

Ecological Mysteries: The Impact of Various Factors on Ecological Balance

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Abstract. "The earth does not belong to us, we belong to the earth" --Mary Matlin. In recent years, there has been a growing emphasis on the imperative of ecological conservation among humanity. This study seeks to model the ecological stability challenges associated with the shift from forested areas to agricultural lands. By employing mathematical modeling, it tracks species dynamics within the ecosystem and evaluates the effects of organic farming practices on ecological balance. In Task One, we have summarized the Dynamic Food Web (DFW) differential equation model by analyzing the impact relationships between species occupying different ecological niches. Initially, we simulate community changes over a one-year period to emphasize the seasonal effects on population variations within each community. Employing the fourth-order Runge-Kutta method, we derive the population curves for various species in the ecosystem throughout the year, thereby assessing the ecosystem's stability. Furthermore, to simulate the agricultural ecosystem over a longer duration, we extend the simulation time to 100 years and refine the model by excluding seasonal factors, enabling a more comprehensive evaluation of the ecosystem's stability. In Task Two, we reintroduce the trees and deer from the original forest ecosystem, eliminate the impacts of herbicides, accounted for more intricate factors related to bat influence, and introduce a new butterfly species. By considering the effects of various species' ecological niches on ecosystem stability, we derive the population curves for species over a 100-year time frame within the ecosystem. In Task Three, we establish seven sub-indicators across three evaluation criteria: economic benefits, environmental impacts, and technical feasibility. We assess four reasonable and reliable organic agricultural management methods and develop an organic agriculture evaluation model. Utilizing the AHP-EWM combined weighting method, we assigned weights to the seven indicators, which are then computed using the arithmetic mean, geometric mean, and eigenvalue methods, followed by normalization. Consequently, we obtain comprehensive scores for the four organic agricultural management schemes, with the highest score reaching 4.70. Finally, we conduct a sensitivity analysis on Model One. The results demonstrate that our model is robust and can offer a reliable reference for practical issues. Additionally, we systematically summarize and analyze the model's strengths and weaknesses. We also craft a letter to farmers engaged in organic agriculture, exploring strategies to augment economic benefits within the organic agricultural framework.

Keywords: Agroecosystems, Agricultural food web, seasonal, growth factors, Dynamic differential equations, AHP-EWM.

1. Introduction

1.1 Problem Background

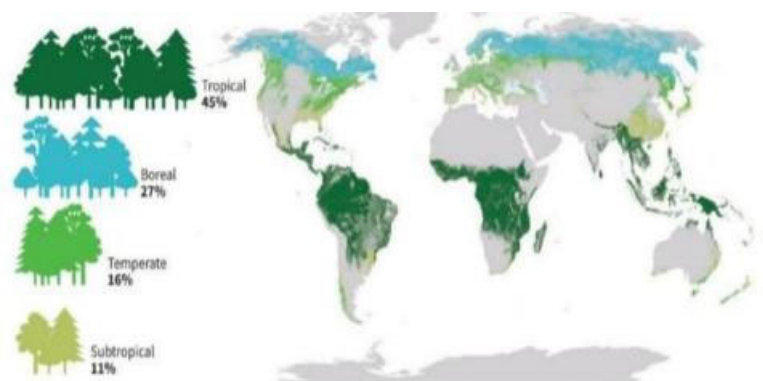


Fig.1 Proportion and distribution of the world's forest area in the field of climate, 2022^[1]

This study aims to simulate ecosystem transitions from forests to farmland through mathematical models, track species changes, and analyze the long-term impacts of agricultural management decisions on ecosystems. We will pay particular attention to the impact of herbicide and insecticide use on plant health, insect populations, bats and bird populations, and how these chemicals alter the balance of ecosystems. In addition, we will explore the advantages and challenges of organic farming, particularly in terms of pest control, crop health and biodiversity.

1.2 Restatement of the Problem

Considering the background information and restricted conditions identified in the problem statement, we need to solve the following problems:

Problem 1 : Establish a basic food web model

Establish a new agro-ecosystem that includes producers, consumers and decomposing agents, and consider seasonal changes and the effects of chemicals on ecosystem stability.

