A Species Population Iteration Model-Based Study on Ecosystem Stability and Sustainable Agriculture During Forest-to-Farmland Transition

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Abstract. Deforestation for agriculture disrupts ecological balance, leading to biodiversity loss and pest invasions. To address this, we establish four models to analyze the transition from forest to farmland and propose sustainable farming practices. The Food Web Model depicts inter-species relationships post-deforestation. The Species Population Iteration Model, based on the Lotka-Volterra Equations, simulates species dynamics considering agricultural cycles and chemical influences. The Stability Evaluation Model, using AHP, quantifies the impact of species interactions and chemical use. The Economy and Sustainability Integrated Model, employing Multi-Objective Optimization, balances ecological sustainability and economic performance. Results show that introducing *Vicia sepium* and magpies reduces vermin populations without affecting wheat yield. Bats further stabilize the ecosystem, increasing wheat production by 37.5%. Removing pesticides and herbicides allows the system to achieve organic equilibrium, optimizing sustainability with a function value of 64.56. Sensitivity analysis confirms the robustness of our model. While our approach provides valuable insights, future research should consider population structures and long-term biodiversity metrics for improved predictions.

Keywords: Lotka-Volterra Equations, inter-species relationships, organic farming, Multi-Objective Optimization.

1. Introduction

Forests play a crucial role in maintaining global biodiversity, regulating climate, and providing ecosystem services. However, large-scale deforestation for agriculture leads to severe ecological consequences, including soil degradation, loss of biodiversity, and pest invasions. The removal of forests disrupts existing food webs, altering species population dynamics and threatening long-term ecosystem stability.

One major challenge in agricultural expansion is finding a sustainable approach that minimizes ecological damage while maintaining economic viability. Traditional farming methods often rely heavily on pesticides and herbicides, which can further destabilize ecosystems by affecting species interactions. Therefore, it is essential to develop a scientific framework that models ecosystem changes, evaluates stability, and proposes optimized agricultural strategies that balance productivity and sustainability [1].

This study addresses these challenges by constructing a series of models to analyze the transition from forest to farmland. We incorporate species interactions, seasonal effects, and chemical influences to simulate population dynamics and optimize farming practices for ecological restoration.

According to current research, models for calculating the changes in species population over time in an ecosystem can be primarily classified into population dynamics models and ecosystem process models. The population dynamics models include the Lotka-Volterra equations [2], population growth model [3], and multi-species dynamics model [4]. The ecosystem process models mainly include the metacommunity model [5] and ecological network model [6].

This paper makes the following key contributions:

1. Ecosystem Transition Modeling: We establish a Food Web Model to depict species interactions after deforestation and track population changes.

2. Species Population Simulation: A Species Population Iteration Model based on the Lotka-Volterra Equations is developed to simulate species population dynamics under agricultural cycles.

3. Ecosystem Stability Evaluation: We introduce an AHP-based Stability Evaluation Model to quantify the impact of species interactions and chemical usage on ecosystem stability.

4. Sustainable Farming Optimization: A Multi-Objective Optimization Model is applied to balance ecological sustainability with economic performance, identifying optimal organic farming strategies.

By integrating ecological and economic factors, this study provides insights into sustainable agriculture, offering a data-driven approach to mitigate the environmental impacts of deforestation while ensuring food security.

2. Methodology

Some commonly used symbols are in Table.1.

Table 1. Description of symbols.

Symbol	Description
N_i	Number of the i-th species
r_i	Growth coefficient of the i-th species
K_i	Environmental holding capacity of the i-th species
α_{ij}	Competition coefficient of the j-th species for the i-th species
e_i	Attraction coefficient of the i-th species
a_i	Predation coefficient of the i-th species

The overall flowchart is displayed in Figure 1:

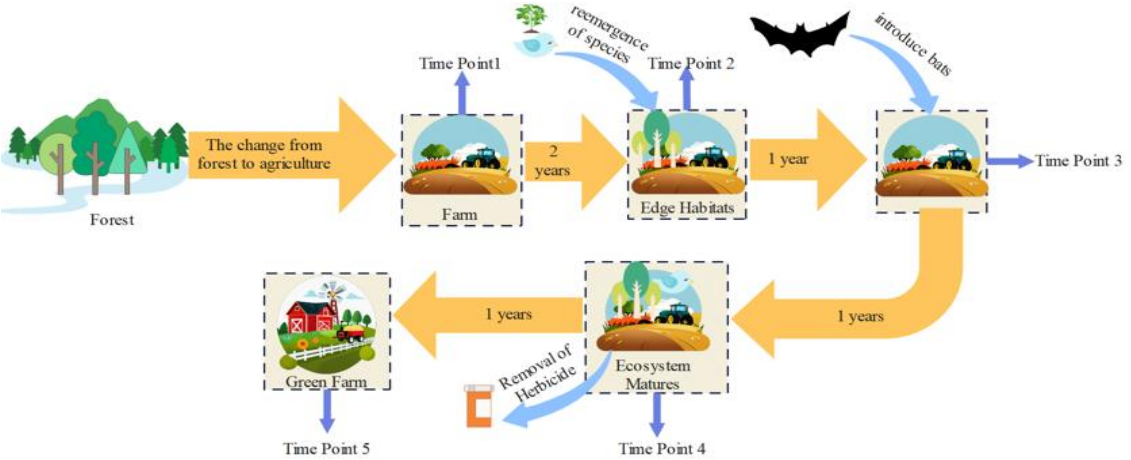

Figure 1. Overall flowchart

Our work is displayed in Figure 2:

