Mathematical Modeling and Algorithm Application
ISSN: 3006-0842 | Vol. 6, No. 1, 2025

Sustainable Agricultural Management Strategies Based on Natural Processes and Human Decision-Making

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Abstract: As agricultural land expands, constructing a sustainable and stable ecological balance has become a crucial issue in agricultural production. This paper aimed to track the evolution of ecosystems and the selection of agricultural patterns. We extended the Lotka-Volterra model under the premise of constructing five subsystems, based on the Logistic growth model, and optimizes the periodic changes of the ecosystem using the RK4 algorithm. Then a biodiversity recovery model is constructed based on the Lotka-Volterra model. Five key indicators are extracted to establish an ecosystem stability model based on dynamic system theory. A Lotka-Volterra model is constructed based on five factors affecting the ecosystem, and appropriate parameters are set to analyze the impact of organic agriculture. The paper details the ecological and economic impacts of shifting to organic agriculture. It suggests that farmers introduce species such as bats and birds for biological control, optimize resource management, and master organic agricultural techniques.

Keywords: Organic Agriculture, Biodiversity Restoration, Lotka-Volterra Model, Dynamic System Theory.

1. Introduction

According to the GFW website, from 2001 to 2023, the global forest cover lost a total of 488 Mha, of which about 25% was used for agricultural development [1]. In traditional agricultural ecosystems, there are complex interrelationships among species, such as crops, insects, bats, birds and chemicals (such as herbicides, pesticides) [2]. The implementation of organic agriculture makes farmers see another possibility of more lasting and environmentally friendly development [3]. In the process of agricultural transformation, how to balance cost and sustainability and make scientific production decisions is an important issue for the development of agricultural ecology.

Sustainable agricultural management strategies that harmonize natural processes with human decision-making have emerged as critical pathways to address global challenges like food security, biodiversity loss, and climate change. A 2025 report by the International Union for Conservation of Nature (IUCN) underscores the potential of Nature-based Solutions (NbS) in agriculture, emphasizing their alignment with biodiversity conservation and farmer livelihoods[3]. The participatory approach to sustainable agriculture has gained traction, as evidenced by a 2024 analysis of New Zealand case studies. Farmers' choices between waste-fed fish ponds and rice-fish rotations were driven by land accessibility, labor availability, and market signals, underscoring the importance of context-specific decision-making tools[4]. Australia's "Carbon+ Biodiversity Pilot" rewards farmers for adopting cover cropping and wildlife corridors, aligning economic incentives with ecosystem health[5]. A 2024 analysis of Sub-Saharan Africa's "climate-smart villages" notes that while intercropping and drought-tolerant quinoa varieties improved yields by 25% during El Niño events, fragmented land tenure and limited access to weather-indexed insurance hindered adoption[6].

1.1. Our work

This paper synthesizes ecological theory with practical decision-making, advocating for a holistic approach to sustainable agriculture. This paper underscores the importance of integrating natural processes (predator-prey dynamics, nutrient cycling) with human interventions (e.g., species reintroduction, policy incentives) to achieve resilient, productive, and environmentally benign farming systems. Then we analyze the effects of different components of organic agriculture on the whole and part of the ecosystem, including but not limited to pest control, crop health, plant reproduction and so on. By evaluating both ecological outcomes and socioeconomic factors, we finally provides a blueprint for balancing food security with biodiversity conservation in agricultural landscapes.

2. Preliminary

2.1. Assumptions

To simplify the given problems and modify it more appropriate for simulating real-life conditions, we make the following basic hypotheses, each of which is properly justified.

1.The impact of climate change on ecosystems is ignored in this model.

2.Interactions between species can be reduced to linear relationships.

3.The dynamic changes of soil nutrients are mainly affected by plant uptake and natural supplement.