Problem 2 : Species reproduction

Over time, the former species gradually returned, and the two native species were introduced into the model to compare and analyze the effects of the introduction.

Problem 3 : Herbicide removal

As ecosystems mature, farmers try to reduce their dependence on chemicals. Report on ecosystem stability after herbicide removal from both consumer and producer perspectives.

Problem 4 : Restoration of ecosystem balance

Analyze the impact of bats on the ecosystem as insectivores and pollinators, and analyze the impact of another species on the ecosystem for comparison.

Problem 5 : Organic agriculture

Consider aspects such as crop health, pest control, biodiversity, long-term sustainability and cost-effectiveness to explore the impact of organic agriculture on ecosystems and their components.

1.3 Our Work

We establish a dynamic food web differential equation model to explore the equilibrium issues of agricultural ecosystems under the influence of different species interactions. By improving the differential equations, we simulate the dynamic balance of agricultural ecosystems under the influence of various factors. We also analyze optimal management models for farmland within the organic farming evaluation model, and our specific work is illustrated in the figure below:

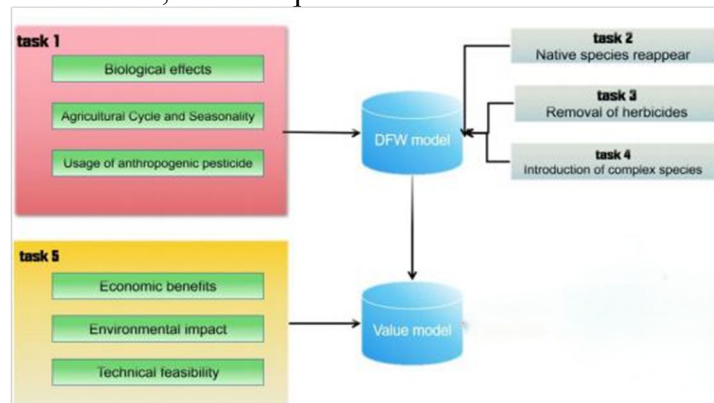


Fig.2 The technical route of our thesis creation

2. Assumptions and Justifications

In order to simplify the given problem and make it more suitable for simulating real-life conditions, we made the following basic assumptions, each of which is reasonable.

Assumption 1: The ecosystem is relatively balanced.

Justification: Ensure that there is no significant change in the indicators of the ecosystem due to potential factors such as species migration and plagues, i.e.

Assumption 2: Linear relationship assumptions:

Justification: Interactions between species (e.g., predation, competition), growth rates, mortality rates, and can be described by linear equations.

Assumption 3: The effects of herbicides and insecticides are instantaneous, and the effects are uniform.

Justification: Simplifying the complex impacts of chemicals on ecosystems makes it easier to analyze their direct effects, especially in the short term, on pest populations and plant health.

3. Notations

The key mathematical notations used in this paper are listed in Table 1.

Table 1: Notations used in this paper

Symbol	Description
r	Plant intrinsic growth rate
KP	Maximum carrying capacity of plants
c	Influence coefficient of insect predation on plants
I	Number of insects
P	Population of producers
A	Number of birds
B	Number of bats
D	Number of decomposers
N	Number of native returning species
C	Herbicide concentration factor
S	Insecticide concentration factor
DE	Mortality rate of species
L	Population of deer
a	Competition coefficient between plants and returning species

4. Dynamic food web differential equation model (DFW Model)

Agricultural ecosystems and forest ecosystems exhibit significant differences in food chains and energy cycles. As ecosystems transition from forest to agricultural systems, species composition within the ecosystem changes, affecting energy cycles and ecological stability, while also impacting the environment. Furthermore, human activities, such as the use of herbicides and insecticides, alter the nutrient cycling and energy transfer within agricultural ecosystems. Thus, this study will consider the entire farmland ecosystem as a research object and develop a dynamic food web differential equation model to analyze the impact of various conditions on ecological stability.

