Farming the Green Future economically based on Lotka-Volterra model and firefly algorithm

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Abstract. With the global agricultural environment changes, agroecosystems face the challenges of inefficient resource utilization and ecological imbalance. This paper explores the relationship between agricultural activities and species dynamics by constructing an agroecosystem model. It analyzes the potential of organic agriculture in enhancing ecosystem stability and other aspects. We proved the stability of the emerging agroecosystem under the model with the Stability index and Shannon's diversity index. The results showed that the crop yield increased after the return of the two species, up to 6.05t/ha per year, and that the agroecosystem, in general, was able to maintain a relatively balanced cyclic steady state.

Keywords: Logistic growth model, Lotka-Volterra model, 4th Runger-Kuta, Cellular Automaton Mode, Firefly algorithm.

1. Introduction

1.1. Background

The conversion of forests to agricultural land leads to ecological changes as crops and farm- ing practices replace the biodiversity found in the forests[1]. In the process, species that originally inhabited the forest gradually disappear and are replaced by species that can adapt to the new environment. Monocropping and agricultural activities (such as the use of pesticides) exacerbated this change, creating food chains dominated by crops and species adapted to the farm environment. As agrarian systems mature, the ecological diversity is usually less than primary forests, although some wildlife is supported. Understanding this process requires consideration of the effects of both natural succession and human agricultural choices[2].

1.2. The related work

Tittonell[3] contrasts ecological intensification with conventional sustainable intensification, arguing that the former prioritizes landscape-level design to leverage natural ecosystem functions, such as pollination and nutrient cycling, thereby reducing reliance on external inputs. Bommarco et al.[4] demonstrate how agroforestry and cover cropping in tropical regions enhance soil fertility while sequestering carbon, underscoring the ecological and economic viability of such models. Parrot Sequoia's multispectral cameras [5] monitor plant health indicators like NDVI (Normalized Difference Vegetation Index), providing actionable insights for sustainable yield maximization. The circular bioeconomy framework, explored by Davies and Shen[6] in China's Agricultural Green Development (AGD) agenda, advocates for waste valorization and resource efficiency. As Kynetec[7] notes, "Regenerative agriculture is not a one-size-fits-all solution, but a spectrum of practices guided by ecological literacy and farmer agency."

1.3. Main Work

The paper investigated the dynamics of an emerging agroecosystem through a series of interconnected tasks. Initially, the framework employs ecological models such as the Logistic Growth model and the Lotka-Volterra model to simulate agricultural cycles, incorporating variables like producer-consumer interactions, chemical inputs, and seasonal fluctuations. Concurrently, stability assessments are conducted using metrics like the Stability Index and the Shannon Diversity Index to quantify ecosystem resilience. Secondly, we involved exploring the ecological impacts of reintroducing key species, such as bees, earthworms, and natural predators into the crop system, utilizing advanced models like the Grid-based Reaction-Diffusion Model and meta-cellular automata for spatial and temporal analysis. The third task critically evaluates the discontinuation of synthetic herbicides and the introduction of bats as biological pest control agents, focusing on ecosystem rebalancing and the comparative efficacy of these interventions. Finally, the framework contrasts the advantages and disadvantages of organic farming strategies against conventional approaches, assessing criteria such as biodiversity enhancement, pest suppression, economic viability, and long-term sustainability. A randomized portfolio approach is employed to synthesize these evaluations, providing a holistic perspective on optimizing agroecological management practices.

2. Preliminary

2.1. Assumptions

1.Identify ecological relationships among species that affect their growth and stability, such as predation, competition, and cooperation. Weeds compete with crops for resources and provide habitat for insects, but insects do not eat weeds [8]. Herbicides affect plant growth and reduce insect populations, and pesticides affect the mortality of insects and their predators.

2.Populations of species cannot grow indefinitely; each species has a maximum carrying capacity (K value). As populations approach or exceed the K value, limited resources can cause growth to slow or decline. All species have a natural mortality rate, reflecting the natural waning process in the absence of external disturbance [9].