2.2. Agricultural Ecological Subsystem

Plants are producers in agricultural ecosystems. With farmland development, the originally rich variety of plants may decrease, and crops are planted instead. Fertilizers and herbicides used in agriculture affect plant health, potentially leading to a decline in plant numbers or reduced species diversity[7].

$$\frac{dP}{dt} = rP(1 - \frac{P}{K}) - \alpha PN + \beta S \tag{1}$$

where N: soil nutrient concentration, which indicates the total amount of nutrients in the soil per unit area. β: the contribution rate of soil nutrients to plant growth reflects the promoting effect of soil nutrient supplementation on plant growth. S: soil nutrient replenishment rate, which indicates the rate at which soil nutrients are replenished by external factors such as fertilization.

Insects are one of the main consumers in agricultural ecosystems, especially pests, which can affect the growth of crops. After the transformation of agriculture, the types and numbers of insect populations may change, especially under the influence of chemicals.

This paper uses the Lotka-Volterra model[8] to describe the dynamic changes of insect populations, with the equation being:

$$\frac{dI}{dt} = \gamma I(1 - \frac{I}{L}) - \delta PI + \eta F \tag{2}$$

where η: the extent to which insect populations are affected by predators such as birds/bats. F: the number of predators, which indicates the control effect on the insect population.

Birds are important control factors in agricultural ecosystems, especially insectivorous birds that help control the number of pests. As the agricultural system matures, bird populations may change with the food chain. Bats play a role in controlling pests in agricultural ecosystems, especially nocturnal insect predators. Bat population growth is related to the number of insects and available habitats[9].

$$\frac{dB}{dt} = \mu B(1 - \frac{B}{M}) - \upsilon BI + \theta I \tag{3}$$

where I: insect biomass, which indicates the food source of birds/bats. θ: the degree of influence of insects on birds/bat populations reflects the supporting effect of insect populations on predator populations.

Soil is the foundation of agricultural production, and soil quality determines the growth potential of crops. With the management of farmland and the use of chemical substances, the organic matter and nutrients in the soil may change.

$$\frac{dN}{dt} = \kappa - \lambda PN + \omega \tag{4}$$

where N: soil nutrient concentration, which indicates the total amount of nutrients in the soil per unit area. κ: soil nutrient replenishment rate, which indicates the rate at which soil nutrients are replenished by external factors such as fertilization. λ: the rate at which plants consume soil nutrients, which reflects the efficiency of soil nutrient uptake by plants. P: plant biomass, which indicates the consumers of soil nutrients. ω: the rate of natural replenishment of soil nutrients, which indicates the replenishment of soil nutrients by natural processes, such as the decomposition of organic matter.

2.3. Number of Species Reintroduced

The number of species reintroduced reflects the quantity of native species that gradually reappear in agricultural ecosystems. Over time, the number of species reintroduced tends to increase gradually, but this growth rate is limited by the adaptability of the current environment[10].

$$\frac{dR}{dt} = \gamma R(1 - \frac{R}{R_{max}}) \tag{5}$$

where γ: growth rate of species regression. R_{max}: the maximum limit on the number of species regressed.

$$R(t) = R_0 e^{\alpha t}(1 - \frac{R(t)}{K}) \tag{6}$$

where r_0: the initial number of species regressions. α: rate of species regression.k: the maximum number of species that an ecosystem can support.

2.4. Notations

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

Table 1. Notations

Symbol	Description
P	plant biomass, which represents the total amount of plants per unit area
I	insect biomass, which indicates the total number of insects per unit area
B	bird/bat biomass, which represents the total number of birds/bats per unit area
α	the rate at which plants consume soil nutrients
L	the rate at which insects consume plant biomass
υ	the rate at which birds/bats consume insect biomass
r	the intrinsic growth rate of the plant
δ	the intrinsic growth rate of insects
μ	the intrinsic growth rate of birds/bats
K	the maximum carrying capacity of a plant in a given environment
γ	the maximum carrying capacity of an insect in a given environment
M	the maximum carrying capacity of birds/bats in a given environment
C	herbicide/insecticide usage
σ	effect coefficient of herbicide/insecticide use on insect mortality
SFR	soil fertility index
SDI	biodiversity index
ES	ecological stability index

3. The impact of chemicals on agricultural ecosystems

The paper constructs a multidimensional and dynamic ecosystem model through the modeling of the six subsystems, which can simulate the changes of various ecological variables in the process of transformation from forest to farmland. The model not only takes into account the dynamic changes of natural ecological elements such as plants, insects, birds/bats, and soil, but also introduces the impact of human decision-making on the ecosystem and the periodic impact of seasons, providing a scientific basis for assessing the sustainability of agricultural policies.