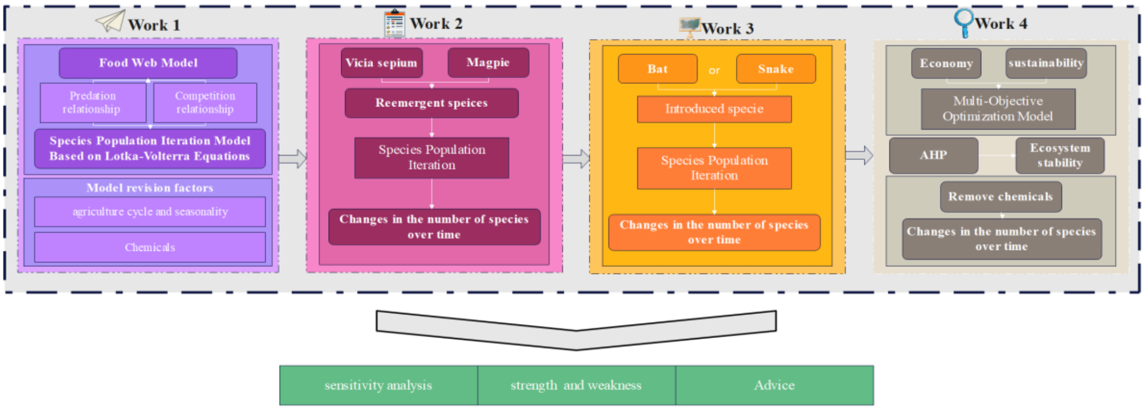

Figure 2. Our work

2.1. Establish Ecosystem Models and Food Web

After removing forest, establish a model of the current ecosystem and draw the food web of the current agricultural ecosystem. We have presented our thought process through a flowchart in Figure3

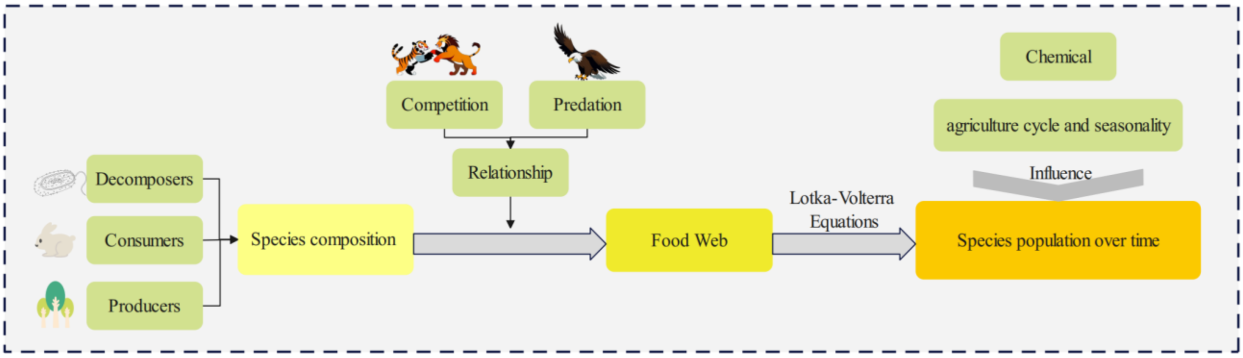

Figure 3. Problem analysis.

Based on the work of the predecessors on agricultural ecosystems, we have selected suitable species and established their corresponding competition and predation relationships. The food web is displayed in Figure 4:

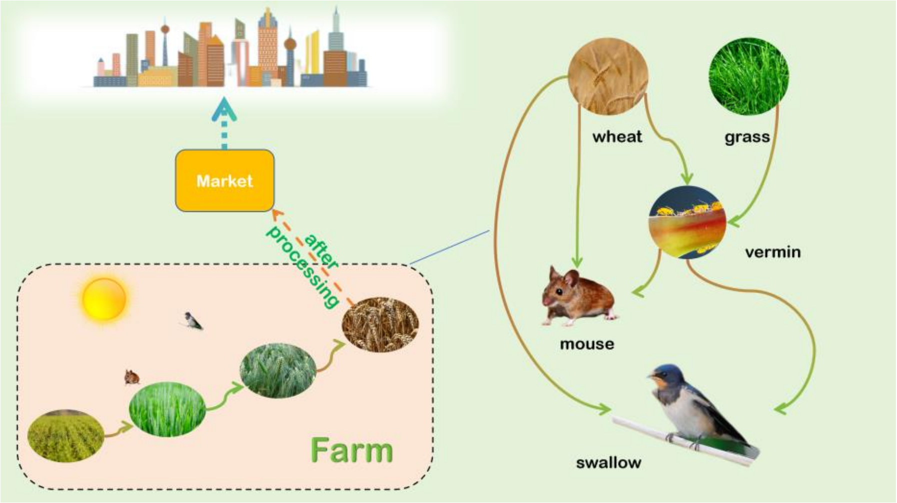

Figure 4. Food web.

From Figure 4, we can categorize the species in this food web and describe the inter-specific relationships.

Producers: Grass, wheat

Consumers: mouse, swallow, vermin

Predation relationship: Mouse prey on wheat and vermin, vermin prey on wheat and grass, and swallow prey on wheat and vermin.

Competition relationship: Wheat competes with mouse, swallow, and vermin, vermin compete with mouse and swallow.

The Species Population Iteration Model is based on the Lotka-Volterra Equations [2]. In the model, we simultaneously consider the predation and competition relationships. This is an innovative aspect.

We can get two basic relationships. First, we consider the mutual influence between predators and prey. Then, we considered the mutual influence between competitors.

In relationship of predators and prey, for the prey (note: we consider that the species can only be preyed upon and cannot prey on other species), the population growth rate of the i-th species can be expressed as:

$$\frac{dN_{prey-i}}{dt} = r_i \cdot N_i - N_i \sum_{k=1}^{n} a_k \cdot N_k \tag{1}$$

Where n=5, when i changes from 1 to 5, the corresponding species are wheat, grass, mouse, vermin and swallow.

The growth rate of the i-th species at time t equals the number of the i-th species growing per unit of time minus the number of the i-th species being preyed upon.

In the predation relationship, for the predators (note: we consider that the species can only prey on other species and cannot be preyed upon), the population growth rate of the i-th species can be expressed as:

$$\frac{\boldsymbol{d}N_{predator-i}}{\boldsymbol{d}t} = N_i \sum_{k=1}^{n} e_k \cdot N_k \tag{2}$$

Where n=5.

The growth rate of the i-th species at time t is indirectly responded to the number of predations per unit of time. And because its mortality rate is much smaller than its birth rate, we ignore its death number.

In the competition relationship (note: we consider the species cannot prey as well as being preyed upon), the population growth rate of the i-th species can be expressed as:

$$\frac{\boldsymbol{d}N_{competition\text{-}\ i}}{\boldsymbol{d}t} = r_i \cdot N_i \left(1 - \frac{N_i + \alpha_{ij} \cdot N_j}{K_i}\right) \tag{3}$$

The growth rate of the i-th species equals the number of natural growths per unit time minus the reduction due to competition.

However, in nature, the relationships of species within an ecosystem are complex. Species may simultaneously have predation and competition relationships. Therefore, we need to modify the basic models.

$$\frac{\boldsymbol{d}N_i}{\boldsymbol{d}t} = \frac{\boldsymbol{d}N_{prey-i}}{\boldsymbol{d}t} + \frac{\boldsymbol{d}N_{predators-i}}{\boldsymbol{d}t} + \frac{\boldsymbol{d}N_{competition-i}}{\boldsymbol{d}t} - r_i \cdot N_i \tag{4}$$

As seen from Eq. (4) above, the actual growth rate of species is determined by three main factors — the number of individuals preyed upon, the number of individuals preying on other species, and the number of competitors.

Based on Eq. (4), and considering the inter-species relationships in the current ecosystem, for wheat, grass, mouse, vermin and swallow Eq. (5) can be expressed in the following form.

$$\frac{\boldsymbol{d}N_1}{\boldsymbol{d}t} = r_1 \cdot N_1 \left(1 - \frac{N_1 + \alpha_{12} \cdot N_2}{K_1}\right) - a_5 \cdot N_5 \cdot N_1 - a_3 \cdot N_3 \cdot N_1 - a_4 \cdot N_4 \cdot N_1 \tag{5}$$

Eq. (5) represents the growth rate of wheat population. Based on Figure 4, this equation takes both predation and competition relationships into account. It reflects the competitive relationship between wheat and grass, as well as the predation relationships of mouse, vermin, and swallows on wheat.

$$\frac{\boldsymbol{d}N_2}{\boldsymbol{d}t} = r_2 \cdot N_2 \left(1 - \frac{N_2 + \alpha_{21} \cdot N_1}{K_2}\right) - a_4 \cdot N_4 \cdot N_2 \tag{6}$$

