Research on the Evolution of Organic Farmland Ecosystems under the Intervention of External Factors

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Abstract

The research on the evolution law of organic farmland ecosystems under the intervention of external factors (such as the return of native species, human decisions, and environmental changes, etc.) holds significant theoretical value and practical significance for the transformation of traditional agriculture into green agriculture. To deeply reveal the dynamic evolution mechanism of the ecosystem, this paper first constructs an ecosystem model based on the Lotka-Volterra differential equations on the basis of comprehensively considering agricultural cycles and seasonal factors. This model is used to describe the interaction relationships among producers, primary consumers, secondary consumers, and top consumers. Subsequently, two types of native species, namely the Brazilian tapir and butterflies, are introduced, and a cellular automaton model is applied to simulate the impacts of their return on the ecosystem. Furthermore, an ecosystem stability evaluation model is established, and the particle swarm optimization algorithm is adopted to determine the optimal weights. Then, the impacts of removing herbicides (in traditional agriculture) and introducing bats and earthworms (in organic agriculture) on the ecosystem stability under the intervention of human decisions are explored. The research results show that: on the one hand, within a single growth cycle, the application of chemical pesticides can suppress the number of pests and promote crop growth in the short term; on the other hand, bats and earthworms can serve as ecological alternative solutions, playing key roles in pest control and soil improvement respectively, enhancing biodiversity and the sustainability of the ecosystem.

Keywords

Organic farmland, ecosystem, external intervention, game theory, stability evaluation.

1. Introduction

On a global scale, the conflict between agricultural expansion and ecological conservation is intensifying. The conversion of forests into farmland has become a core driving factor endangering biodiversity and soil health. Taking the Brazilian Amazon Basin as a typical example, in the past two decades, the rapid expansion of the soybean and beef cattle industries has led to the disappearance of more than 1.2 million square kilometers of forests, and the rate of soil organic matter loss has accelerated by more than four times compared to the natural state [1]. Traditional agriculture highly depends on chemical pesticides and herbicides.

Although it can effectively suppress pest outbreaks and maintain crop growth in the short term, long - term continuous application has triggered a series of serious problems. The soil microbial community is imbalanced, and the proportion of pest populations with drug resistance is constantly increasing, thus falling into a vicious cycle of "pesticide dependence - ecological degradation". This linear growth model characterized by high resource input and high environmental consumption not only directly threatens food security but also gradually erodes the ecological resilience of the agricultural system to resist external disturbances, posing an unprecedented and severe challenge to the sustainable development of agriculture [2].

Facing the numerous difficulties of the traditional agricultural development model, organic agriculture, as a sustainable agricultural production method, has received increasing attention from the academic and industrial communities. Organic agriculture emphasizes the use of eco - friendly means such as promoting the return of native species and optimizing the structure of the ecosystem to achieve the coordinated progress of agricultural production and ecological conservation, and is regarded as an important path to solve the problem of agricultural sustainability. A large number of research results have fully revealed the positive responses of the ecosystem under the organic agriculture model. Many studies have shown [3 - 5] that the introduction of pollinating insects into the farmland ecosystem can significantly improve the pollination efficiency of crops, thereby enhancing the stability of crop yields. For example, in a long - term study of orchards in a certain area, it was found that after the introduction of pollinating insects such as bees, the fruit yield maintained a stable growth trend in multiple growing seasons, and the fluctuation range was significantly reduced [6]. At the same time, large mammals, with their unique seed - dispersal functions, can accelerate the restoration process of vegetation diversity. Relevant research was carried out in the African savannah region, and it was found that large mammals such as elephants widely disperse a variety of plant seeds during their activities, which significantly increases the vegetation species richness in the region within a few years, effectively optimizing the structure and function of the ecosystem [7].

However, although organic agriculture shows great development potential, there are still many research gaps in the evolution mechanism of the farmland ecosystem under external intervention [8 - 9]. First, the impact mechanism of the return of multiple species on the ecosystem has not been fully clarified. Different species play different roles in the ecosystem, and their interaction relationships are complex. How the coordinated return of multiple species affects the material cycle, energy flow, and inter - species relationships in the ecosystem remains to be further explored. Second, the research on the impact relationship between the two agricultural models of traditional agriculture and organic agriculture on the robustness of the ecosystem is still weak [10]. There are significant differences between the two in terms of input factors and production methods. How these differences shape the ability of the ecosystem to respond to external disturbances, and how the two dynamically affect the robustness of the ecosystem at different spatio - temporal scales, urgently need further research [11-].