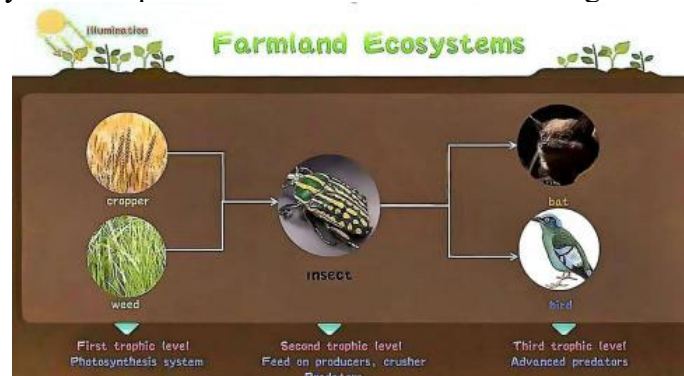


Fig.3 Food web diagram of a farmland ecosystem

4.1 Data Collection

To establish this dynamic food web, we collect information on the types of producers, primarily crops, and their annual yields per acre, as well as the types and population densities of primary consumers, mainly insects. We also explore the impacts of precipitation levels, temperature, and crop growth cycle values. Additionally, we gather data on the annual usage levels and frequencies of herbicides and insecticides in the United States. Table 2 lists the sources of the data collected.

Table 2: Data Sources

Database Names	Data Websites
FAOSTAT	https://www.fao.org/faostat/zh/#data/QI
GBIF	https://www.gbif.org/occurrence/search
Climate Data Online	https://www.ncdc.noaa.gov/cdo-web/
NASA Earth Data	https://www.earthdata.nasa.gov

Figure 4 shows the visualization curve of annual herbicide usage levels in the United States from 1990 to 2022.

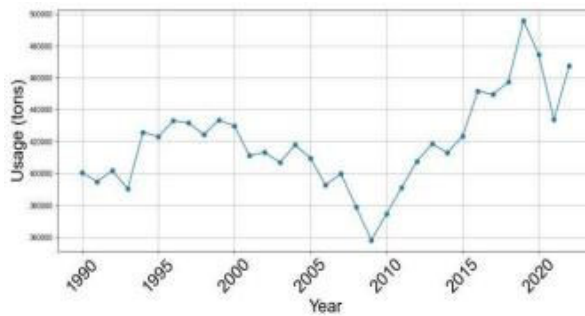


Fig.4 Annual pesticide use in the United States

4.2 Establishment of the DFW model

To construct a food web model for the new agricultural ecosystem, we need to consider producers, consumers and various external factors including the use of herbicides and insecticides as well as seasonal changes.

To tackle this issue, we utilize dynamic differential equations to simulate the dynamic changes in the populations of these organisms. Different species occupy distinct ecological niches within the ecosystem, leading to population changes influenced by various factors.

(1) Producer (Plant) Growth Model

Crops and weeds in farmland are at the first trophic level. The growth of plants is influenced by natural growth and predation from the next trophic level, while seasonal periodic factors also impact plant growth. Additionally, the number of weeds is affected by herbicide concentration. Thus, we derive the differential equation for crop population:

$$\frac{dP}{dt} = r \cdot G(t) \cdot P \left(1 - \frac{P}{K} \right) - cPI - PC \tag{1}$$

Where: r is the inherent growth rate of plants, K is the maximum carrying capacity of plants, c is the predation impact coefficient on plants by the next trophic level, I is the number of the next trophic level, C indicates the usage of herbicides, varying over time. For crops, C equals 0, while for weeds, C equals 1.

(2) Primary Predators (Insects) Population Change Equation

This paper only considers insects as primary predators in the agricultural ecosystem to make it simple. Crops serve as food sources for insects, and their numbers depend on the quantity of crops. Due to the energy flow and material transfer in the food chain, herbicides can leave residues in insects. Birds and bats feed on insects, influencing their populations

$$\frac{dI}{dt} = \alpha_1 I \left(1 - \frac{I}{K_1} \right) - \gamma I - \beta_1 I B - \beta_2 I A - S I \tag{2}$$

Where: α_1 represents the growth rate of insects, γ indicates the natural death rate of pests, β are predation coefficients for bats and birds, respectively, S denotes the impact factor of insecticides.

