &= \frac{dV}{dt} = r_V \left(1 - \frac{V}{K_V} \right) - \beta_V \beta_I V C_p - \varepsilon B
 \end{aligned}
 \tag{10}$$

Then this paper recalculates and conclude that the populations of producers and consumers showed an increasing trend after the removal of herbicides, demonstrating that herbicides have a negative impact on farmland ecosystems for both producers and consumers. The calculation results clearly show that the four populations of plants, insects, birds, and bats showed an increase after the removal of herbicides, and that this increase occurred at a high rate. In farming ecosystems, it is evident that herbicides have a detrimental impact on both producers and consumers. As a result, the future model will not take herbicides into account.

4. Organic Farming

XGBoost (Extreme Gradient Boosting) is an optimization algorithm based on Gradient Boosting Decision Tree (GBDT), which has become a very popular machine learning model in recent years by improving the performance of the algorithm [6].

4.1. Construct Target

1. Objective function

$$L(\theta) = \sum_{i=1}^n l(y_i, \hat{y}_i) + \sum_{k=1}^K \Omega(f_k), \quad (11)$$

Where $l(y_i, \hat{y}_i)$ is the loss function, which represents the error between the predicted value and the true value $\Omega(f_k)$ is the regularization term, which is used to penalize the complexity of the model and avoid overfitting.

2. Regularization term

$$\Omega(f_k) = \gamma T + \frac{1}{2} \lambda \sum_{j=1}^T w_j^2, \quad (12)$$

Where T is the number of leaf nodes of the tree, w_j is the weight of each leaf node, γ and λ are the hyperparameters of regularization.

3. Gradient update

$$f_{t+1}(x) = f_t(x) + \eta \cdot \delta f_t(x) \quad (13)$$

Where $f_t(x)$ is the hyperparameters of regularization, η is the learning rate, $\delta f_t(x)$ is the optimized increment of the first round.

Analyzing the effects of organic farming on agro-ecosystems and its possible effects on farmers' economic and sustainable development are important when determining whether or not farmers are implementing these practices. Pest management, crop health, plant reproduction, biodiversity, long-term sustainability, and cost-effectiveness are some of the elements that make up this problem. Therefore, evaluating the possible benefits of organic agriculture may be aided by creating objective functions and limitations for ecological and economic development.

Organic agriculture emphasizes the protection of ecosystems, including soil health, biodiversity and water conservation. In the long term, the sustainability of agriculture is an important factor in the objective function, i.e., to achieve ecological stability by reducing the use of chemical substances and increasing the resilience of land and ecosystems. So, the objective function can be expressed as:

$$\text{Maximize } Z = \omega \cdot \text{Profit} + \mu \cdot \text{Sustainability} \quad (14)$$

Where ω and μ are weighting factors to balance the relationship between economic efficiency and sustainability.

The economic benefits are mainly derived from the market price of the crop, the yield, and the cost of production. Specifically:

$$\text{Profit} = P_{\text{organic}} \cdot Y_{\text{organic}} - C_{\text{organic}} \quad (15)$$

Where P_{organic} is the market price of the organic crop, Y_{organic} is the yield of the organic crop, C_{organic} is the cost of producing the organic crop.

Sustainability mainly includes the following factors: Pest control: Organic farming methods use natural methods to control pests, which reduces environmental pollution and enhances the long-term resilience of agro-ecosystems compared to conventional chemical methods. Crop health: Organic farming reduces the use of chemical fertilizers and pesticides, which contributes to the long-term health of crops. Plant reproduction and biodiversity: Organic farming methods promote plant

diversity and natural crop reproduction by maintaining soil health and ecological balance. Land Sustainability: By avoiding the excessive use of chemicals and increasing the organic matter of the soil, it promotes the sustainable use of the soil. Thus, the sustainability objective can be expressed as follows:

$$Sustainability = f (Pest Control, Crop Health, Biodiversity, Soil Health) \quad (16)$$

Each of these factors (e.g., pest control, crop health, etc.) can be quantified based on its positive impact on the ecosystem.

4.2. Constraints

In the model, practical constraints need to be considered, and the following are possible constraints:

1. Budget constraint: Organic farming can be high in terms of initial investment, so the available capital of farmers is a constraint.

$$C_{organic} \leq B \quad (17)$$

Where $C_{organic}$ is the farmer's budget.

2. Crop yield constraints:

Organic farming may not be as productive as conventional farming; therefore, a yield floor needs to be set to ensure basic crop production.

$$Y_{organic} \geq Y_{min} \quad (18)$$

Where Y_{min} is the minimum yield that the farmer wishes to obtain.

3. Sustainability and ecological conservation constraints: Organic farming emphasizes soil health and biodiversity conservation, and therefore, there is a need to ensure that farming practices do not negatively impact ecosystems.

$$\begin{aligned} Biodiversity^2 &\geq Biodiversity_{min} \\ Soil\ Health^2 &\geq Soil\ Health_{min} \end{aligned} \quad (19)$$

4. Market demand constraints: Farmers must produce organic crops to meet market demand.

$$Y_{organic} \leq D_{max} \quad (20)$$

Where D_{max} is the largest market demand for organic crops.

5. Productivity constraints: Organic agriculture may face higher production costs and therefore needs to be optimized for cost efficiency.

$$\frac{C_{organic}}{\bar{Y}_{organic}} \leq \sigma \quad (21)$$

Where σ is the ratio of acceptable production cost to output.

Combining the objective function with the constraints, the final model can be integrated and represented as:

$$MaxZ = \omega \cdot (P_{organic} \cdot Y_{organic} - C_{organic}) + \mu \cdot f(PC, CH, BI, SH) \quad (22)$$

$$s.t. C_{organic} \leq B$$

$$Y_{organic} \geq Y_{min}$$

$$Biodiversity \geq Biodiversity_{min}$$

$$Soil\ Health \geq Soil\ Health_{min}$$

$$Y_{organic} \leq D_{max}$$

Where *PC* is Pest Control, *CH* is Crop Health, *BI* is Biodiversity, *SH* is Soil Health.

5. Summary

This study systematically reveals the evolutionary mechanisms of farmland ecosystems and the development path of organic agriculture through the cross-application of the Logistic growth model and the XGBoost algorithm. The study constructed a farmland food web model based on the logistic growth model, encompassing plant, insect, bird, bat populations, and soil nutrients, to quantitatively analyse the impact mechanisms of chemical pesticides on ecosystems. It confirmed that the use of chemical pesticides leads to a significant decline in the populations of various biological species and soil nutrient content, triggering fluctuations in ecosystem stability. After introducing a species regression model, ecosystem stability significantly improved compared to the non-regression state; further removing the impact of herbicides, population sizes of various groups showed a high-growth trend, fully validating the overall negative impact of chemical pesticides on farmland ecosystems and the restorative potential of biological regulation.

At the organic agriculture decision-making level, the study based on a multi-objective optimisation model constructed using XGBoost indicates that by balancing economic profits with ecological sustainability objectives, combined with constraints such as budget, yield, and ecological protection, the feasibility of implementing organic agriculture can be scientifically assessed. This study provides quantitative evidence and decision-making tools for understanding the ecological costs of chemical agriculture and exploring sustainable agricultural models. Future research could further integrate long-term field trial data to optimise the parameter system of organic agriculture models or explore adaptive adjustments to biological control strategies under climate change, providing more precise theoretical support for the sustainable management of farmland ecosystems.

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