In view of the above research gaps, on the basis of fully considering agricultural cycles and seasonal factors, this study first constructs an ecosystem model based on the Lotka - Volterra differential equations. This model accurately describes the complex interaction relationships among producers, primary consumers, secondary consumers, and top consumers. Subsequently, this study introduces two representative native species, the Brazilian tapir and butterflies, and uses the cellular automaton model to simulate the evolution process of the ecosystem after their return. To achieve a quantitative assessment of ecosystem stability, this study constructs an ecosystem stability assessment model and uses the particle swarm optimization algorithm to determine the optimal weights of each assessment index. Through this model, this study deeply explores the impacts of removing herbicides in traditional agriculture and introducing bats and earthworms in organic agriculture on ecosystem stability under the intervention of human decisions. The research results show that within a single growth cycle, chemical pesticides can suppress the number of pests and promote crop growth in the short term. However, from the long - term perspective of the sustainable development of the ecosystem, bats and earthworms play key roles in pest control and soil improvement respectively in organic agriculture, significantly enhancing biodiversity and the sustainability of the ecosystem. At the same time, the study found that with the continuous use of herbicides, the health of crops gradually deteriorates. In the long run, organic agriculture is superior to traditional agriculture in terms of both economic and ecological benefits, providing important theoretical basis and practical reference for the exploration of the global sustainable development path of agriculture.

2. Research Hypotheses and Data Sources

(1) Research Hypotheses

The population size of decomposers differs from that of producers and consumers. Their impact on the environment is mainly achieved through nutrient cycling. Based on this, the role of decomposers on the environment is manifested as an indirect effect transmitted through primary producers rather than directly contributing to the formation of the food web. This leads to Hypothesis 1: :the food web model does not take into account decomposers and their impacts. In the idealized model, for the sake of simplifying the analysis, considering the assumption that environmental resources are abundant and infinite, the limitation of environmental carrying capacity on the growth of producers is ignored, and the growth process is abstracted as exponential growth. This leads to Hypothesis 2: this model does not consider the impact of environmental carrying capacity on the number of producers. In the short term, the natural mortality rate of populations is usually at a low level. Given that death mainly results from the predation pressure of natural enemies, Hypothesis 3 can be proposed: in the short term, the mortality rate of producers due to natural death is negligible compared to that caused by predation by natural enemies. In the agricultural ecosystem, the scale of human hunting is small and the number is limited. For the purpose of simplifying the model, it is ignored, resulting in Hypothesis 4: the impact of human predation on the consumer populations in the agricultural ecosystem is not considered.

Table 1. Data and Database Websites

Database Names	Database Websites
Land type conversion data	https://www.mdpi.com/journal/land
Brazilian crop earnings data	https://www.tridge.com.preview-prices
Brazilian Soybean data	https://agenciadenoticias.ibge.gov.br
Traditional agricultural data	https://sindiveg.org.br
Ecosystem data	https://www.unep.org>

Table 2. Parameter value assignment

Symbol	Value	Symbol	Value	Symbol	Value	Symbol	Value
r_P	0.75	K_C	50	β_{PC}	0.4	α_C	0.9
r_C	2	K_M	5	β_{CM}	0.4	α_M	0.25
r_M	0.15	K_B	0.5	β_{MB}	0.075	α_B	0.25
r_B	0.075						

When studying the impacts of the introduction of earthworms and bats on the ecosystem, considering that their numbers are relatively small compared to other species, they can be neglected, thus leading to Hypothesis 5: the numbers of introduced bats and earthworms are ignored. The impacts of the use of herbicides and insecticides, as well as the introduction of bats and earthworms on secondary and tertiary consumers, are manifested as indirect effects transmitted through primary consumers. Considering this impact pattern, Hypothesis 6 is proposed: the use of herbicides and insecticides, agricultural cycles, seasonal changes, and the introduction of earthworms and bats have no direct impact on secondary and tertiary consumers. To eliminate the interference of non - system species on the stability assessment, we only consider the total population numbers of species within the food chain model. Based on this idea, Hypothesis 7 is obtained: the entire ecosystem does not consider the population numbers of any species other than primary producers, primary consumers, secondary consumers, and tertiary consumers.

(2) Data sources

In recent years, land grabbing, illegal natural resource extraction, and speculation on public lands have led to a significant increase in deforestation in Brazil [2-3]. Agricultural demand is the main cause of deforestation, with forests being replaced by agriculture and pasturelands [4-5].

The study area selected for this paper is Mato Grosso State in Brazil, covering 903,202 square kilometers and located within three of Brazil's biomes: the Amazon, Cerrado, and Pantanal wetlands.Based on the agricultural conditions in this region, for the analysis in this paper, we chose soybeans as the primary producers, insects as the primary consumers, birds as the secondary consumers, and eagles as the tertiary consumers. The bats introduced in section 7.3.1(2) can be considered natural enemies controlling pest populations and pollinators promoting plant reproduction. The earthworms introduced in section 7.3.1(3) can be regarded as decomposers and a food source for consumers. The data is organized in Table 2.