3.Ecosystems are self-regulating, restoring equilibrium through species redistribution and population dynamics. Species populations usually vary with seasons and agricultural cycles.

4.Assuming no weather extremes or sudden disasters during the simulation period, population changes are determined only by inter-species interactions and resource changes [10].

2.2. Notations

The core symbols and their definitions used in this study are summarized in Table 1.

Table.1. Notations

Symbol	Description
P(t)	Number of crop populations
W(t)	Number of weed populations
I(t)	Number of primary consumer (insect) populations
C(t)	The difference between the highest and lowest values of the signal within a cycle
B(t)	Number of subconsumer populations
E(t)	Number of bee populations
A(t)	Number of Earthworm populations
K	Maximum load capacity
r	Growth parameter
S(t)	Seasonal variation factor

3. Model Construction

3.1. Modeling ecosystems

We must construct a food web model that integrates the agricultural cycle, seasonal varia- tions, and dynamic stability. The model will include the following elements: producers (crops and weeds), primary consumers (insects), secondary consumers (insect predators), and the impact of chemicals (herbicides and pesticides) on the ecological balance.

The model is situated in a temperate climate zone with four distinct seasons, and agricultural production is significantly influenced by seasonality. The growth cycle of crops is well-defined. The area is 5km x 5km, totaling 25 square kilometers (2500hectare), which includes a certain amount of farmland and some edge habitats [2]. It is shown in Figure 1.

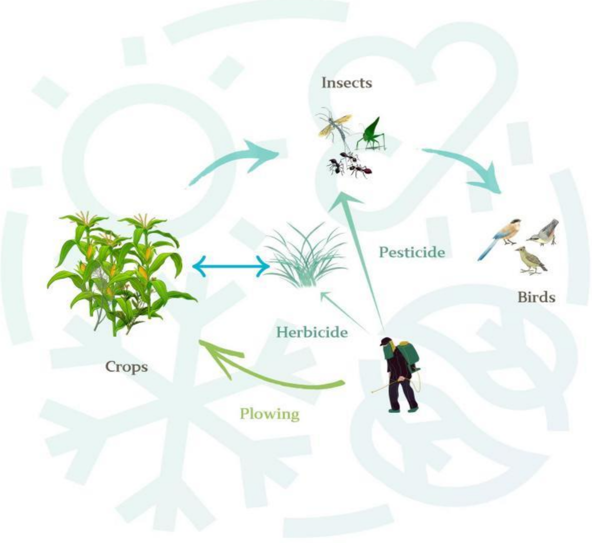

Figure 1. Schematic for the model

In building this ecosystem model, we will use a combination of the Logistic growth model and the Lotka-Volterra model to account for population growth and interspecies interactions. The logistic model describes the self-growth of species under the environment's carrying capacity, and the Lotka-Volterra model describes the interactions between species, such as predation and com- petition. By combining these two models, we can model ecosystems more holistically, considering resource constraints and reflecting interactions between species. The model will be solved by nu- merical methods (fourth-order Runge-Kuta method) to simulate changes in species numbers under different conditions and reveal the dynamic relationship between agricultural activities and economical systems.

We simulated the population changes of crops, weeds, insects, and predators over 800 days, as shown in Figure 2 The results show that they are in a fluctuating equilibrium and are characterized by seasonality and agro-cyclicality.

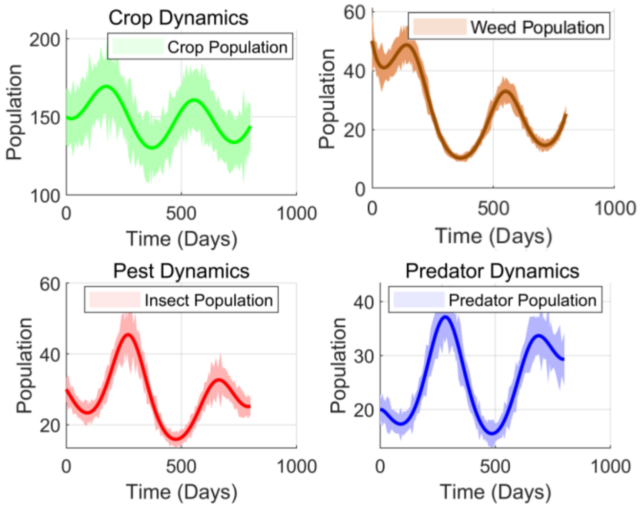

Figure 2. Population Dynamics of Crops, Weeds, Insects, Predators, and Total Population