(3) Bat Population Change Equation: Insects serve as a food source for bats, and bats act as secondary predators and are at the highest trophic level. The enrichment of nutrients in the food chain causes significant residues of herbicides and insecticides to occur within the bat population, greatly affecting their numbers

$$\frac{dB}{dt} = \alpha_2 I B - \delta \cdot D(t) \cdot B \tag{3}$$

Where, α_2 is the reproduction rate of bats, and δ indicates the mortality rate of bats, while $D(t) = 0.5 \cdot (1 + \sin(2\pi/12))$ represents seasonal effects on bat mortality.

(4) Bird Population Change Equation: In the agricultural ecosystem, birds share similar ecological niches with bats.

$$\frac{dA}{dt} = \alpha_3 I A - \epsilon \cdot D(t) \cdot A \tag{4}$$

Where, α_3 is the growth rate for birds. ϵ is the natural mortality rate for birds. $D(t)$ indicates seasonal effects on bird mortality.

(5) Pesticide (Herbicide and Insecticide) Efficacy Equation: Research indicates that after the usage of pesticides, the efficacy level follows an exponential relationship over a certain period.

$$(\text{pesticides}) = e^{-\left(\frac{t-t_0}{\sigma}\right)^2} \tag{5}$$

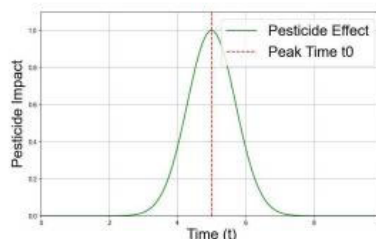


Fig.5 The degree of pesticide influence changes over time.

(6) The equation for the variation in decomposer populations

The presence of decomposers in the ecosystem contributes to the maintenance of the structure and functional integrity of the ecosystem. Through the process of decomposition, they enable the proper cycling of materials and energy within the ecosystem. This ensures a balance among producers, consumers, and decomposers.

$$\frac{dD}{dt} = \theta_1 \cdot (P+I+B+A) - \theta_2 \cdot D \tag{6}$$

Where, θ_1 represents the influence coefficient of decomposers acquiring nutrients through the death of producers and consumers. θ_2 denotes the natural mortality rate of decomposers.

4.3 Results Presentation

We carry out seasonal simulations of the changes in the ecosystem, setting the simulation time to one year to fully reflect the role of seasonal growth factors, which used the fourth-order Runge-Kutta method to be calculate.

To simulate the changes in this agricultural system over a longer period, we set the simulation time to 100 years, and the effects of seasonal factors can be considered negligible on this scale.

In summary, we update the dynamic food web differential equations as follows:

$$\begin{cases} \frac{dP}{dt} = rP \left(1 - \frac{P}{K}\right) - cPI - PC \\ \frac{dI}{dt} = a_1 I \left(1 - \frac{I}{K_1}\right) - \gamma I - \beta_1 IB - \beta_2 IA - SI \\ \frac{dB}{dt} = a_2 IB - \delta B \\ \frac{dA}{dt} = a_3 IA - \epsilon A \\ (\text{pesticides}) = e^{-\left(\frac{t-t_0}{\sigma}\right)^2} \\ \frac{dD}{dt} = \theta_1 \cdot (P + I + B + A) - \theta_2 \cdot D \end{cases}$$

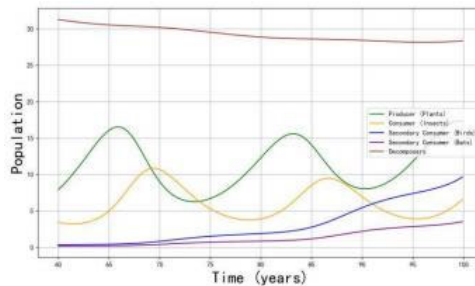


Fig.6 Agricultural food web dynamics

As illustrated in the figure 6, the quantities of plants and insects fluctuate in a dynamic equilibrium, and due to the direct predation of insects on plants, the population curve of insects exhibits a lag effect. The populations of birds and bats show a slow upward trend, while the population of decomposers slightly declines and tends to stabilize.

Within the time frame specified by the model, the agricultural ecosystem has maintained a relatively stable dynamic equilibrium. Hence, we can conclude that the stability of this agricultural ecosystem is reliable.

