Sustainable Development Research of Organic Agricultural Ecosystem Based on System Dynamics Model

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Abstract. The conversion of forests to agricultural ecosystems has become an increasingly prominent trend worldwide. Against this backdrop, this article employs system dynamics modeling to delve into the sustainable development pathways of organic agricultural ecosystems, aiming to provide valuable insights for practice and research in related fields. In order to explore the ecological stability of forests converted to agricultural land, based on ecological causality and food web theory, this article constructs a species dynamics model for the corn food chain, analyzes the changes in species numbers before and after the use of pesticides and herbicides, and finds that chemical agents benefit agriculture in the short term, but destroy the ecological balance in the long term. In order to study the impact of species recolonization, this article elucidated relevant indicators and models, analyzed the trend of indicators after the introduction of soybeans and stinkbugs, and came to the conclusion that soybeans help to improve the stability and stinkbugs destabilize the ecological balance in the short term. Exploring the impacts of human decision-making, it was found that discontinuing the use of herbicides improved stability and biodiversity, and that the introduction of bats was more effective than that of gray starlings. The innovation of this study lies in constructing system dynamics models and differential equations to comprehensively analyze the impacts of multiple factors, accurately distinguish the roles of different species in different stages, propose and evaluate specific organic agricultural strategies, thereby providing a scientific basis for the sustainable development of agricultural ecosystems.

Keywords: Agricultural ecosystem, Chemical agents, Species recolonization, Ecological stability, System dynamics modeling.

1. Introduction

This article investigates the construction of sustainable agro-ecosystems in organic agriculture following the conversion of forests to farmland, focusing on the roles of ecosystem stability, species regression impacts, herbicide deactivation effects, and organic farming practices. Recent studies have highlighted the significance of ecosystem stability and biodiversity in sustainable agriculture; for instance, Smith et al. demonstrated a strong correlation between ecosystem stability and species diversity, emphasizing the need for diverse plant communities in organic farming systems. However, current research often has notable limitations, as it tends to focus on single factors in isolation, lacking a systematic consideration of ecosystem dynamics and the synergistic effects of multiple strategies. For example, Jones and Taylor (2020) examined the detrimental effects of herbicides on soil microbial communities, underscoring the importance of minimizing chemical inputs in organic agriculture. Furthermore, studies on species regression frequently fail to differentiate between the varying impacts of different species and their roles at different growth stages; Anderson (2019) pointed out that early colonizing species are crucial for the establishment of subsequent species, yet many studies overlook these dynamics. To address these gaps, this article constructs system dynamics models and differential equations to comprehensively analyze the effects of various factors.

By integrating insights from existing literature, it proposes and evaluates specific organic agriculture strategies, thereby providing a scientific basis for the sustainable development of agro-ecosystems.

2. Ecological factors on agricultural ecosystems

2.1. Ecosystem Causal Diagram

System dynamics models excel at dealing with the interactions between natural processes and Human behavioral decision-making. Figure 1 illustrates the causal relationships of a complete ecosystem, where the direction of association between elements such as pests, insectivores, soil fertility, earthworms, etc., can be visualized.[1]