3. Model I: Basic Food Web Model

(1) Model Establishment

Taking primary consumers as an example, we first consider the ideal situation where primary consumers live in an environment with unlimited space, food, and other resources, without competition or predators. Let r_c be the growth rate of the producers, then the population C should satisfy the following equation: Taking primary consumers as an example, we first consider the ideal situation where primary consumers live in an environment with unlimited space, food, and other resources, without competition or predators. Let r_c be the growth rate of the producers, then the population C should satisfy the following equation:

$$\frac{dC}{dt} = r_C C \tag{1}$$

Considering the limitations of natural resources, as the population size increases, we commonly use a logistic growth model to describe the population's evolution. Equation (1) is rewritten as:

$$\frac{dC}{dt} = r_C C\left(1 - \frac{C}{K_C}\right) \tag{2}$$

where K_C is the environmental carrying capacity of the primary consumers. At this point, we incorporate the effects of food (primary producers) and predators (secondary consumers) in the food chain of primary consumers, considering the impact of predation and being preyed upon. Equation (2) is rewritten as:

$$\frac{dC}{dt} = r_C C\left(1 - \frac{C}{K_C}\right) + \beta_{PC} P - \alpha_C C \tag{3}$$

where β_{PC} is the predation rate of primary consumers on primary producers, and α_C is the mortality rate of primary consumers (including natural mortality and mortality due to predation). Similarly, the differential equations for producers, secondary consumers, and tertiary consumers are as follows:

$$\frac{dP}{dt} = r_P P - \beta_{PC} P \tag{4}$$

$$\frac{dM}{dt} = r_M M\left(1 - \frac{M}{K_M}\right) + \beta_{CM} C - \alpha_M M \tag{5}$$

$$\frac{dB}{dt} = r_B B\left(1 - \frac{B}{K_B}\right) + \beta_{MB} M - \alpha_B B \tag{6}$$

Based on assumptions 2 and 3, the effect of environmental carrying capacity on producers and natural mortality are not considered here.

Based on relevant ecological and agricultural literature, as well as reports from the Agricultural and Environmental Departments of Mato Grosso State, Brazil, we set the follow-ing initial values in Table 2. With the help of MATLAB, we obtained the population dynamics of four species over time, shown in Figure 1. The predation relationship in the Lotka-Volterra equations is as follows: primary consumers prey on primary producers, and the increase in primary producers drives the growth of primary consumers. Subsequently, the increased primary consumer population suppresses the growth of primary producers, stabilizing the primary consumer population. Similarly, secondary consumers prey on primary consumers, and their populations stabilize through mutual regulation. Tertiary consumers prey on secondary consumers, and after reaching a certain level, their population stabilizes and remains relatively smaller due to limitations in predation and energy transfer.

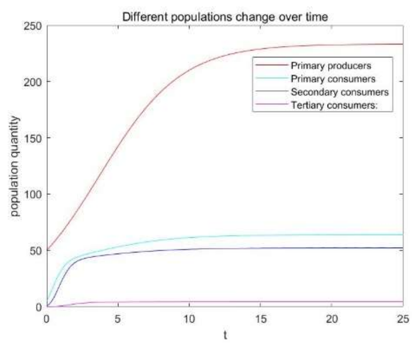

Figure 1. The population quantity of the four species change over time

(3) Incorporate Agricultural Cycles and Seasonal Factors

First, consider the impact of the agricultural cycle and seasonality on primary producers. Since the study area is Mato Grosso, Brazil, the primary producer is selected as the crop soybean. The growth process of primary producers is divided into different stages, including land preparation, sowing, growing season, fertilization and pest control, and harvesting. These stages have different effects on the growth rate of soybeans. Therefore, we need to use a piecewise function to represent the variation of the soybean growth rate over time within one cycle (since soybean is a double-cropping crop, we only consider the cycle from Octo-ber of one year to March of the next year as the research period):

$$r_P(t)=\begin{cases} r_{P\_\max}\cdot\left(1+\eta\cdot\left(\frac{t-t_{\text{plant}}}{t_{\text{growth}}-t_{\text{plant}}}\right)\right) & \text{for } t\in[t_{\text{plant}},t_{\text{growth}}] \\ r_{P\_\max} & \text{for } t\in[t_{\text{growth}},t_{\text{fertilizer}}] \\ r_{P\_\max}\cdot(1+\gamma) & \text{for } t\in[t_{\text{fertilizer}},t_{\text{harvest}}] \\ \sigma & \text{for } t\in[t_{\text{harvest}},T] \end{cases} \tag{7}$$