The results in Figure 2 show that the crop population is stable with fluctuations, reflecting seasonal variations. The high yield of various crops, with an average annual yield reaching 5.04 t/ha, indicates that agricultural management measures have promoted their growth. Pest populations correlated with crop populations with a lag, with pests increasing when crops were high but slightly decreasing numbers due to insecticides. Predator numbers correlated with pest numbers and showed lagging, with lower numbers indicating their moderating role in controlling pests. Weed populations were initially high and maintained mainly at low levels after the annual cycle of herbicide application. Insecticide and herbicide use significantly affected pest and weed populations, with agent efficacy decaying over time, demonstrating short-term effects versus long-term challenges.

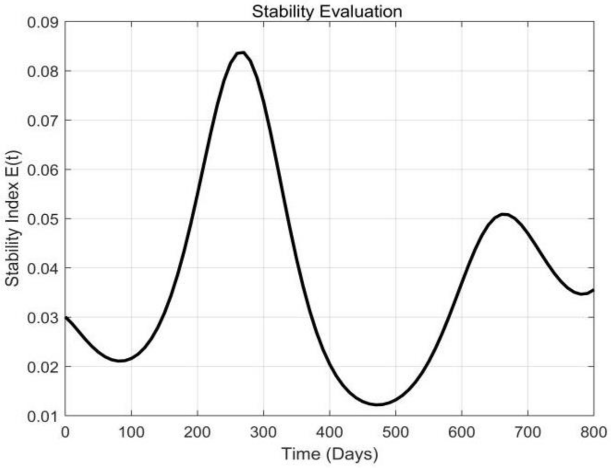

Figure 3. Population Dynamics of Crops, Weeds, Insects, Predators, and Total Population

As shown in Figure 3, the stability index E(t) fluctuates periodically with time, and the fluctuation amplitude is relatively tiny. It always stays within a specific range without drastic changes. This indicates that the species populations in the ecosystem maintain a dynamic balance, the in- teractions between the species are stable, and the system has strong stability. It can effectively maintain the ecological balance with external disturbances.

In summary, the simulation verified the validity of the model and showed that agricultural management practices using chemicals have important effects on ecosystem stability and species population dynamics.

3.2. Species Reintroduction

As the agroecosystems agroecosystems of marginal habitats mature, it was required to reintroduce two native species, assess their shadows on the ecosystems, and analyze their impacts on the ecosystems. We chose the following two species.

The return of bees could increase the biodiversity of the ecosystem by promoting crop yield and quality through pollination. Moreover, there may be some level of competition or interaction between bees and insects that can suppress insect populations.

The return of soil worms can increase the efficiency of organic matter decomposition in the soil, helping to improve soil fertility and increase crop resistance to pests and diseases. Soil worms' activities in the soil affect insect habitats, indirectly suppressing insect populations.

Both species can find habitats in agroecosystems without disturbing the existing ecological balance. The ecological services they provide will help enhance the sustainability of agricultural production while increasing the biodiversity and stability of agroecosystems.

We visualized the ecosystem model after regression of two species by Grid-based Reaction-Diffusion Model. In Figure 3, at week four, both species have just returned from four weeks of the ecosystem model and have relatively small populations. Hence, the impact on the ecosystem and other species is insignificant. By the fifteenth week, after a period of reproduction, these two species are gradually distributed evenly in the model and begin to play their role in promoting crop growth and effectively controlling the number of insect populations.