5. Species Reintroduction and Impact of Human Agents on DFW model

Once the agricultural ecosystem reaches stability, we implement a series of measures to update it. This includes reintroducing native species, changing anthropogenic factors, and introducing complex ecological niche species. Below, we outline the model's establishment.

5.1 Food Web Model after Reintroducing Native Species



Fig.7 Schematic diagram of the model

Trees, as first-level producers, intensify the competition among the producers. Deer feed on trees, and their population numbers are related to the population of trees. They also lead to the population dynamics of decomposers.

(1) Population Equation of Trees: The introduction of trees affects the population densities of crops and weeds as well as being affected by the deer population.

$$\frac{dT}{dt} = r_T T \left(1 - \frac{T}{K_T} - \frac{a_{TP} P}{K_T}\right) - a_4 TL \tag{7}$$

Where, r_T is the growth rate of trees. K_T is the maximum environmental carrying capacity for trees. α_{TP} is the competition coefficient of crops and weeds against trees. P is the number of plants

(2) Population Number Equation of Deer: Deer are herbivores feeding on trees, and the number of deer is directly determined by the number of trees.

$$\frac{dL}{dt} = \beta_3 TL - DE_L \tag{8}$$

Where DE_L represents the death rate of deer.

(3) Updated Decomposer Equation: The existence of trees and deer alters the population of decomposers. The updated decomposer numbers are influenced by the populations of crops, weeds, trees, birds, bats, insects, and deer.

$$\frac{dD}{dt} = DE(P+I+L+A+B+T) - d_D D \tag{9}$$

(4) Updated Crop and Weed Equations: These are primarily affected by tree competition.

$$\frac{dP}{dt} = r_P P \left(1 - \frac{P}{K_P} - \frac{\alpha_{PT}}{K_P} T \right) - cPI - \alpha_1 PC + D d_D \tag{10}$$

Where, r_P is the growth rate of plants. K_P is the maximum environmental carrying capacity of plants. α_{TP} is the competition coefficient between plants and trees.

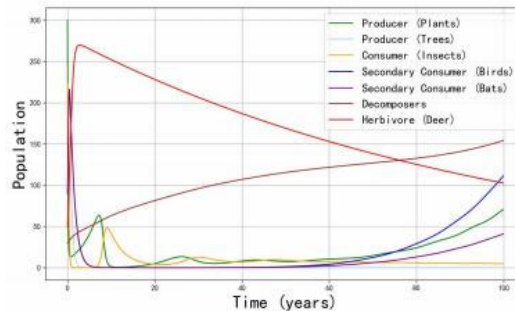


Fig.8 Agricultural food web dynamics with decomposers and new species

As shown in Figure 8 after introducing native species (trees and deer) and performed a visualization. It can be observed that after experiencing a short period of species outbreak, the population of deer shows a downward trend, while the populations of birds and decomposers exhibit an upward trend. The populations of other species remain at a certain dynamic equilibrium.

5.2 Analysis of the Ecosystem After Human Removal of Herbicides

When an agricultural ecosystem reaches stability, the use of herbicides an unnecessary variable. Therefore, for this balanced agricultural ecosystem, we eliminate the use of herbicides in order to model and analyze the new ecosystem.

Below is our reconstruction of the model's varying components:

(1) The differential equation for the population of producers is as follows: The population of producers is directly influenced by the use of herbicides.

$$\frac{dP}{dt} = r_P P \left(1 - \frac{P}{K_P} - \frac{\alpha_{PT}}{K_P} T \right) - cPI + d_D D \tag{11}$$

In this context, r_P represents the growth rate of plants. K_P is the maximum environmental carrying capacity for plants. α_{PT} is the competition coefficient of trees against plants. d_D denotes the impact coefficient of decomposers on plants. c is the herbivory coefficient of insects.

(2) Differential Equation for Insect Population: The removal of herbicides has also altered the interaction relationship between pests and crops.

$$\frac{dI}{dt} = r_I I \left(1 - \frac{I}{K_I} \right) + cPI - \beta_1 IN - \beta_2 IA \tag{12}$$

In this context, r_I represents the growth rate of insects. K_I is the maximum environmental carrying capacity for insects. β_1 is the predation coefficient of bats. β_2 is the predation coefficient of birds.