3.1. Visualization of Results

Based on the above model, we uses the fourth-order Runge-Kutta method to numerically solve the input initial conditions and parameter values. At each time step, the time variation of P(t) and I(t) is obtained by repeated calculation.as shown in Figure 1:

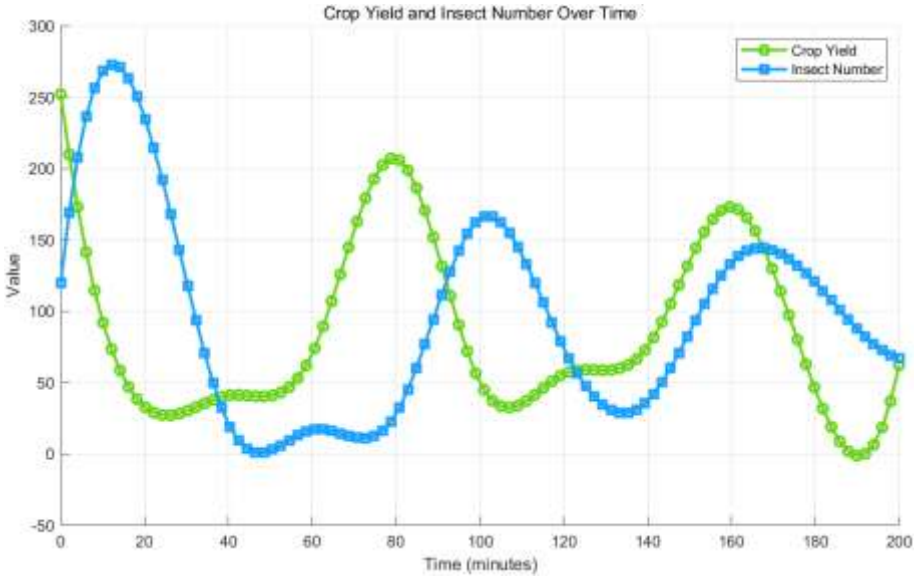


Figure 1. Crop and insect population dynamics

Generally, the quantities of crops and insects exhibit periodic fluctuations, indicating that they are influenced by seasonal changes. As can be seen from the above figure, the high degree of overlap between the two curves reflects the interdependence of the quantities of crops and insects.

Through this model, this paper can analyze the impact of different agricultural practices on the ecosystem. Pesticides can effectively control pests, but they can have a negative impact on birds/bats, which in turn affects plants. Therefore, using low-intensity pesticides or organic farming may be more conducive to the balance of the ecosystem and the sustainable development of agriculture.