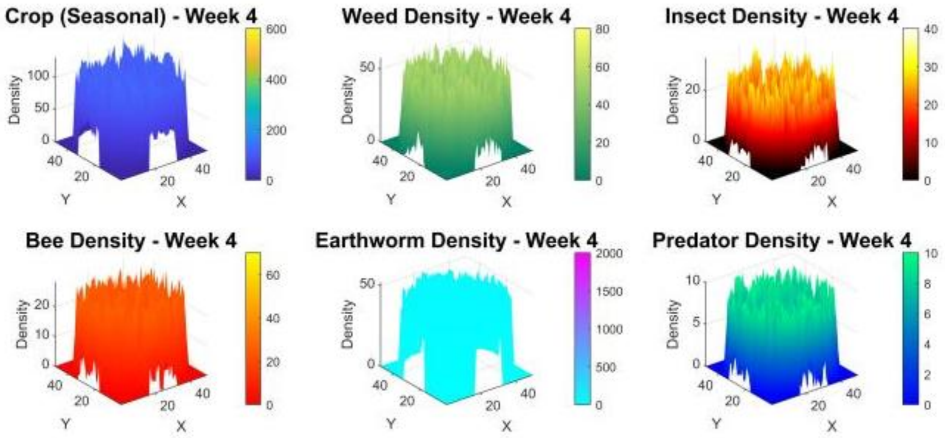

Figure 4. Later population dynamics

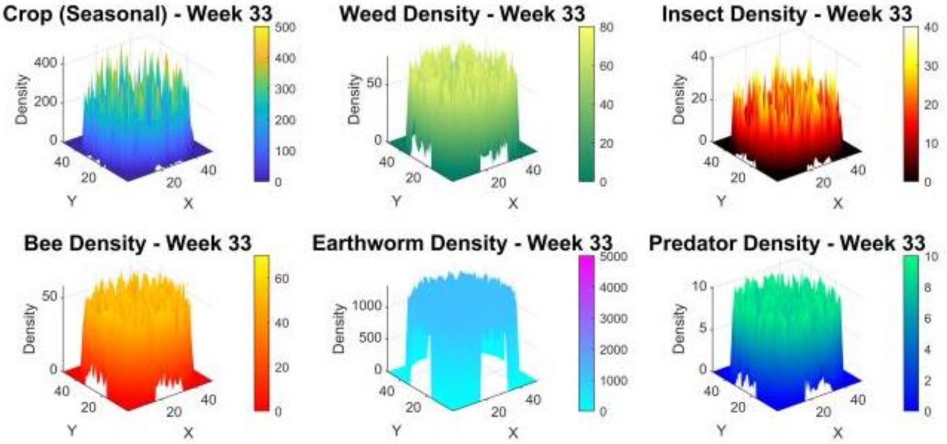

Figure 4. Later population dynamics

In Figure 4, at week 33, the number of crops reached its maximum due to seasonal changes and the mutually reinforcing effects of these two species. In contrast, the number of insect populations remained stable without significant changes, further highlighting the important roles of these two species in the ecosystem. After entering the 55th week, with the arrival of winter, the number of each species in the ecosystem decreased slightly, but overall, it remained relatively stable. This suggests that the ecosystem maintained a relatively balanced cyclical stable state through the self-feedback regulation mechanism after the return of these two species. It also proves the feasibility of our established model.

3.3. Ecosystem Stability Assessment

We developed a meta-cellular automata model that synthesizes a resilient ecosystem through dynamic fluctuations, spatial heterogeneity, the survival of key functional groups, and visualization of harmful feedback mechanisms [7].

Figure 5 shows that the populations of crops, insects, predators, and other species fluctuate seasonally without unidirectional growth or collapse. The cyclical fluctuations indicate that the system can adapt to external seasonal changes, and the species maintains a dynamic equilibrium through interactions. Species formed localized aggregations in the 3D grid, but there was no large-scale monopolization by a single species. Key species such as bees and soil worms are always in the scene (yellow and purple dots do not disappear), reflecting their continuous contribution to ecological functions. Bees are scattered around the crop clusters (dense green areas) to promote pollination, and soil worms are dispersed to show that soil fertility is uniformly supportive of crop growth.