Eq. (6) represents the growth rate of grass population. This equation takes both predation and competition relationships into account. It reflects the competitive relationship between grass and wheat, as well as the predation relationship of vermin on grass.

$$\frac{\boldsymbol{d}N_3}{\boldsymbol{d}t} = r_3 \cdot N_3 \left(1 - \frac{N_3}{K_3}\right) + e_1 \cdot N_1 \cdot N_3 + e_4 \cdot N_4 \cdot N_3 \tag{7}$$

Eq. (7) represents the growth rate of mouse population. To simplify the equation, only the predation relationships are considered. It reflects the predation of mouse on wheat and vermin.

$$\frac{\boldsymbol{d}N_4}{\boldsymbol{d}t} = r_4 \cdot N_4 \left(1 - \frac{N_4}{K_4}\right) + e_1 \cdot N_1 \cdot N_4 + e_2 \cdot N_2 \cdot N_4 - a_3 \cdot N_3 \cdot N_4 - a_5 \cdot N_5 \cdot N_4 \tag{8}$$

Eq. (8) represents the growth rate of vermin population. This equation takes predation relationships into account. It reflects the predation relationships of vermin on wheat and grass, as well as the predation of mouse and swallow on vermin.

$$\frac{dN_5}{dt} = r_5 \cdot N_5 \left(1 - \frac{N_5}{K_5}\right) + e_1 \cdot N_1 \cdot N_5 + e_4 \cdot N_4 \cdot N_5 \tag{9}$$

Eq. (9) represents the growth rate of swallow population. This equation takes predation relationships into account. It reflects the predation relationship of swallow on both wheat and vermin.

We have considered other factors in the model. The relationship between agricultural cycles, seasonality, and the use of chemicals is closely intertwined. To better illustrate their interactions, we will use Figure 5.

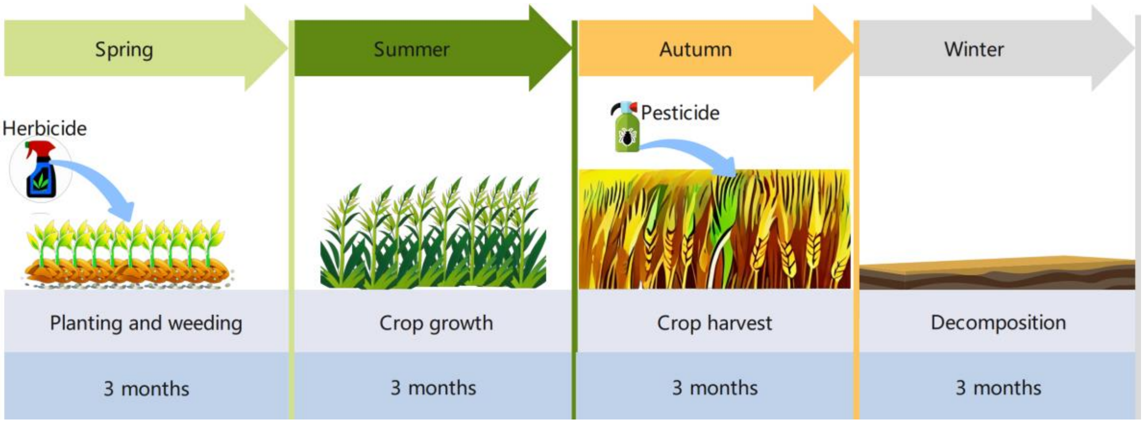

Figure 5. Agriculture cycle and its seasonality

2.2. Bats move in the ecosystem

We will introduce bats into the ecosystem described above. With the introduction of a new specie, it is necessary to reassess the inter-species relationships and redraw the food web diagram.

From Figure 7, we can see that the population of swallows in the fourth year fluctuates significantly. It peaks at the 39th month, reaching 0.48 individuals per square meter. The population reaches its lowest point in the 40th month, at 0.028 individuals per square meter. We speculate that the introduction of bats disrupted the previously stable food sources for swallows. The population trend of wheat in the fourth year is the same as in the previous three years, but its peak has increased by 37.5%, reaching 154 plants per square meter. The main reason for this is attributed to the pollination effect of bats.

After the introduction of bats into the ecosystem, we have summarized the population changes of all species over the first four years in the same chart. Due to the different units between species and the significant differences in their numbers, we performed normalization to obtain the following chart.