where $r_P(t)\in[0,1]$, $r_{P\_\max}=1$. t_{plant} represents the planting time, which is October of the first year, denoted as $t_{plant}=10/12$, and similarly for subsequent time points. t_{growth} represents the time when soybeans enter the growing season, which is mid-November of the first year. $t_{fertilizer}$ is the time for fertilization and pest control, which is December of the first year. $t_{harvest}$ is the time for soybean harvesting, which is January of the second year. At this point, the soybean growth rate is no longer considered, and a harvest coefficient σ is introduced, with a value of -15. T represents the end of the agricultural cycle, which is March of the second year.

Next, consider the seasonal effects on primary consumers. Since the study area is Mato Grosso State, Brazil, primary consumers are selected as insects. Insect numbers and activity in Mato Grosso exhibit significant seasonal variation, particularly between the rainy and dry seasons. The rainy season typically lasts from November to March, during which insect numbers and activity increase; the dry season spans from May to September, with a decrease in insect numbers. Thus, we assume an agricultural cycle t (in years) from October to March of the following year. The growth rate fluctuates between a maximum range of 0.4 in the rainy and dry seasons, with an average growth rate of 0.1 for the entire year. Insect numbers peak at the beginning of the rainy season in November. Therefore, the growth rate of insects follows a sinusoidal function model:

$$r_C(t)=0.4\sin\left(2\pi t-\frac{4}{3}\pi\right)+0.1 \tag{8}$$

Based on assumption 6, we only consider the changes in primary producers and primary consumers with respect to the agricultural cycle and seasonality. Secondary and tertiary consumers follow the corresponding changes according to the predation equations in section 4.1. By solving equations (3) to (7) simultaneously, the population dynamics of the four species over time are shown in Figure 2.

(4) Incorporate Herbicide and Insecticide Effects

Chemical substances, such as herbicides and pesticides, directly affect the population dynamics of organisms like plants and insects. In this section of the model construction, we incorporate these effects, focusing on their direct impact on the mortality or growth rates of various species. The main function of herbicides is to eliminate weeds, thereby aiding soybean growth, with an herbicide impact coefficient $\theta_1 = 0.3$. In contrast, pesticides directly suppress insect population numbers, with an impact coefficient $\theta_2 = -0.6$. The differential equations are rewritten as follows:

$$\frac{dP}{dt} = r_P P - \beta_{PC} P + \theta_1 P \tag{9}$$

$$\frac{dC}{dt} = r_C C\left(1 - \frac{C}{K_C}\right) + \beta_{PC} P - \alpha_C C + \theta_2 C \tag{10}$$

Based on assumption 6, we assume that the direct effects of herbicides and pesticides on secondary and tertiary consumers are negligible. However, according to the predation equations, their populations change accordingly. By solving equations (5) to (9) simultaneously, the population dynamics of the four species over time are shown in Figure 3.

4. Model Ⅱ: Cellular Automata Model for Simulating the Reemergence of Native Species

(1) Model Establishment

Define a cellular set $U \subset N^2$, with the affected farmland area $\Omega \in 100 \times 100$。 Seven states are specified, $U = \{0,1,2,3,4,5,6\}$, where 0 represents empty land, 1 represents primary producers, 2 represents primary consumers, 3 represents secondary consumers, 4 represents tertiary consumers, 5 represents butterflies, and 6 represents the Brazilian tapir. At the initial time, the proportions of different species are 40%, 8%, 5%, 2%, 3%, 2%.

For each cell (i,j) in a different state, it will be influenced by its neighbors and will have different probabilities of transitioning to other states. Based on mechanistic analysis, the following planting rule is derived.