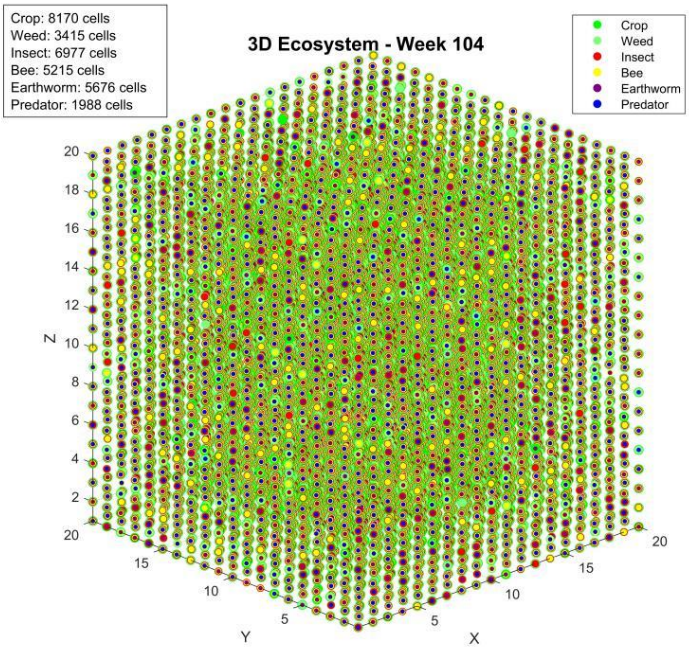

Figure 5. Images of ecosystems generated by meta cellular auto mata

The continued operation of these ecological processes (e.g., decomposition, pollination) enhances the system's resistance to disturbance. Populations of all species were consistently greater than zero, with no species extinctions, indicating redundancy and resilience of the system. The species were driven by seasonal variation and biological interactions, resulting in a dynamic equilibrium rather than static stagnation, consistent with the stability characteristic of natural ecosystems.

4. Predicting possible precursor signals

Firstly, feature extraction is performed on the raw signal data, including statistical features (such as mean, variance, kurtosis) and spectral features (such as spectral energy, main frequency components, spectral density, etc.) [9]. By setting appropriate window sizes and step sizes, the continuous signal is divided into multiple segments, and then feature calculations are performed on each segment. Next, the calculated feature vectors are subjected to differential processing to enhance the sensitivity of the model to signal changes, which helps to better capture the feature variations of precursor signals. After completing feature extraction, random oversampling techniques are used to address the issue of class imbalance in the dataset, ensuring that each class has an equal impact during the training process.

Train the model on processed data using a decision tree classifier, and improve the predictive performance of the model by optimizing hyperparameters. The classifier will classify the signals in the test dataset based on the patterns learned from the training data to predict whether they are precursor signals.

We can consider using a sliding window method to extract data between partitions. Calculate features every 48 data sets as the window size. This approach allows us to observe the changes in features within each interval more closely, thereby more accurately grasping the trend changes. By analyzing the characteristics within different intervals, we can identify potential trends and provide timely warnings.

4.1. Herbicide removal

After the ecosystem has matured and herbicide use has ceased, the stability of producers and consumers needs to be assessed. Bats are then included in food chain models to bring the system back into balance, analyze their interrelationships with insects (including bees), plants, and predators, and assess the impact of bats on ecosystem stability. Subsequently, another beneficial species is chosen to replace the bats, and the differences in the roles of the two species in maintaining ecological stability are compared.