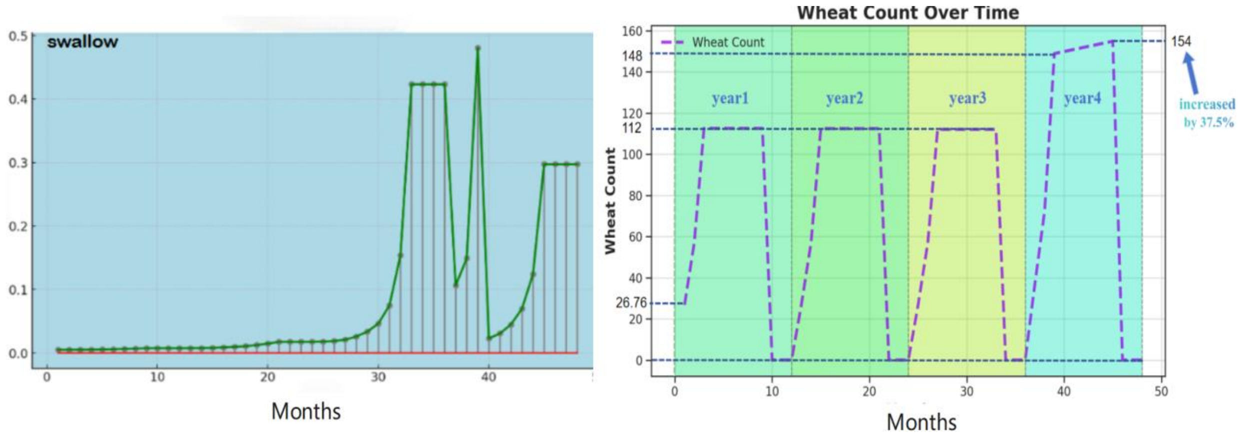

Figure 6. The population changes of swallow and wheat.

2.3. Removing herbicides

We attempted to remove herbicides and discuss how the populations of various species change over time. The herbicide coefficient $\Theta_{herbicide}$ for grass becomes 0 after removing the herbicide, which is the only change in the system. We continue to use the Species Population Iteration Model for the calculations. The changes in species populations in the fifth year will primarily be presented through visualization methods to illustrate how their numbers evolve over time. The changes of species are displayed in Figure 7:

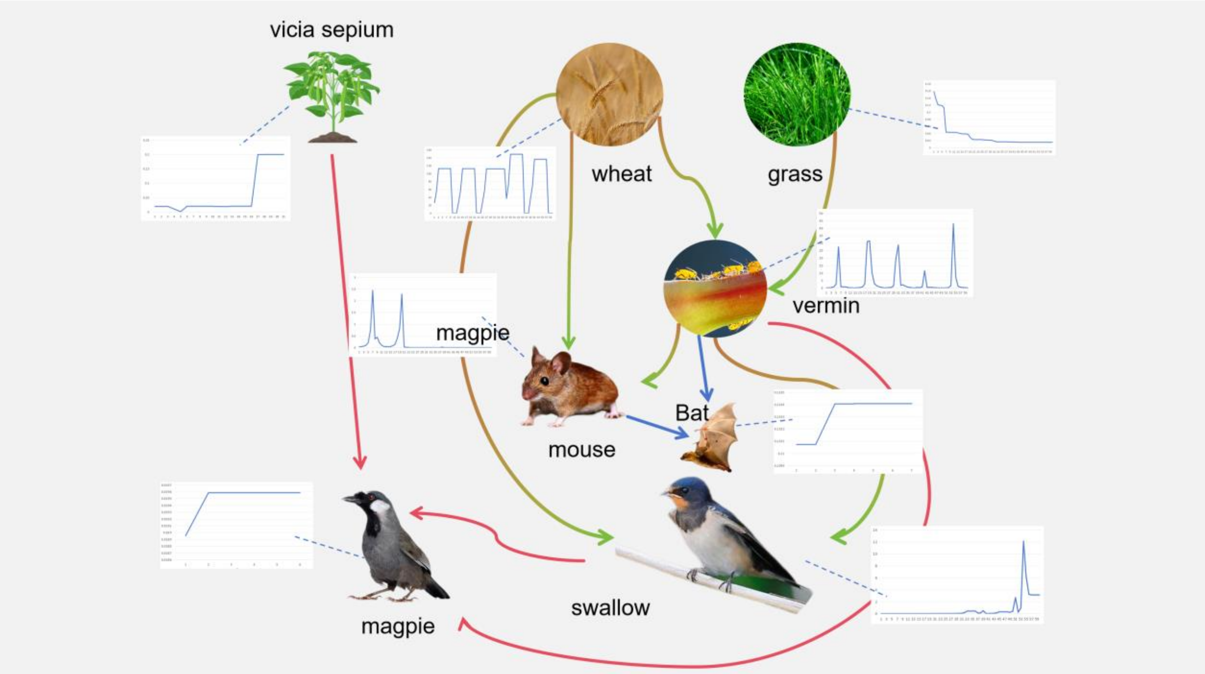

Figure 7. The changes of species over the first five years.