Planting rule: For a cell that is not planted, the probability

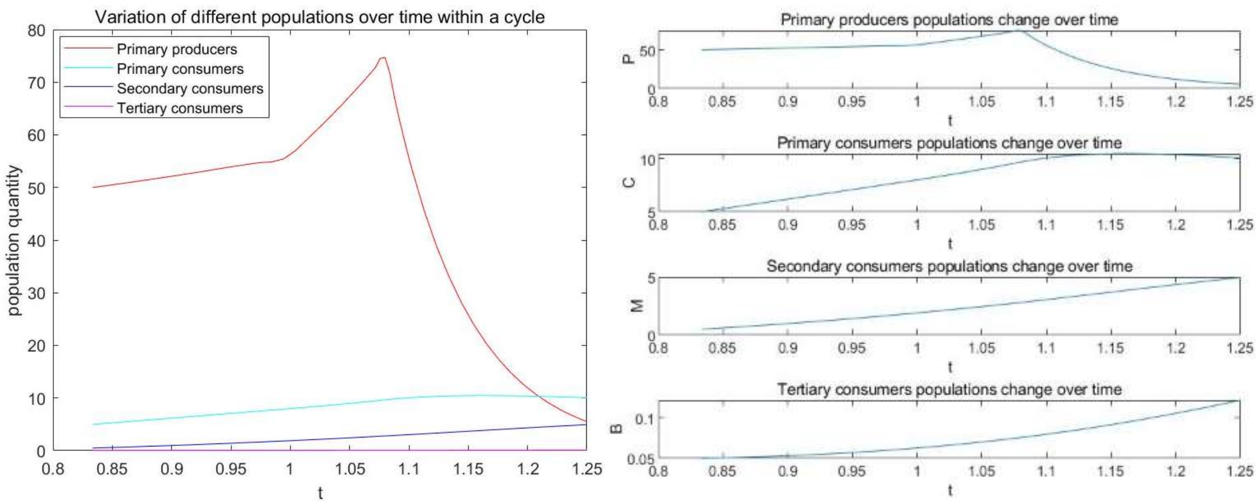

Figure 2. Population changes considering agricultural cycles and seasonal effects

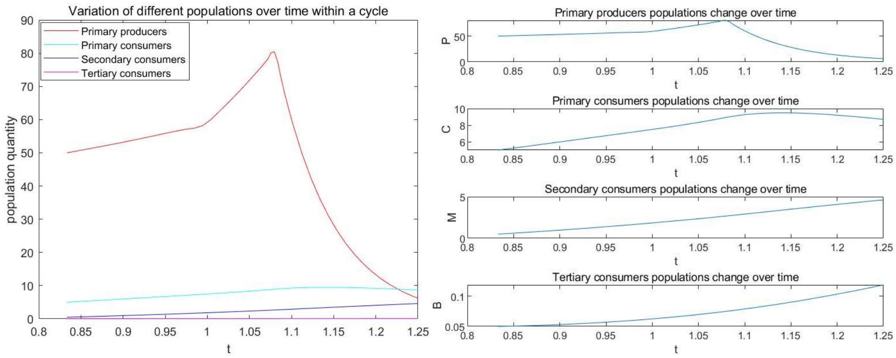

Figure 3. Population changes considering the effects of herbicides and insecticidesof not planting soybeans in the next period P_P is:

$$P_P = sigmoid\left[r_P \times \left(1 - \frac{\sum N(U_n^P)}{\sum N(U_n)}\right)\right] \tag{11}$$

where U_n represents the neighbors of the current cell, U_n^P represents the cells among the neighbors that are in the farmland state, $\sum N(U_n^P)$ is the total number of farmland neighbors, and $\sum N(U_n)$ is the total number of neighbors. r_P is the farmland growth rate.

Foraging rule for primary and secondary consumers:

$$P_C = sigmoid[r_c \times (1 - P_M)] \tag{12}$$

$$P_M = sigmoid[r_M \times (1 - P_B)] \tag{13}$$

where r_c is the growth rate of primary consumers, and r_M is the growth rate of secondary consumers.

$$P_B = sigmoid\left[r_B \times \left(1 - \frac{\sum N(U_n^B)}{\sum N(U_n)}\right)\right] \tag{14}$$

where U_n^B represents the cells among the neighbors that are in the state of tertiary consumers, and r_B is the growth rate of tertiary consumers. Empty cell rule:

$$P_D = sigmoid\,(\overline{\alpha_C + \alpha_M + \alpha_B}) \tag{15}$$

where α_C , α_C and α_C represent the mortality rates of primary consumers, secondary consumers, and tertiary consumers, respectively.

Foraging rule for new species:

$$P_H = \frac{\sum N(U_n^H)}{\sum N(U_n)} \times r_H \tag{16}$$

$$P_T = \frac{\sum N(U_n^T)}{\sum N(U_n)} \times r_T \tag{17}$$

where U_n^H and U_n^T represent the cells among the neighbors that are in the state of butterflies and Brazilian tapirs, respectively, and r_H, r_T are the growth rates of butterflies and Brazilian tapirs, respectively.