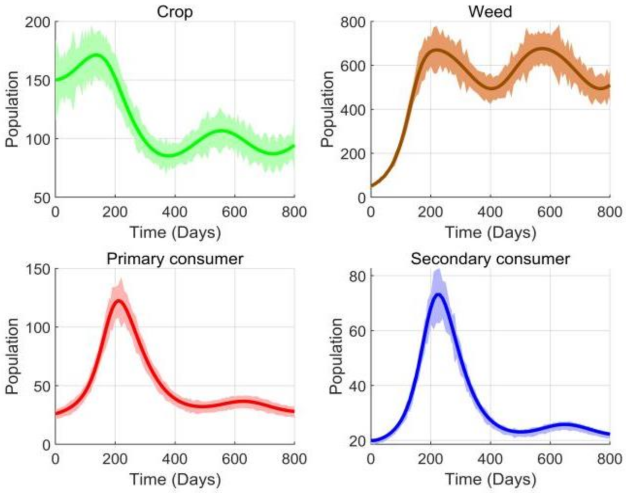

Figure 6. Species dynamics after herbicide removal

As seen in Figure 6, during the initial cessation of herbicide use, weeds increased rapidly due to the loss of their main inhibiting factor. The proliferation of weeds led to their competition with crops for limited resources, leading to a significant decline in crop populations. This change not only affected producer populations but also had a knock-on effect on primary and secondary consumers. As crop resources declined, so did the numbers of insects (primary consumers) and their predators (secondary consumers), showing a close correlation with changes in crop populations. This phenomenon suggests that herbicide use has an important role in regulating the population structure and species interactions in ecosystems, that the dynamic equilibrium of ecosystems was disrupted, and that species interactions were significantly affected by the withdrawal of herbicides.

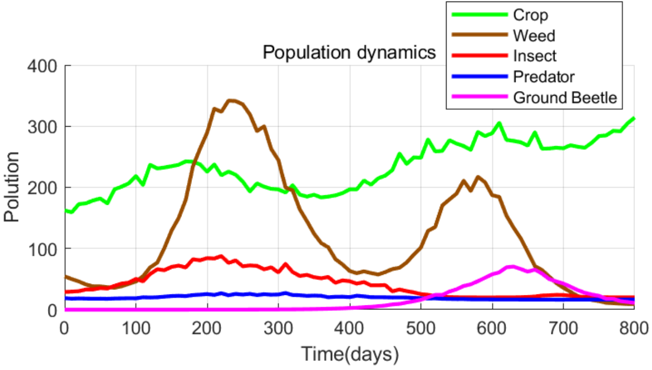

Figure 7. Population dynamics of the step beetle after its introduction

As shown in Figure 7, we introduced step beetles when the weed population declined due to seasonal changes. The step beetles feed on the weeds, thus effectively controlling the weed population to normal levels. When the weed population declined, the step beetles began to turn to insects as a new food source, resulting in a decline in the insect population. At the same time, there is a competitive relationship between the step beetles and the predators that prey on the insects, which inhibit each other. As weed populations rise again with the change of seasons, the step beetles exert control over weed populations, allowing the crop to access more of its limited resources and promoting crop population growth.

Bats contribute directly to crop growth by feeding on insects and promoting pollination, whereas weed suppression affects weed populations indirectly by increasing the ability of crops to compete for resources. A competitive relationship between bats and predators creates a direct interaction.

Step beetles directly affect weed and insect populations by directly feeding on them and affecting the populations of both species. The impact of the step beetle on crops is indirect, contribut- ing indirectly to crop growth, mainly by controlling weeds and insects. Competitive relationships characterize the interactions between step beetles and insect predators. Both bats and step beetles can maintain ecosystem stability through different mechanisms, ensuring balance and interaction between species.

5. Multi-objective optimization

To solve the multidimensional optimization problem that farmers may face when adopting organic farming methods, we constructed a multi-objective optimization model combined with a firefly algorithm. Below is the framework of a specific mathematical model we built, incorpo- rating multiple objectives of pest control, crop health, plant reproduction, biodiversity, long-term sustainability, and cost-effectiveness.

5.1. Firefly Algorithm

Since this model is for a multi-objective optimization problem, we adopt the Firefly Algo- rithm, a heuristic optimization algorithm, to simulate the process of fireflies attracting each other by their flashes during the searching process and use the Pareto optimal solution set to solve the above objective function set.