We consider wheat and grass as the cornerstone of the ecosystem as producers, while vermin serve as the main agricultural pests in this ecosystem. Therefore, it is necessary to separately discuss the population change trends of wheat, grass, and vermin in the fifth year. The changes over the past 5 years are displayed in Figure 8:

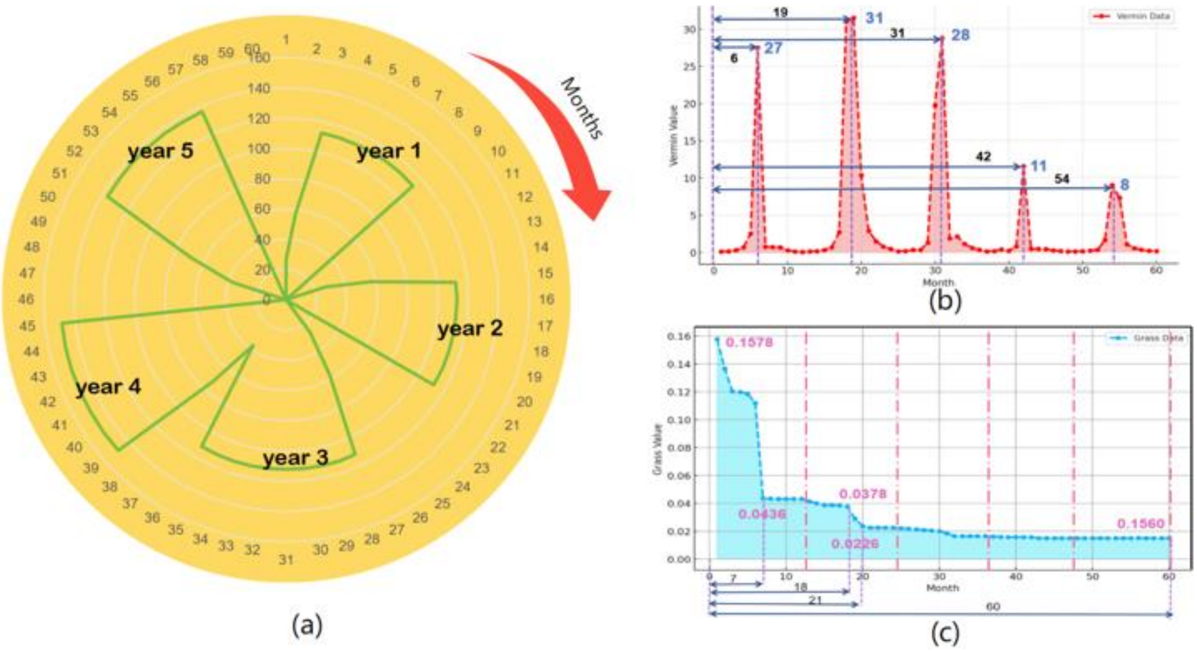

Figure 8. The changes over the past 5 years.

From Figure 8(a), it can be seen that: The wheat harvest in the fifth year decreased compared to the fourth year, dropping to 137 plants per square meter. We speculate that this is primarily due to the removal of herbicides, causing wheat to compete with grass for limited resources. However, the harvest quantity in the fifth year is still higher than in the first three years, due to the reemergence of species and the introduction of bats.

From Figure 8(b), it can be seen that: The peak population of vermin in the fifth year decreased compared to the fourth year, reaching 8 individuals per square meter. We speculate that this may be due to the decrease in wheat population, which resulted in fewer food resources available for the vermin.

From Figure 8(c), it is evident that: After the removal of herbicides, the grass population did not show a significant increase and stabilized at 0.156 plants per square meter. This suggests that the ecosystem has a relatively low dependency on chemicals to maintain stability.

1) AHP method

We consider that the stability of the ecosystem includes five indicators: Pest control, grass control, wheat health, and biodiversity and plant reproduction. Because these evaluation criteria are difficult to quantify, we find it more appropriate to use the AHP method.

Firstly, we construct a judgment matrix and perform pairwise comparisons for all the indicators, assigning scores based on their relative importance.

Table 2. The judgement matrix.

Indicator	Pest control	Grass control	Crop Health	Biodiversity	Plant Reproduction
Pest control	1	1	2	0.2	2
Grass control	1	1	2	0.2	2
Crop Health	0.5	0.5	1	0.25	3
Biodiversity	5	5	4	1	6
Plant Reproduction	0.5	0.5	0.333	0.167	1

From this scoring, it is clear that biodiversity scores higher compared to other indicators, as biodiversity determines the balance and stability of the ecosystem.

By calculating the eigenvector and the maximum eigenvalue of the judgment matrix, we obtain the weight of each indicator's impact on the stability of the ecosystem.

The weights for pest control, weed control, crop health, biodiversity, and plant reproduction are 0.1438, 0.1438, 0.1077, 0.5407, 0.05407.

If we want to consider the impact of chemicals on ecosystem stability, we can approach it from the weights. We can approximate that chemicals correspond to the indicators of pest control and weed control. Therefore, the impact of chemicals on ecosystem stability is the sum of the weights for pest control and weed control, which equals 0.2876.