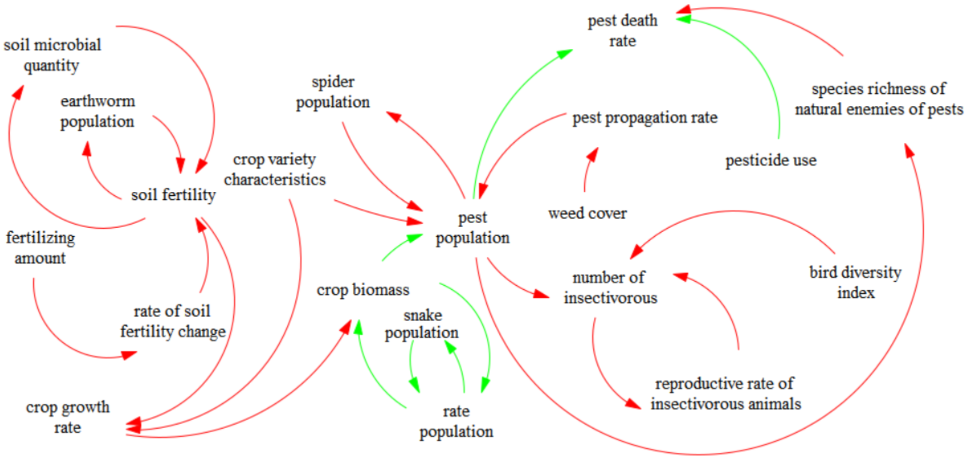


Figure 1: Complete Ecosystem Causal Diagram

2.2. System dynamics model

In the complex ecosystem of agricultural production, the use of pesticides, herbicides and other chemical agents can lead to significant changes in the environment[2]. This article combines the food chain relationship and system dynamics model related to corn, and quantitatively analyzes the dynamics of the number of each species through differential equations.

The growth of weeds is influenced by factors such as intrinsic growth, pest feeding, competition from corn, herbicide action, and natural death. The following is the calculation formula for the rate of change in quantity[3].

$$\frac{dW}{dt} = r_w(t)\cdot W\left(1-\frac{W}{E_w}\right) - \alpha_{wi}W\cdot I - \varphi_{wc}\cdot C\cdot W - \delta_w W\cdot e^{-\omega t} - \gamma_w W \tag{1}$$

where $r_w(t)$ represents the intrinsic growth rate of weeds at time t, E_w is the maximum environmental carrying capacity of weeds, α_{wi} is the feeding coefficient of pests on weeds, φ_{wc} is the influence coefficient of a unit of corn on a unit of weeds, δ_w is the killing coefficient of herbicides on weeds, $e^{-\omega t}$ is the attenuation coefficient of herbicides, and γ_w is the natural mortality rate of weeds.

The growth of corn is influenced by its intrinsic growth, pest feeding, weed competition, and natural death. Overuse of herbicides can reduce its health status or yield. The following is the calculation formula for the rate of change in quantity.

$$\frac{dC}{dt} = r_c(t)\cdot C\left(1-\frac{C}{E_c}\right) - \alpha_{ci}C\cdot I - \varphi_{wc}\cdot C\cdot W - \gamma_c C \tag{2}$$

where $r_c(t)$ represents the intrinsic growth rate of maize at time, E_c is the maximum environmental carrying capacity of maize, α_{ci} is the feeding coefficient of pests on maize, φ_{wc} is the influence coefficient of unit weeds on unit maize, and γ_c is the natural mortality rate of maize.[4]

Pests feed on corn, and their numbers are affected by their own growth, corn resources, bird predation, pesticide killing, and natural death. The following is the calculation formula for the rate of change in quantity.

$$\frac{\mathrm{dI}}{\mathrm{dt}} = \mathrm{r_i(t)} \cdot \mathrm{I}(1 - \frac{\mathrm{I}}{\mathrm{E_i}}) + \alpha_{\mathrm{ic}}\mathrm{I} \cdot \mathrm{C} - \beta_{\mathrm{i}}\mathrm{BD} \cdot \mathrm{I} - \delta_{\mathrm{i}}\mathrm{I} \cdot \mathrm{e}^{-\varepsilon\mathrm{t}} - \gamma_{\mathrm{i}}\mathrm{I} \tag{3}$$

where $\mathrm{r_i(t)}$ represents the intrinsic growth rate of pests, $\mathrm{E_i}$ is the maximum environmental carrying capacity of pests, $\alpha_{\mathrm{ic}}$is the reproduction coefficient of pests from consuming unit maize, β_{i} is the predation coefficient of birds on pests, BD is the number of birds, δ_{i} is the killing coefficient of pesticides on pests, $\mathrm{e}^{-\varepsilon\mathrm{t}}$ is the decay coefficient of pesticides, and, γ_{i} is the natural mortality rate of pests.