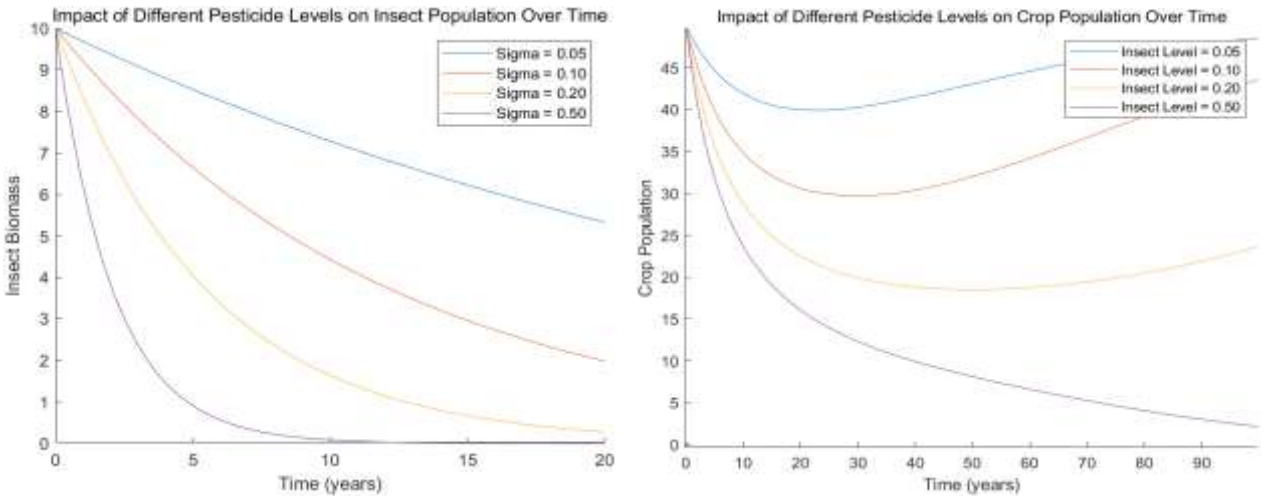


Figure 2. The effects of pesticides on insects and crops

Additionally, Figure 2 shows that high doses of pesticides can quickly eliminate pests but also have a negative impact on crop yield. Using the aforementioned methods, this paper further discusses the effects of chemicals on soil fertility, biodiversity, and other aspects.

Considering all these factors, a radar chart is created in Figure 3.



Figure 3. Effects of chemicals

Figure 3 provides a comprehensive perspective for this paper, showing the impact of chemicals on agricultural ecosystems. While chemicals play a significant role in eliminating pests and increasing crop yields, their destructive effects on biodiversity and the ecological environment cannot be ignored. Therefore, in the agricultural production process, it is important to use chemicals in moderation.

4. Analysis of Species Reintroduction

As species are reintroduced, the stability of the ecosystem may change. The diversity of species and the interactions between them can promote the recovery of the ecosystem, leading to increased stability. The return of species not only affects the stability of ecosystems but also promotes the recovery of soil, especially through the return of plant species. These plants, through nitrogen fixation and the decomposition of organic matter, contribute to the restoration of soil fertility.

Figure 4 indicates that with the return of species, both the stability of the local ecosystem and the degree of soil fertility recovery have improved.

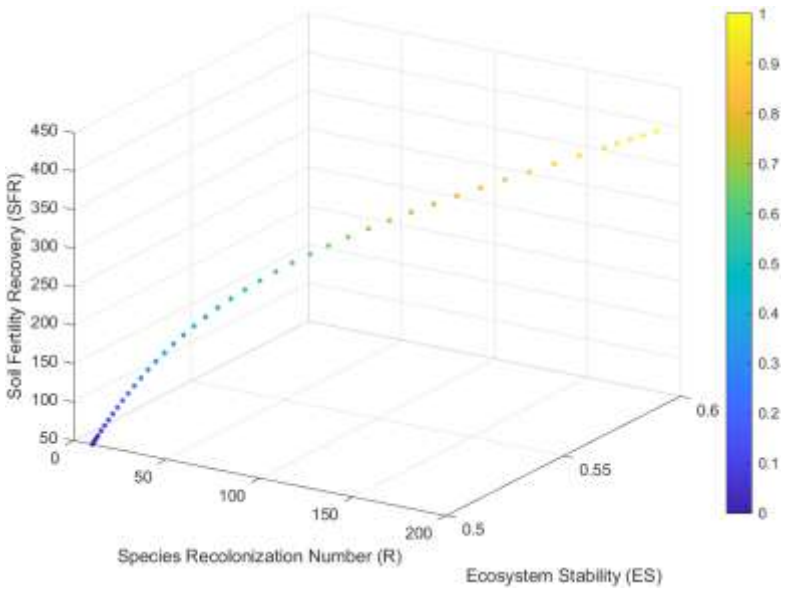


Figure 4. Effects of species reintroduction

These conclusions are drawn from the biodiversity model of species reintroduction established in this paper. Next, taking two species as examples, the impact of species reintroduction on agricultural ecosystems will be studied.