Similarly, if we consider the impact of the interactions between bats, insects, plants, and predators on the ecosystem, we can approximate that the magnitude of this impact equals the sum of the weights for crop health, biodiversity, and plant reproduction's influence on the ecosystem. The total is 0.7024.

2) Multi-objective optimization

The sustainability of the agricultural ecosystem can be reflected by the number of species $E(T)$ in the ecosystem, while the economic viability can be reflected by the profit $Y(T)$ generated from the farmland in a given year. To solve for the maximum combined effect of $E(T)$ and $Y(T)$, using multi-objective optimization is highly appropriate.

$$L = \alpha \int_0^T Y(T)dT + \beta \int_0^T E(T)dT \tag{10}$$

Where $\alpha = 0.4, \beta = 0.6, \mathrm{T} = 12$. They are the correction coefficients. Based on the previous analysis, we can list the following table.

Table 3. The value of $Y(T)$ and $E(T)$.

Variable	Year1	Year2	Year3	Year4	Year5
$Y(T)$	1.02	1.02	1.30	1.37	1.45
$E(T)$	5	5	7	8	8

By substituting the parameters into the above formula, the calculation results for each year are 40.896, 40.896, 56.64, 64.176, and 64.56, respectively. Therefore, it can be concluded that when the organic farming state is reached, the sustainability and economy performance are optimal.

3. Results

3.1. Iteration Results Analysis

In the previous discussion, we comprehensively consider the impact of agricultural cycles, seasonality, and the effect of chemicals on species growth rates. The following table shows the impact coefficients for calculating the growth rate of different species. Table.4 displays the value of the impact coefficients.

Table 4. The value of the impact coefficients.

Comparison	1 (Wheat)	2 (Grass)	3 (Mouse)	4 (Vermin)	5 (Swallow)	6 (Vicia sepium)	7 (Magpie)	8 (Bat)
r_i	1/12	1/12	1/24	5/24	1/30	1.0	0.3	0.4
K_i	150	150	0.1	40	0.1	150	0.08	0.05
α_{ij}	0.31	0.6	/	/	/	/	/	/
e_i	0.1	0.1	0.1	0.1	0.1	0.1	/	/
a_i	/	/	0.05	0.2	0.3	/	0.3	0.2

Some parameters here will be used in the later chapters:

Table 5. The initial population of each species.

Wheat	Grass	Mouse	Vermin	Swallow	Vivia sepium	Magpie	Bat
15	1	0.04	0.1	0.005	0.02	0.004	0.1

Using these data, we perform iterations in Python, with species population updated on an annual basis. This allows us to obtain the relationship between species populations and time.

We plot the number of species over time for all species in the current ecosystem (Figure 9):

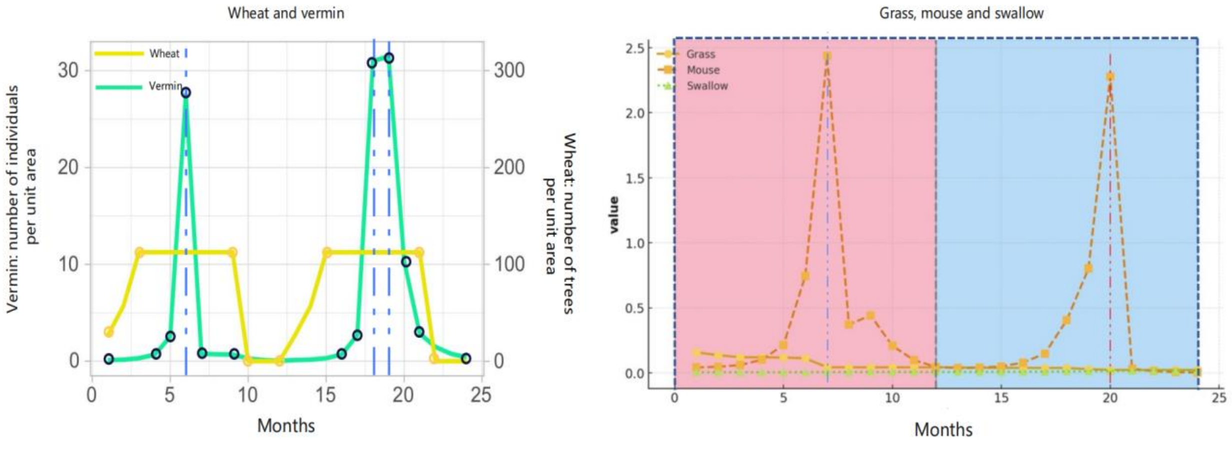

Figure 9. The population trends of tall species over time.