In the firefly algorithm, it is assumed that each firefly represents a decision scheme x, and its flash intensity I(x) is related to the merit of the objective function value. For multi-objective optimization problems, you can somehow (such as the weighting method) combine objective function value and calculate the firefly’s "brightness". The basic steps of the algorithm are as follows.

1.Initialization: Randomize a group of fireflies; each corresponds to a solution x_i.

2.Evaluate brightness: Calculate each firefly’s brightness according to the objective function’s value.

3.Update position: fireflies adjust their position according to their brightness and distance to attract fireflies that are brighter than themselves.

5.2. Analysis of results

Each curve in the Figure 8 represents the path of a "firefly" in the optimization process, starting from the initial parameter combination and approaching the optimal solution after several iterations. Each "firefly" has certain rules (such as attraction and neighborhood search) that update and ultimately converge to the optimal solution area. The position of each point in the figure represents the parameter combination after a certain iteration, while the line segment represents the trajectory of the "firefly" in the iterative process.

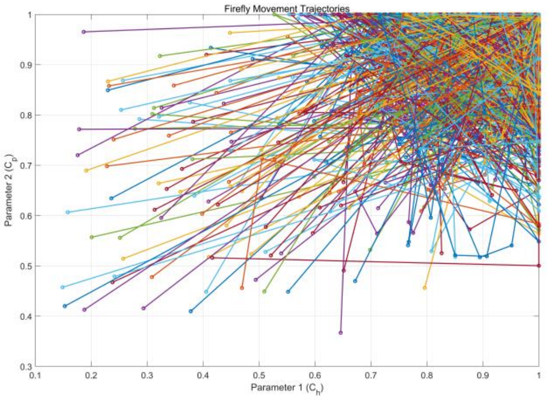

Figure 8 Firefly Algorithm Patrol Superiority Trajectory

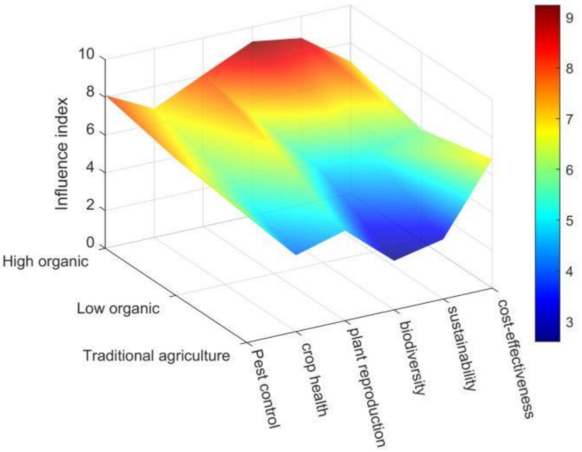

Figure 9 Weighting of the impact of different organic strategies on the objectives

In Figure 9, the simulation results show that with the introduction of biocontrol measures (e.g., the introduction of natural enemies) in organic farming, the health of the crop improves, and the number of pests decreases significantly. By adjusting the biocontrol coefficients, the pest populations were effectively suppressed, and the crops were able to grow stably; with the reduction of chemical fertilizers and the introduction of natural pollination of crops by beneficial species, the health status and reproductive capacity of crops were significantly improved; not only that, organic agriculture in various ways improves the ecosystem diversity, but also protects and increases the number of plant and animal species in the field and stabilizes the ecological chain. In the long run, it improves the farmland's environmental and economic benefits and realizes the farmland ecosystem's sustainable development.

5.3. Sensitivity Analysis

This paper made reasonable estimates for most of the parameters in the ecosystem model. Considering that some initial parameters in the model remained unchanged during the simulation experiment, such as γH KP . Therefore, based on the dynamic model, we adjusted each of the above parameters of the ecosystem dynamic equations by ±5% and ± 10%, respectively, and calculated the average total biomass of the four species during the simulation period, and the results are shown in Figure 10.