Based on these rules, we can write the time iteration update formula. Let $U^t(i,j)$ represent the state of the cell at position (i,j) at time t, The update formula is as follows:

$$U^{t+1}(i,j)\begin{cases} 0 & if\ U^t(i,j)=0\ and\ \xi_0 \le P_P \\ 1 & if\ U^t(i,j)=0\ and\ \xi_1 \le P_C \\ 2 & if\ U^t(i,j)=0\ and\ \xi_2 \le P_M \\ 3 & if\ U^t(i,j)=0\ and\ \xi_3 \le P_B \\ 4 & if\ U^t(i,j)=0\ and\ \xi_4 \le P_H \\ 5 & if\ U^t(i,j)=0\ and\ \xi_5 \le P_T \\ 6 & if\ U^t(i,j)=0\ and\ \xi_6 \le P_D \end{cases} \tag{18}$$

where $\xi_0, \xi_1, \xi_2, \xi_3, \xi_4, \xi_5, \xi_6$ is a random number uniformly distributed between [0,1], used to decide whether a state transition occurs. Each cell's state is updated according to the current state and the corresponding probability rules. If the transition condition is met, the state is updated; otherwise, the current state is maintained.

For each state, the total amount is governed by a differential equation:

$$\frac{dN(U_\lambda)}{dx} = [N(U_\lambda^{t+1}) - N(U_\lambda^t)] - N(U_{D_\lambda}^t) \tag{19}$$

where the index set is $\lambda = \{P, C, M, B, H, T\}$, $N(U_\lambda)$ is the number of species, $N(U_\lambda^{t+1})$ is the number of species λ at time $t+1$, $N(U_{D_\lambda}^t)$ is the number of species λ that die at time t.

(2) Simulation Results

For the cellular automaton model of the new agricultural ecosystem introducing two native species, the decomposition process is simulated through time iteration for solution. The final result is shown in Figure 4. The numbers next to the legend represent the seven different states. Green represents the Brazilian tapir cells, and magenta represents butterfly cells.

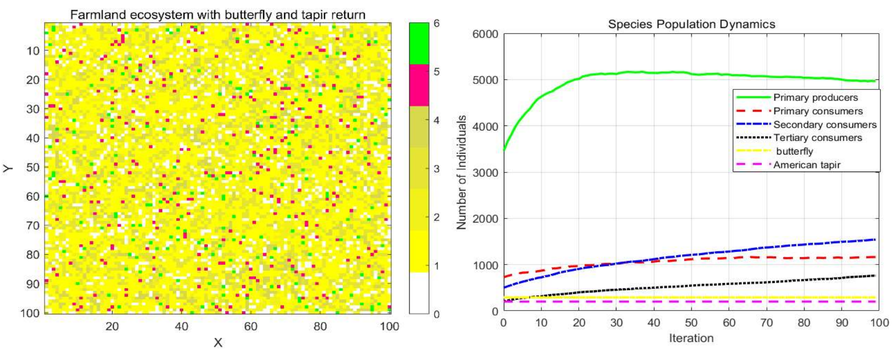

Figure 4. Results of Cellular Automaton Mode

We also plotted the popula-tion changes of each species over 100 iterations. We observe that due to the introduction of native species, the new agricultural system enters a defensive phase in the early stages: but-terflies return, leading to an increase in primary consumer numbers, and an increase in sec-ondary consumer prey, which indirectly stimulates the reproduction of secondary consumers. The return of the Brazilian tapir increases herbivore numbers, leading to an increase in top consumer prey, which indirectly stimulates the reproduction of top consumers. At the same time, the return of both species consumes weeds and trees in the system and enhances the cross-pollination advantage for soybeans, benefiting soybean reproduction. In the later stag-es of species return, the ecosystem becomes stable, and soybean numbers decrease but re-main higher than the initial state.

5. Mode Ⅲ: Ecological System Stability Assessment Model

(1) Model Establishment

To comprehensively assess the stability of the ecosystem, we designed three evaluation indicators: Total Biomass of the Ecosystem (TB), Shannon-Wiener Diversity Index (SD), and Biomass-Proportion Response Index (PR). The weights $w_r(r=1,2,3)$ are assigned using the Particle Swarm Optimization (PSO) algorithm, and the Ecosystem Stability Assessment Model (ESS) is constructed as follows:

$$ESS = w_1 \cdot TB + w_2 \cdot SD + w_3 \cdot PR \tag{20}$$

Assume there are n species, with the population size of the i -th species denoted as v_i .Therefore, the biomass of the ecosystem is given by:

$$TB = \sum_{i}^{n} v_i \tag{21}$$

The Shannon-Wiener Diversity Index is a metric used to measure species diversity in a biological community or ecosystem, where p_i is the proportion of individuals of the i -th species in the community.