3.2. Comparison between Snakes and Bats

The introduction of bats can reduce harmful species and provide pollination for wheat, thereby improving yields. Therefore, the introduction of bats is beneficial for restoring the stability of the ecosystem. When snakes are used as a replacement for bats, snakes prey on mice, and by doing so, they can reduce the number of harmful species and indirectly improve wheat yields. Hence, the introduction of snakes also helps restore the ecosystem. To compare their effects, it is necessary to focus on the population of wheat and the number of harmful species.

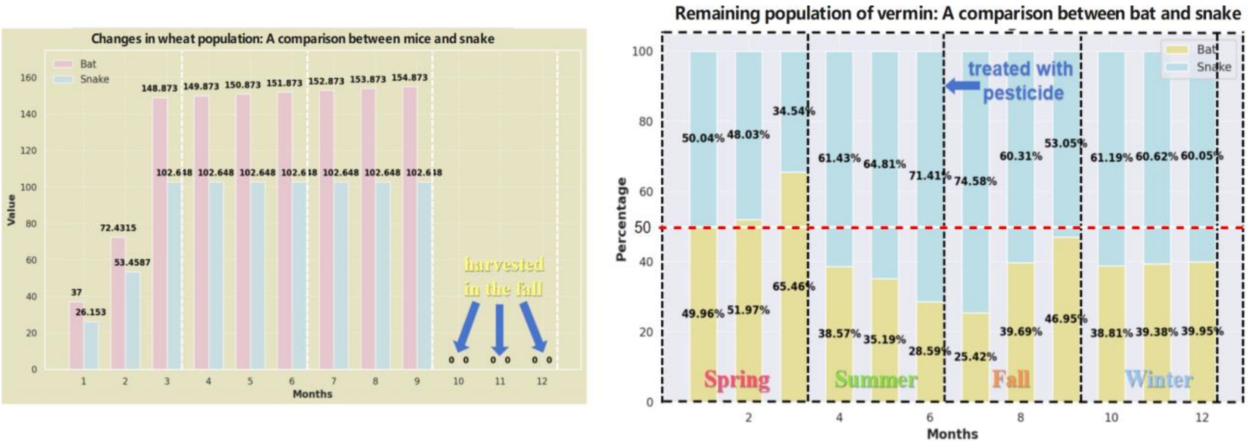

Figure 10. Wheat and Vermin Population Changes.

From the left side of Figure 10, it can be seen that: When the introduced specie is a snake, the wheat population each month is consistently lower than when the introduced specie is a bat. When snakes are introduced, the harvested wheat quantity is 102.618 plants per square meter. When bats are introduced, the harvested wheat quantity is 154.875 plants per square meter. This is because snakes do not have a pollination effect on wheat.

From the right side of Figure 10, it can be seen that: When the introduced species is a snake, the remaining vermin population each month is generally lower than when the introduced specie is a bat. When snakes are introduced, the average remaining vermin population is 58.4%. When bats are introduced, the average remaining vermin population is 42.6%. This is because the inter-species relationships involving bats are more complex than those involving snakes.

In summary, the introduction of bats brings greater benefits to the restoration of the ecosystem.

4. Conclusions and future work

This study examines the ecological transition from forest to farmland and proposes sustainable agricultural strategies through a series of mathematical models. We establish four key models: Food Web Model, Species Population Iteration Model, AHP-Based Stability Evaluation Model, and Multi-Objective Optimization Model, to analyze species interactions, ecosystem stability, and economic sustainability.

Our results show that introducing *Vicia sepium* and magpies can effectively control pest populations without affecting wheat yield, while bats further enhance ecosystem stability by increasing wheat production by 37.5% [7]. Additionally, the removal of pesticides and herbicides enables the ecosystem to reach an organic equilibrium, optimizing both sustainability and economic performance. Sensitivity analysis confirms the robustness of our models [8]. The study highlights the importance of balancing species interactions and agricultural interventions to achieve sustainable farming practices.

Despite the effectiveness of our approach, some limitations exist. Our models assume homogeneous population structures and do not fully account for long-term biodiversity trends [9]. Additionally, the impact of climate change on ecosystem dynamics is not explicitly considered.

To further improve the study, we propose the following future directions:

1. Incorporating Detailed Population Structures: Future models should consider species age distribution, genetic diversity, and reproductive cycles for more precise predictions [10].
2. Long-Term Biodiversity Monitoring: Extending the model to track ecosystem changes over decades will help evaluate the true sustainability of proposed farming methods.
3. Climate Change Adaptation: Integrating climate models to assess how temperature, precipitation, and extreme weather influence species interactions and agricultural productivity.
4. Advanced Optimization Techniques: Exploring deep reinforcement learning and evolutionary algorithms to refine sustainable farming strategies under varying environmental constraints [11].
5. Real-World Validation: Collaborating with agricultural and ecological experts to validate our model using field data and case studies from different regions.

By addressing these aspects, future research can further enhance our understanding of sustainable agriculture and provide more practical recommendations for balancing food production with ecological conservation.

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