Birds (sparrows) as secondary consumers, their quantity is affected by their own growth, pest resources, owl predation, and natural death. The following is the calculation formula for the rate of change in quantity.

$$\frac{dBD}{dt} = r_{bd}(t) \cdot BD(1 - \frac{BD}{E_{bd}}) + \alpha_{bdi}BD \cdot I - \beta_{bd}O \cdot BD - \gamma_{bd}BD \tag{4}$$

where $\mathrm{r_{bd}(t)}$ represents the intrinsic growth rate of birds, $\mathrm{E_{bd}}$ is the maximum environmental carrying capacity of birds, α_{bdi} is the gain from birds consuming unit pests, β_{bd} is the predation coefficient of owls on sparrows, O is the number of owls, and γ_{bd} is the natural mortality rate of birds.

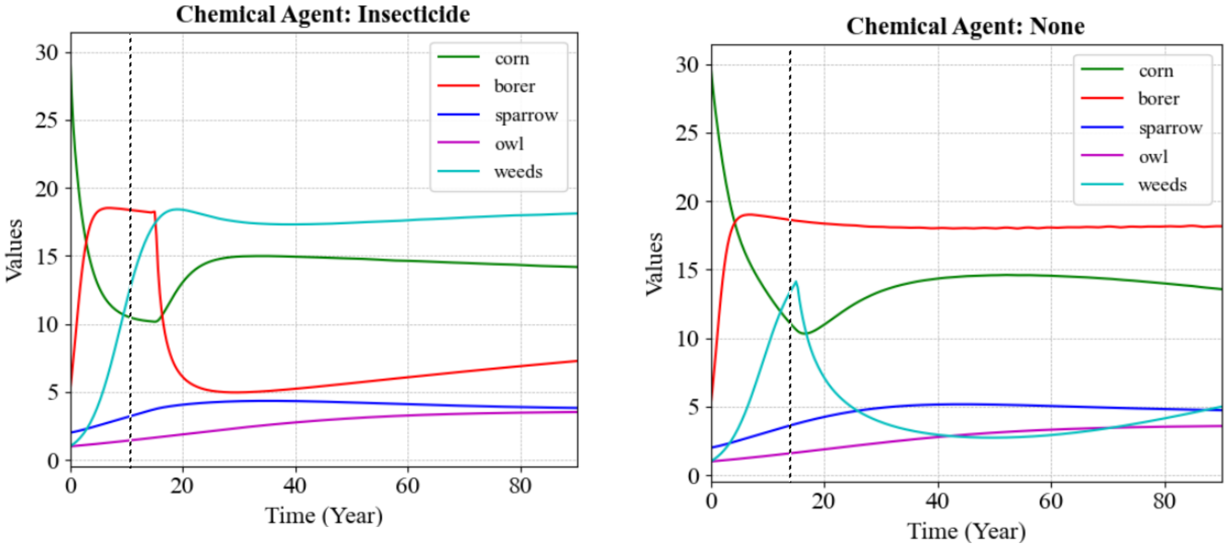
Owls are at a higher trophic level and feed on sparrows. The following is the calculation formula for the rate of change in quantity.

$$\frac{dO}{dt} = r_o(t) \cdot O(1 - \frac{O}{E_o}) + \alpha_{obd}O \cdot B - \gamma_o B \tag{5}$$

where $\mathrm{r_o(t)}$ represents the intrinsic growth rate of owls, $\mathrm{E_o}$ is the maximum environmental carrying capacity of owls, α_{obd} is the gain from owls consuming sparrows, and γ_{o} is the natural mortality rate of birds.

2.3. Analysis of model results

Using the principles of system dynamics, iteratively solve the above differential equation, record the number of biological populations at different time points, and draw Figure 2.



(a) Before and after the use of pesticides (b) Before and after the use of herbicides

Figure 2 Comparison of Species Numbers Before and After the Use of Pesticides and Herbicides

This article combines the two figures (a) and (b) in Figure 2 to analyze the dynamic changes in species numbers before and after the use of chemical agents, and draws the following conclusions.