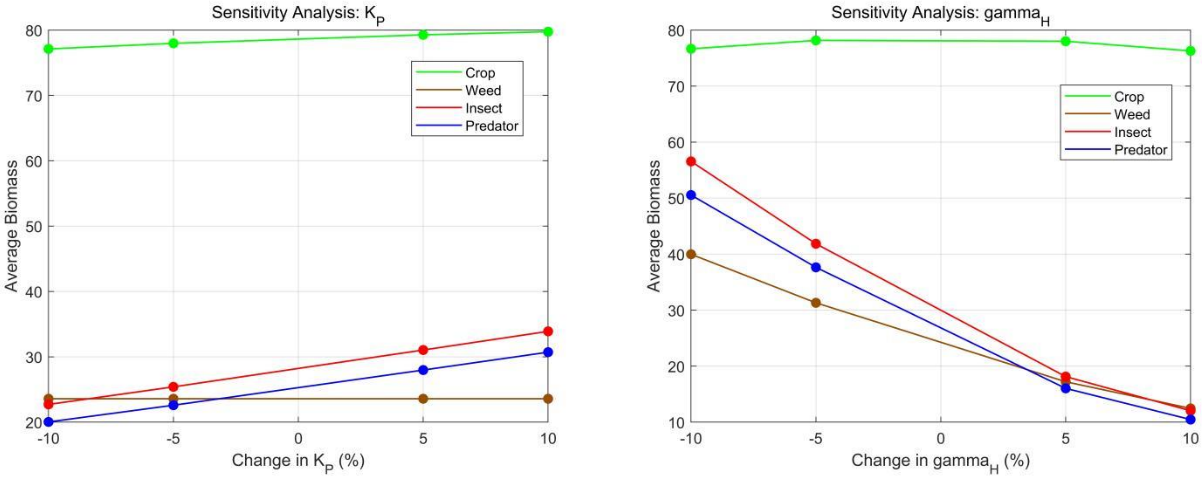

Figure 10 Sensitivity analysis

As can be seen from Figure 10, the average biomass of each species is more stable with KP . However, the change of γH on the average biomass of each species is more obvious, but the effect of γH on the total biomass is small and within acceptable limits. Our model performed well in the sensitivity analyses of various parameters, which suggests that our model has good long-term stability.

The model integrates crops, insects, bats, birds, and chemicals and can comprehensively reflect the dynamics of agroecosystems. It reflects agricultural cycles and seasonal changes and assesses the impacts of chemical substance use on ecosystems, which has high application value.

This model can help farmers make favorable agricultural development choices in the long run by analyzing profit and sustainability. Especially in organic agriculture, where long-term re- turns may outweigh short-term gains, it provides farmers with guidance to help them make long- term planning and investment decisions. Much of the data in the model is derived based on assumptions, such as market prices, yields, and costs of organic crops, which may differ from the actual situation. The model's accu- racy relies on the quality of the input data, so if the data are inaccurate, the model's predictions may be affected, leading to bias. 2 Although the model can be analyzed theoretically, it lacks vali- dation against actual agroecosystems. Without the support of field data, the predictive ability and reliability of the model may be limited. 3 The model assumes that all species are spatially evenly distributed and does not consider ecological differences in land areas, such as soil quality and cli- matic conditions. As a result, the model may not fully adapt to the complexity of real agricultural scenarios.

6. Conclusion

This paper used algorithms such as fourth-order Lungkuta and Firefly to solve the model. These algorithms have a strong global search capability, are suitable for solving complex parameter optimization problems in ecosystem models, and can efficiently find optimal agricultural management strategies. The model utilizes systematic thinking, focusing on species interactions and the effects of chemical substances. By reasonably setting parameters, such as pesticide concentration and crop growth cycle, the model can accurately reflect the changes in the agroecosystem, ensure that the results meet the actual needs, and effectively solve the problems in agricultural production. In the future, we can further improve the model's multidimensional analysis ability by introducing more ecology and agricultural economics theories, especially in agrarian models such as organic farming, where long-term returns are better than short-term returns, to provide farmers with more accurate decision support.

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