$$SD = -\sum_{i=1}^{n} p_i \ln p_i \tag{22}$$

$$p_i = \frac{v_i}{TB} \tag{23}$$

PR reflects the ecosystem's responsiveness to environmental changes or disturbances. When the ecosystem undergoes changes, the proportion of species individuals may rapidly change. The PR index can quickly capture these changes and assess the health and recovery capacity of the ecosystem. p_i is the current individual proportion of the i -th species in the community, and p_{ij} is the individual proportion of the i -th species in the community after a very short time j (as $j \to 0$). For ease of subsequent analysis, the index has been normalized.

$$PR = PR_{\max} - \frac{\lim_{j \to 0} \sum_{i=1}^{n} (p_i - p_{ij})^2}{n} \tag{24}$$

To determine the weights, we use the Particle Swarm Optimization (PSO) algorithm for parameter optimization. $P_i^{(0)}$ represents the initial position of the i-th particle, $v_i^{(0)}$ represents the initial velocity of the i-th particle, $\omega^{(t)}$ is the adaptive inertia weight at time t, ω_{max} is the maximum adaptive weight, set to 0.9, and ω_{min} is the minimum adaptive weight, set to 0.4.

$$\omega^{(t)} = \omega_{max} - (\omega_{max} - \omega_{min}) \times \frac{t}{T} \tag{25}$$

For each particle $i (i = 1, 2, \ldots, N)$,

$$v_i^{(t)} = \omega^{(t)} \times v_i^{(t-1)} + c_1 \times r_{1,i}^{(t)} \times \left(P_{best,i}^{(t-1)} - P_i^{(t-1)}\right) + c_2 \times r_{2,i}^{(t)} \times \left(P_{global\ best}^{(t-1)} - P_i^{(t-1)}\right) \tag{26}$$

where c_1 is the individual experience factor, c_2 is the social experience factor, both set to 1.5. $r_{1,i}^{(t)}$, $r_{2,i}^{(t)}$ are random vectors, with each element in the range [0, 1]. To control the convergence speed, we impose a velocity limit:

$$v_i^{(t)} = clip\ (v_i^{(t)}, -v_{max}, v_{max}) \tag{27}$$

and update the position as follows:

$$P_i^{(t)} = P_i^{(t-1)} + v_i^{(t)} \tag{28}$$

We define the scenario in Section 5.3, which considers the effects of herbicides and insecticides, as the "Original condition" and consider this state as the ecological equilibrium state.

As the ecosystem gradually matures, farmers may attempt to reduce their reliance on chemicals by removing herbicides. However, we argue that because the ecosystem has already adapted to the environment with herbicide use, the populations cannot return to the initial state before herbicide use. For primary producers, the promoting effect of herbicides on soybean quantity disappears, and due to the dependency formed on herbicides, their removal will suppress their numbers. For primary consumers, the removal of herbicides increases the number of weeds in the fields, thereby increasing the available food, which has a certain promoting effect on their numbers. We incorporate bats into the food web model. Then , we have.

$$\frac{dP}{dt} = r_P P - \beta_{PC} P + \vartheta_1 P t + \kappa_1 P \tag{29}$$

$$\frac{dC}{dt} = r_C C\left(1 - \frac{C}{K_C}\right) + \beta_{PC} P - \alpha_C C + \theta_2 C + \vartheta_2 P t + \kappa_2 C \tag{30}$$

Futhermore, we selected earthworms and incorporated them into the food web model. Since earthworms act as decomposers (breaking down organic waste and returning nutrients to the soil) and as food for primary consumers, they have a certain promoting effect on the number of primary producers. Additionally, earthworms exert a certain promoting effect on primary consumer insects, with the suppressive factor. We have:

$$\frac{dP}{dt} = r_P P - \beta_{PC} P + \vartheta_1 Pt + \psi_1 P \tag{31}$$

$$\frac{dC}{dt} = r_C C\left(1 - \frac{C}{K_C}\right) + \beta_{PC} P - \alpha_C C + \theta_2 C + \vartheta_2 Pt + \psi_2 C \tag{32}$$

(2) Simulation Results

Using the population change data from the three ecological system modifications obtained, we will incorporate these data into the ESS model to further assess the overall stability of the ecosystem under these three scenarios. The result is showed in Figures 5-6. The analysis of Biodiversity: From Figure 5, it can be observed that both "After bats inclusion" and "After earthworms inclusion" result in an SD value higher than the "Original condition." This is because the removal of herbicides improves the living environment for organisms, leading to an increase in biodiversity. From Figure 6, we can observe the following:

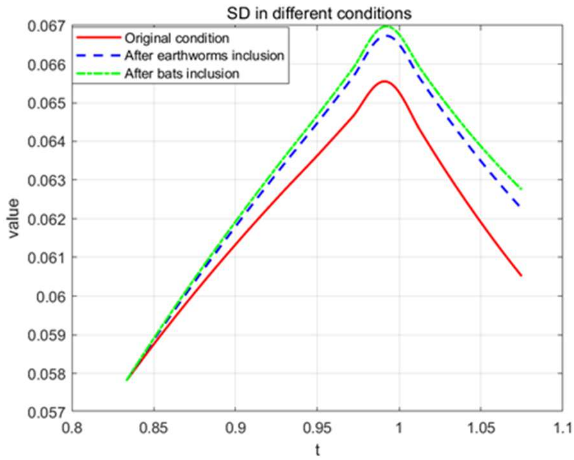

Figure 5. SD in different condions

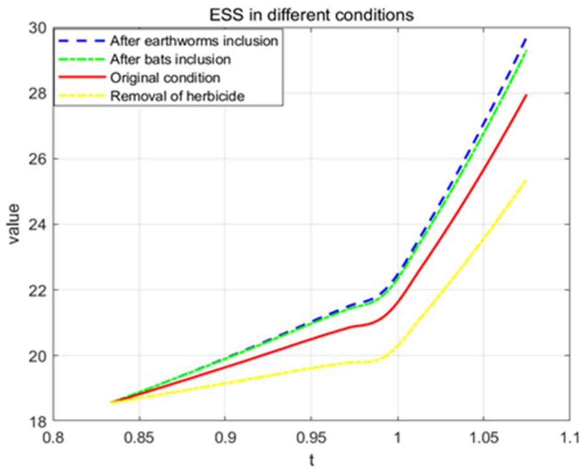

Figure 6. ESS in different condions

(a) The trends of all four curves indicate that as time progresses, the ecosystem ma-tures and the ESS value increases, especially during the crop growth period when the ESS value rises most rapidly.

(b) After the removal of herbicides, weeds proliferate and compete for resources with crops, threatening the ecological balance of the producers. The growth of weeds also stimulates the expansion of primary consumers, increasing the risk of pest out-breaks and leading to a deterioration in ecosystem stability. The ESS value is much lower than that of the Original condition.

(c) After the inclusion of bats, the ecological balance of producers gradually recovers. Additionally, bats help control the pest population and prevent the over-expansion of primary consumers, improving the overall stability of the ecosystem. The ESS value surpasses that of the Original condition.

(d) After the inclusion of earthworms, the ecological balance of producers gradually recovers as well. Earthworms also serve as food for primary consumers, indirectly affecting secondary and tertiary consumers, which increases the total biomass of the ecosystem. Therefore, earthworms improve the ecosys-tem's stability to an even higher level, with the ESS value exceeding that of the Original condition.

Comparison of the effects of bats and earthworms: In the early stages, the effects of introducing earthworms and bats are almost identical. In the later stages, the ESS value of earthworms slightly surpasses that of bats. Therefore, introducing earthworms is more beneficial for ecosystem restoration than introducing bats. Factors influencing this result include their ecological niches in the ecosystem and their impact on the complexity and richness of the food chain and food web.

6. Conclusion

The Predator-Prey Population Model is our fundamental model, which runs throughout the paper. The results derived from this model serve as input data for subsequent models. Therefore, we conducted sensitivity analysis on this model, focusing on parameter adjustments in two equations from model 1.

We modified the herbicide impact coefficient in the differential equation that incorporates the application of herbicides and insecticides to a range of 0.3±0.05. We calculated the error rate by substituting the modified impact coefficient into the original differential equation and comparing the results with the previous outcomes. After calculation, we found that when the herbicide impact coefficient changes, the error rate is less than 5%, which meets our expectations.

Similarly, we modified the insecticide impact coefficient in the same differential equation to a range of -0.6±0.1. We calculated the error rate by substituting the modified coefficient into the original differential equation and comparing the results with the previous outcomes. After calculation, we found that when the insecticide impact coefficient changes, the error rate is less than 5%, which meets our expectations.Thus, this model has passed the sensitivity analysis.

Finally, we summarize and discuss some of the advantages and disadvantages of the models presented in this paper:

(1) Predator-prey Population Model is based on the Lotka-Volterra differential equations, with strong generalizability, allowing for improvements and optimizations based on different scenarios.

(2) Ecological System Stability Assessment Model is built on ecological principles, with the weights determined through particle swarm optimization, making the model more accurate and reliable.

(3) Our game model seeks the optimal solution by achieving a Nash equilibrium, with strong interpretability and innovation.

(4) To simplify the analysis, our Predator-prey Population Model generalizes species, such as considering primary consumers as insects, without accounting for other herbi-vores or interactions among herbivore species.Our model neglects the impact of human predation, which may need to be considered separately in reality, adding complexity.

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