Figure (a) shows that under the action of pesticides, the number of pests increases and the number of corns decreases in the initial stage. After the use of pesticides, the number of pests decreases and the number of corns rebounds and tends to stabilize. In the later stage, the number of pests slowly increases with the decay of the efficacy.

Figure (b) shows that before the use of herbicides, the number of corns decreased, and after the use, the number of weeds decreased, the competition pressure on corn decreased, and the number increased and tended to stabilize. The number of pests first increased and then decreased, and finally stabilized.

Sparrows and owls, due to their diverse food sources, have remained relatively stable in quantity. From a long-term perspective, although chemical agents have certain benefits for agricultural production in the short term, they can disrupt ecological balance and weaken the self-regulation ability of ecosystems.

2.4. Dynamic analysis of species regression based on model solving

In the process of transforming forests into agricultural ecosystems, this article quantitatively analyzes the impact of local species regression through the following indicators and models.

The number of species regression reflects the dynamic changes of species regression[5]. The following is the calculation formula for the rate of change in quantity.

$$\frac{dSR}{dt} = \alpha \cdot SR \cdot e^{\varepsilon t}(1 - \frac{SR}{SR_{max}}) \tag{6}$$

where α is the rate of species regression, $e^{\varepsilon t}$ is the attenuation efficiency, and SR_{max} is the maximum capacity of species.

Crop yield is regulated by its own growth and species regression. The following is the calculation formula for the rate of change in quantity.

$$\frac{dM}{dt} = r_M(t) \cdot M(1 - \frac{M}{M_{max}}) + \beta \cdot SR \cdot (1 - \frac{SR}{SR_{\max}}) \tag{7}$$

where $r_M(t)$ is the crop growth rate, M_{max} is the maximum capacity of the crop, and $\beta \cdot SR \cdot (1 - \frac{SR}{SR_{max}})$ is the self-regulation term of the crop.

The stability of ecosystems is related to the proportion of returning species. The following is the calculation formula for the rate of change.

$$\frac{dES}{dt} = \alpha \cdot ES \cdot \frac{SR(t)}{K} \cdot (1 - \frac{ES}{ES_{max}}) \tag{8}$$

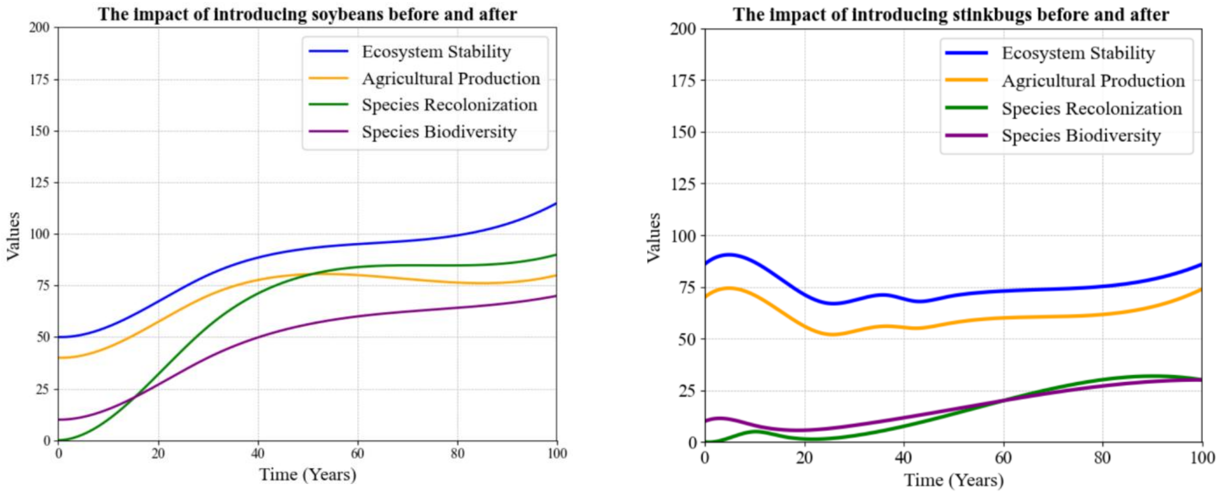
where α is the growth rate of species return and K is the maximum capacity of the ecosystem.