(3)Differential Equation for Bird Population:

$$\frac{dA}{dt} = \alpha_A I A - \epsilon A \tag{13}$$

Where, α_A is the growth coefficient of birds predated on insects. ϵ is the natural mortality rate of birds.

Figure 9 has two graph, the upper graph records the variations in species populations over a 100-year period, while the lower graph reflects the population changes during the initial 20 years, over the initial 20-year time scale, the agricultural ecosystem exhibits complex trends. In the longer time scale from year 20 to year 100, the population curves of various species (excluding trees and decomposers) display a dynamic equilibrium trend with fluctuations.

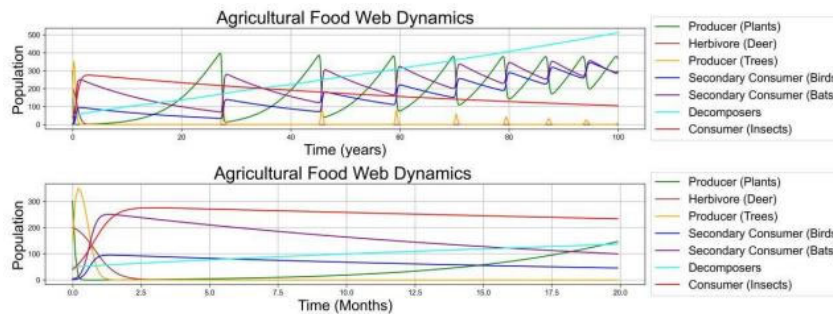


Fig.9 Agricultural food web dynamics(without pesticides)

5.3 Introduction of Species with Complex Ecological Niches

Given the diversity of bat species, we consider the roles of different bat species in the agricultural ecosystem, including their function as secondary predators capturing insects, as well as the ecological niche introduced by a new species, butterflies. The model is improved as follows:

(1) Differential Equation for Plant Population:

$$\frac{dP}{dt} = r_p P \left(1 - \frac{P}{K_p}\right) + (b_1 B I + \rho H) - c P I + d_D D \tag{14}$$

. r_p : natural growth rate of plants . K_p : maximum environmental carrying capacity for plants . b_1 : influence coefficient of bats on plants (bats preying on insects) . ρ : influence coefficient of butterflies on plants (pollination) . c : insect predation efficiency . d_D : impact coefficient of decomposers on plants (from organic and inorganic matter)

(2) Differential Equation for Insect Population:

$$\frac{dI}{dt} = \alpha_1 P I - \gamma I - (b_1 I B + b_2 I A) \tag{15}$$

. α_1 : growth rate of insects . γ : mortality rate of insects . b_2 : predation efficiency of birds on insects

(3) Differential Equation for Insect Population:

$$\frac{dB}{dt} = \alpha_2 B I - \delta B \tag{16}$$

. α_2 : growth rate of insects . δ : mortality rate of insects

(4)Differential Equation for Bat Population:

$$\frac{dA}{dt} = \alpha_3 A I - \epsilon A \tag{17}$$

. α_3 :growth rate of bats . ϵ : mortality rate of bats

(5)Differential Equation for Decomposer Population:

$$\frac{dD}{dt} = d_N (P + I + B + A) - d_D D \tag{18}$$

. d_N : nutrient coefficient for decomposers captured from organic matter . d_D : mortality rate of decomposers

(6)Differential Equation for Butterfly Population:

$$\frac{dH}{dt} = \rho PH - d_H H \tag{19}$$

. ρ : the growth rate of butterflies . d_H : the mortality rate of butterflies

By solving these differential equations, we have obtained the population dynamics of various species in the agricultural ecosystem, The resulting population change curves are illustrated in Figure 10.