Biodiversity is related to the proportion of each species. The following is the calculation formula.

$$H' = -\sum_{i=1}^{S} p_i \ln p_i \tag{9}$$

$H'$is the diversity index, S is the number of species, and p_i is the proportion of the number of individuals of the I-th species to the total number of individuals.

Similarly, using the method described above, draw Figure 3.



(a) Effects before and after the introduction of soy

(b) Effects before and after the introduction of bugs

Figure 3 Comparison of effects before and after the introduction of soybean and bug

This article combines the two figures (a) and (b) in Figure 3 to analyze the ecosystem changes before and after the introduction of soybeans and stink bugs, and draws the following conclusions.

From 0 to 10 years before the introduction of soybeans, arious indicators such as ecosystem stability and crop yield steadily and slowly increased; After the introduction, the nitrogen fixation index rapidly increased, and the growth was constrained by pests and diseases in the later stage of resource saturation, reaching a new steady state of the system.

Before the introduction of stink bugs, the indicators positively influenced by soybeans steadily increased; After its introduction, it preys on leguminous plants and destroys the nitrogen fixation system, leading to reduced crop yields and decreased biodiversity. In the later stage, ecological self-regulation stabilizes the indicators but it is difficult to restore them to previous levels.

From the perspective of feedback mechanisms, the species regression effect varies by species: positive feedback (such as soybean) promotes system optimization, negative feedback (such as stink bug) may cause long-term imbalance, and ecosystems achieve self-regulation through the interaction of positive and negative feedback.

3. Evaluate the impact of human decisions on the ecosystem

3.1. Impact of Herbicide Removal on Ecosystem Stability

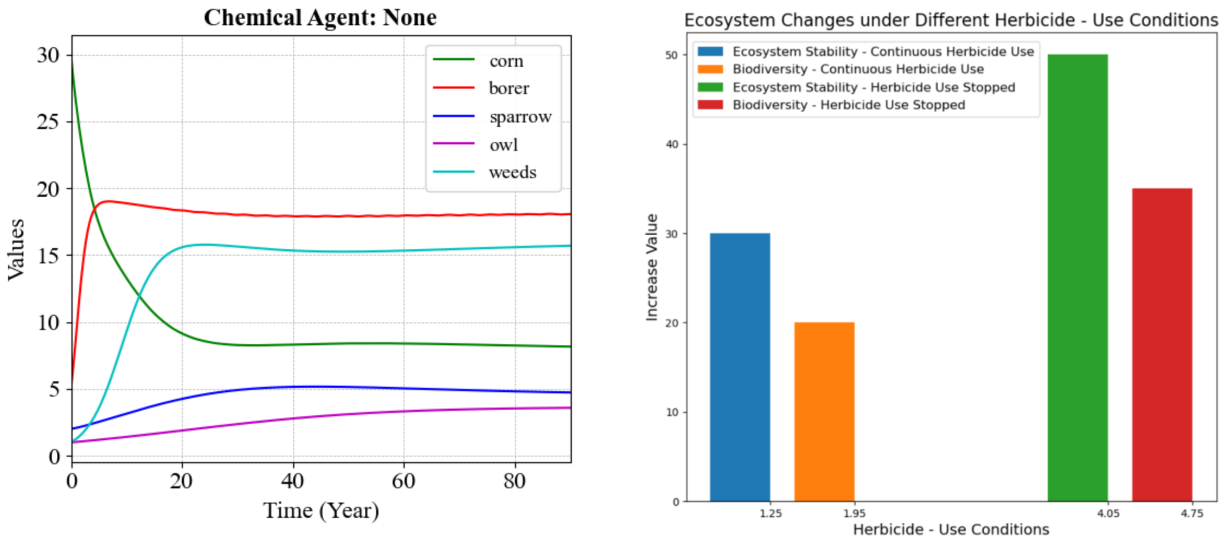
In the process of ecosystem development, this article analyzes the changes in producers and consumers and their impact on ecological stability after the discontinuation of herbicides through model analysis[6].

Based on the above model, after discontinuing the herbicide, the killing coefficient of the herbicide on weeds becomes 0. The following is the updated formula for the rate of change in weed quantity.

$$\frac{dW}{dt} = r_w(t) \cdot W\left(1 - \frac{W}{E_w}\right) - \alpha_{wi} W \cdot I - \varphi_{wc} \cdot C \cdot W - \gamma_w W \tag{10}$$

where $r_w(t)$ represents the intrinsic growth rate of weeds at time, E_w is the maximum environmental carrying capacity of weeds, α_{wi} is the feeding coefficient of pests on weeds, φ_{wc} is the influence coefficient of unit corn on unit weeds, and γ_w is the natural mortality rate of weeds.

Similarly, using the method described above, draw Figure 4.



(a) The Impact of Discontinuing Herbicides

(b) Changes in environmental stability and biodiversity

Figure 4 Diagram of Changes after Discontinuing Herbicides

This article combines the two figures (a) and (b) in Figure 4 to analyze the ecosystem changes before and after discontinuing herbicides, and draws the following conclusions[7].

Short term weeds grow rapidly due to inhibition and competition for resources with corn, leading to a decrease in the quantity of corn; The number of long-term producers (weeds+corn) increases, while the number of consumers (pests, birds, etc.) tends to stabilize with the abundance of food resources.

Compared with the continuous use of herbicides, the stability and biodiversity of the ecosystem are significantly improved after discontinuation, and the energy flow path of the food web is more complex[8].

From the perspective of ecosystem regulation mechanisms, long-term discontinuation of herbicides can reduce human interference, enrich the variety of producers, optimize the structure of the food chain, and enhance the stability and self-regulation ability of ecosystems.

3.2. Introduction of Bats and Restoration of Ecological Balance

This article first explores the impact of incorporating bats into the food web model and analyzing their effects on ecological balance using the following indicators and models.

After incorporating bats into the food web model, their population will gradually increase. [9]The following is the formula for the rate of change in population.

$$\frac{dBT}{dt} = \phi BT\left(1-\frac{BT}{BT_{\max}}\right) - \mu BTP \tag{11}$$

where ϕ is the growth rate of bats, $BT_{\max}$ is the maximum carrying capacity of bats, μ is the predation efficiency of bats on insects, P represents the population quantity of pests.

Based on the above model, the number of pests is affected by bat predation. The following is the updated formula for the rate of change in pest numbers[10].

$$\frac{dI}{dt} = \varrho - \sigma BTI \tag{12}$$

where ϱ is the natural growth rate of pests, and σ is the predation rate of bats on pests.

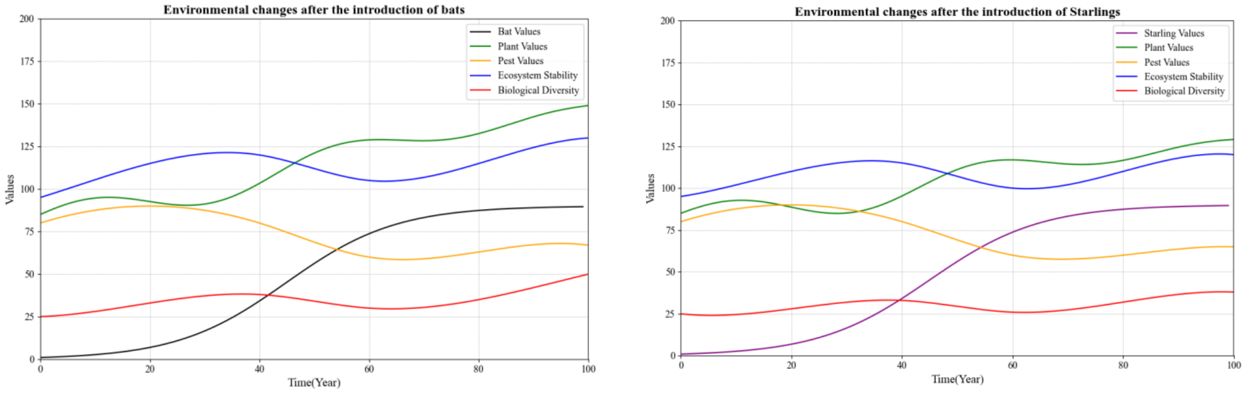
$$\frac{dP}{dt} = rP\left(1-\frac{P}{K}\right) - \alpha PI + \lambda \mathrm{BTM} \tag{13}$$