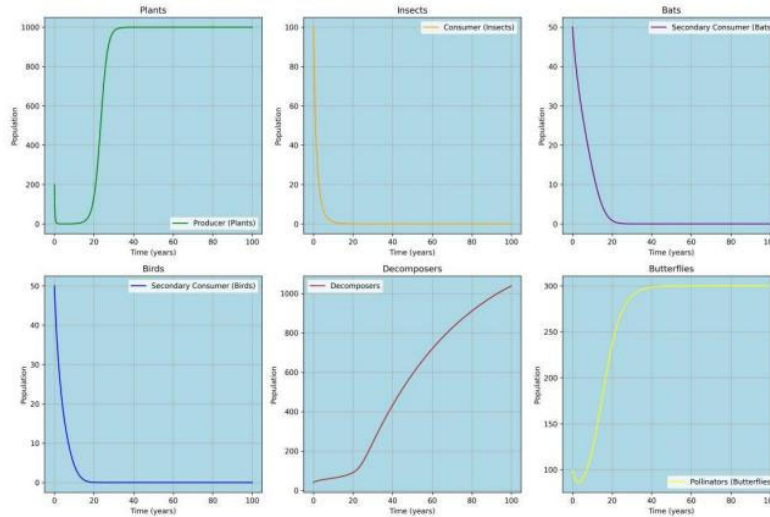


Fig.10 Impact of Bats and Butterflies on Food Web Dynamics (Smoothed)

6. Organic Agriculture Evaluation Model

6.1 The AHP-EWM integrated evaluation model

We have established an agricultural ecosystem evaluation model and selected three primary indicators (economic benefits, environmental impact, and technical feasibility) and seven secondary indicators. Additionally, we avoid selecting many unrelated indicators, which allow for better mechanistic analysis of the impact of each indicator.

The established hierarchical structure model is shown in Figure 11:

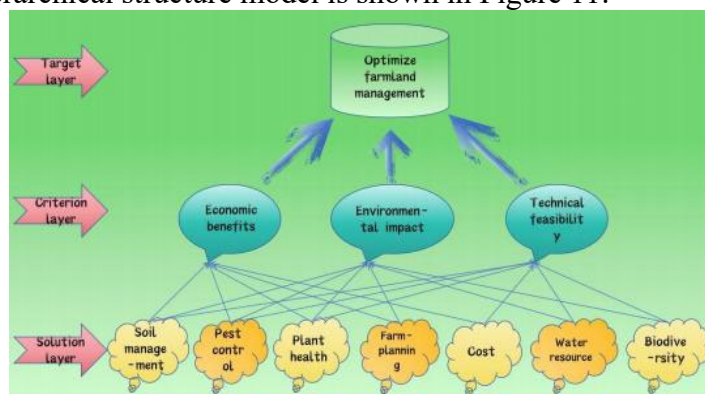


Fig.11 Hierarchical structure model

6.2 The Solution Of the Model

In order to explore more reasonable and effective farmland management practices, we selected four reliable farmland management methods. We obtain data on various indicators under different management practices, with each method placing different emphases on secondary indicators. After standardizing and normalizing the data, the proportions of each indicator for the four management methods are shown in Table 3:

Table.3 The index weight of the four management styles

Index	style 1	style 2	style 3	style 4
Soil management	0.1905	0.2000	0.2143	0.2273
Pest control	0.1667	0.1714	0.1785	0.1818
Plant health	0.1429	0.1429	0.1429	0.1364
Farm-planning	0.2143	0.2286	0.2500	0.2727
Cost	0.1190	0.1143	0.1071	0.0909
Water resource management	0.0952	0.0857	0.0714	0.0455
Biodiversity	0.0714	0.0571	0.0357	0.0455

For this matrix, we conduct a consistency check by calculating the consistency index (CI) and the consistency ratio (CR), with the formulas as follows:

Consistency Index (CI):

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{20}$$

λ_{max} is the maximum eigenvalue among them Consistency Ratio (CR):

$$CR = \frac{CI}{RI} \tag{21}$$

Among them, RI is a consistency indicator obtained from Table 4.

Table 4 Average Random Consistency Index (RI)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.52	0.89	1.12	1.26	1.36	1.41	1.46	1.49

Through calculations, we obtain $CR=0.05713 < 0.1$, indicating that the consistency test has passed. We then calculate the weights using the arithmetic mean method.