where r is the growth rate of plants, K is the environmental capacity of plants, α is the predation relationship between plants and insects, and λ is the pollination rate of bats.

In terms of ecological indicators, ecosystem stability (same as formula 8) and biodiversity (same as formula 9) will be adjusted accordingly with the dynamic changes of bat populations.

Meanwhile, to determine the differences in the roles of other species and bats in the ecosystem, we introduced another insect - eating bird, the white - cheeked starling. The indicators for measuring the environmental changes after incorporating it into the food web are roughly the same as those for bats.

Similarly, using the method described above, draw Figure 5.



(a) Environmental changes after the introduction of bats

(b) Environmental changes after the introduction of white - cheeked starlings

Figure 5 Comparison of Environmental Changes after Introducing Bats and White - cheeked Starlings Respectively

This article combines the two figures (a) and (b) in Figure 5 to compare and analyze the environmental changes after introducing bats and grey starlings, and draws the following conclusions.

The bat population grows rapidly after the adaptation period, and due to effective pest control and pollination, the number of plants increases significantly. Ecological stability and biodiversity gradually improve and tend to stabilize.

Although grey starlings can control insects, their lack of pollination function results in weaker plant growth rate and ecological index improvement effects compared to bats.

From the perspective of ecological functional mechanisms, bats, with their dual functions of insect control and pollination, have a more significant impact on improving the stability and diversity of ecosystems, which is more conducive to the restoration of ecological balance[11].

4. Conclusion

This article assesses the impact of human decisions on agricultural ecosystems by constructing a system dynamics model. The results show that although pesticides and herbicides can control pests and reduce weed competition in the short term, they will disrupt the ecological balance in the long run. Discontinuing the use of herbicides can enhance the stability and diversity of ecosystems, while introducing bats proves to be superior to gray starlings in terms of insect control, promoting plant growth, and improving ecological stability and diversity. Therefore, agricultural production needs to reduce the use of chemicals and rationally utilize beneficial organisms to promote sustainable development.

This research is of far-reaching significance. On the one hand, it provides a systematic framework for analyzing the dynamic balance of agricultural ecosystems in the process of forest conversion to farmland. By quantifying the interactions of multiple factors, such as chemical agents and species introduction, it breaks through the limitations of single-factor studies and offers a scientific basis for the refined management of ecosystems. On the other hand, the research results have direct guiding value for practice. Clarifying the effectiveness of strategies such as the precise introduction of species can provide references for farmers' production decisions and support the formulation of green agricultural policies, helping to realize the coordinated development of agricultural economic benefits and ecological protection.

Looking to the future, the research can be deepened from multiple dimensions. For instance, environmental variables such as climate change can be further incorporated, the interaction mechanisms between microorganisms, animals, and plants can be refined, and spatial dimension analysis can be added to reveal regional differences in ecosystems, thereby improving the model's ability to simulate complex realities. At the same time, it is necessary to further explore the synergistic effects of different organic agricultural strategies and develop customized schemes in combination with local agricultural production practices to promote the more efficient transformation of research results into practical driving forces for sustainable agricultural development.

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