Geometric Mean Method for Weight Calculation:

$$\omega_i = \frac{1}{n} \sum_{j=1}^n \frac{a_{ij}}{\sum_{k=1}^n a_{kj}} \quad (i=1,2,3\dots n) \tag{22}$$

Where ω_i represents the weight of each indicator

Eigenvalue method for determining weights:

$$\omega_i = \frac{\left(\prod_{j=1}^n a_{ij} \right)^{\frac{1}{n}}}{\sum_{k=1}^n \left(\prod_{j=1}^n a_{kj} \right)^{\frac{1}{n}}} \tag{23}$$

Calculate the maximum eigenvalue of the matrix and its corresponding eigenvector, then normalize the obtained eigenvector.

The weights of each indicator are obtained using both the AHP and EWM methods, and the comprehensive weights are derived using the following formula:

$$\omega^* = \frac{\sqrt{\omega_{ik} \omega_{jk}}}{\sum_{l=1}^m \sqrt{\omega_{jl} \omega_{il}}} \tag{24}$$

The weight table obtained using the AHP method and the EWM method, combined in the AHP-EWM weighting method, is shown in Table 5.

Table 5 Weight

	AHP	EWM	AHP-EWM
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Soil management	0.0706	0.0420	0.0568
Pest control	0.1718	0.0603	0.1161
Plant health	0.0483	0.0906	0.0694
Farm-planning	0.0247	0.0322	0.0284
Cost	0.0973	0.1516	0.1245
Water resource management	0.3325	0.3070	0.3198
Biodiversity	0.2546	0.3152	0.2850

6.3 Optimal Management Strategies for Agricultural Land

The comprehensive scores for each management approach are shown in the figure below. From the graph, it can be seen that Management Approach 1 can achieve a high level of farmland management, resulting in significant ecological and economic benefits.

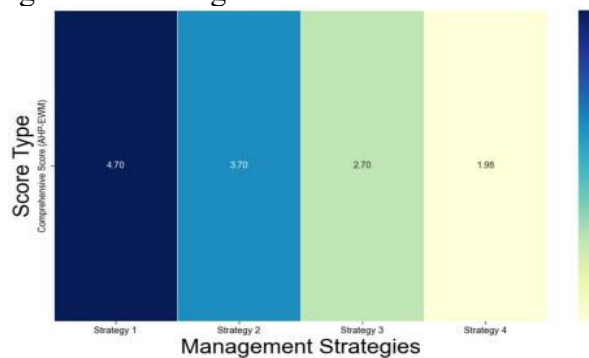


Fig.12 Heatmap of Management Strategies Scores

7. Sensitivity Analysis

In the dynamic differential equation model we constructed, there are multiple parameters, necessitating sensitivity analysis. We select a key parameter: the maximum carrying capacity of the plants (K). The results of the sensitivity analysis indicate that our model demonstrates good stability.

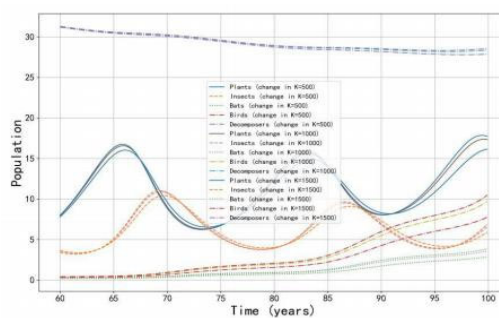


Fig.13 Population density curves for the maximum carrying capacity of the plants

From the figure 13, it can be observed that our model is quite stable and can be further expanded. Additionally, this model can be applied in reality and provide effective references for practical situations.

8. Model Evaluation and Further Discussion

8.1 Strengths

1.For Model One (the dynamic food web differential equation model), it can clearly describe the changes in the system over time, making it suitable for addressing non-equilibrium issues.

Additionally, dynamic differential equations can integrate multiple variables and their interactions, making them suitable for simulating the complex agricultural ecosystem environment in this study.

2.For Model Two (the organic agriculture evaluation model), we employed the AHP-EWM method, which combines weighting method offers the flexibility of subjective weighting and the impartiality of objective weighting, resulting in more robust weights.

8.2 Weaknesses

1.For Model One, the system's sensitivity to initial conditions can lead to different outcomes.

2.For Model Two,the AHP method can only find the best solution from existing solutions and cannot provide new solutions.

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