4.1. Comparative Study of Multiple Species

After these two species returned to the local area, crop yields increased significantly and the number of pests decreased. Apparently, species reintroduction can help restore ecological balance and realize the potential of sustainable agricultural practices. The results emphasize the importance of reducing chemical inputs and promoting natural predator-prey interactions to enhance ecosystem resilience and economic viability. The model can provide important references for farmers in balancing agricultural productivity and ecological sustainability. It is shown in Figure 5 and 6.

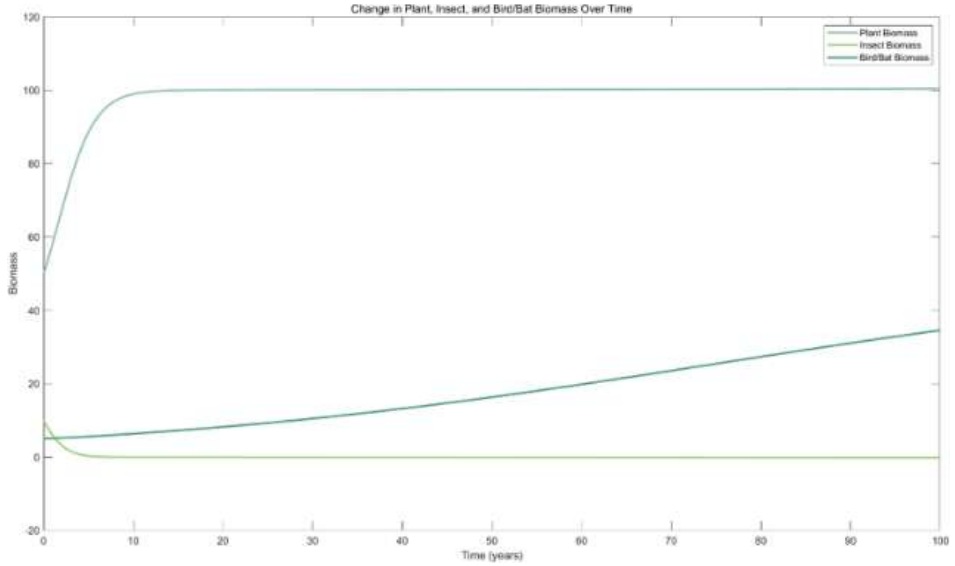


Figure 5. Changes in Plant, insect and Birds

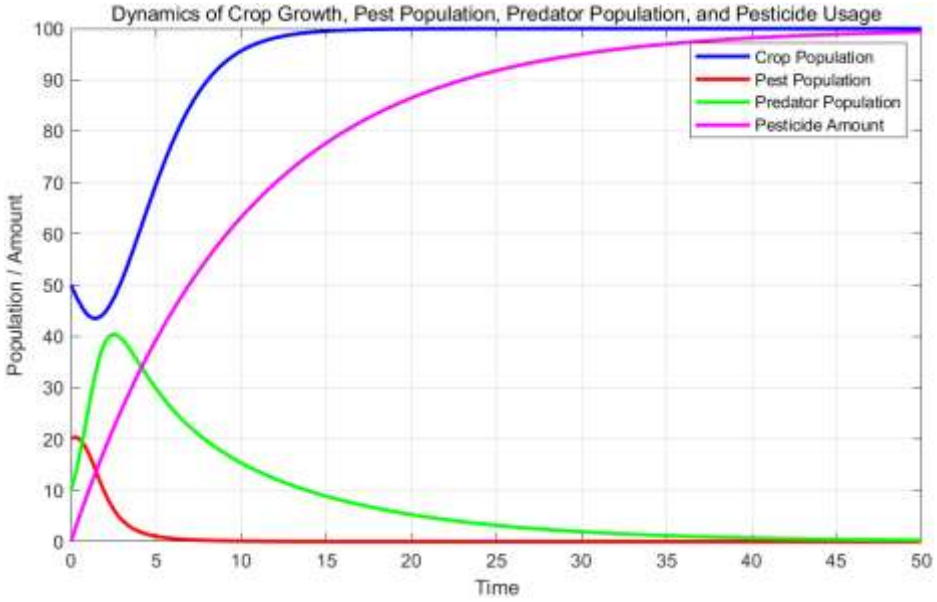


Figure 6. Changes in Crop, Pest and Predator

4.2. Species Comparison

After the introduction of bats, the insect population was effectively controlled, plant growth was promoted, and the ecosystem tended to stabilize. To enhance the scientific nature of the study, this paper decided to introduce owls to study their impact on the overall stability of the ecosystem. The results are shown in Figure 7.

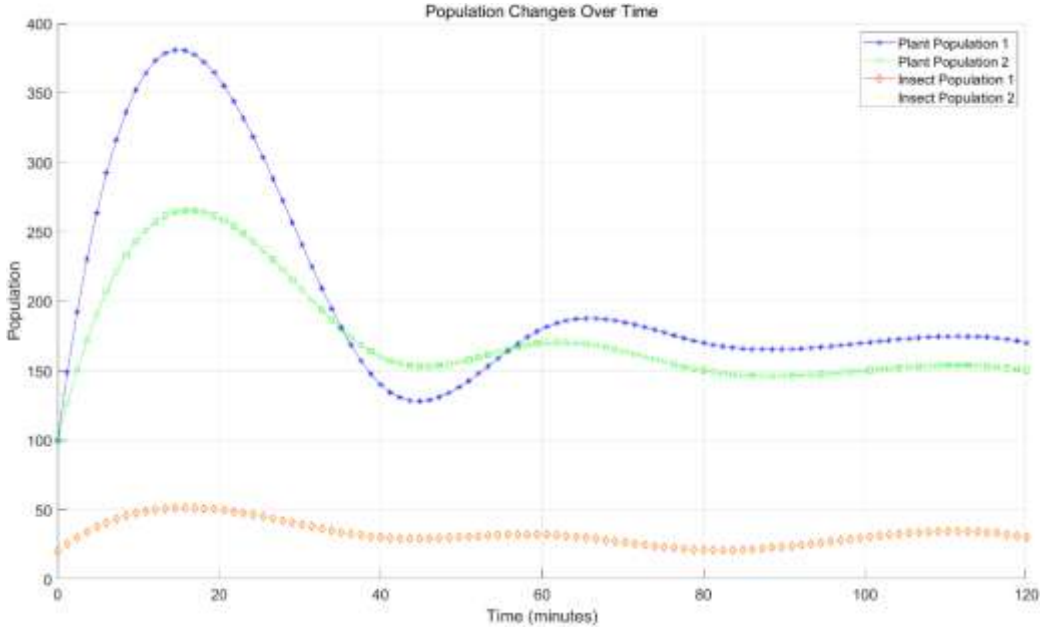


Figure 7. Changes in species populations

Owls are similar to bats in controlling insect populations, but since owls lack pollination functions, their promoting effect on plants is relatively limited. Therefore, the role of owls in restoring ecological balance is not as effective as that of bats.

4.3. Analysis of Organic Agricultural Ecosystem

The study shows that green agriculture can achieve ecosystem stability and balance species populations by reducing pesticide use. The model also reveals the balance between short-term agricultural productivity and long-term ecosystem sustainability. Although crop yields may be slightly lower than traditional agriculture in the early stages, it brings many benefits in the long run, such as improving soil health, reducing pest resistance, and enhancing biodiversity. By introducing natural enemies and reducing chemical inputs, farmers can build more resilient and sustainable agricultural systems. These findings provide valuable references for policymakers and farmers to transform to green agricultural practices. By comparing with traditional agriculture, this paper obtained the impact of organic agriculture on the ecosystem in five aspects such as crop yield and pest control, as in Figure 8:

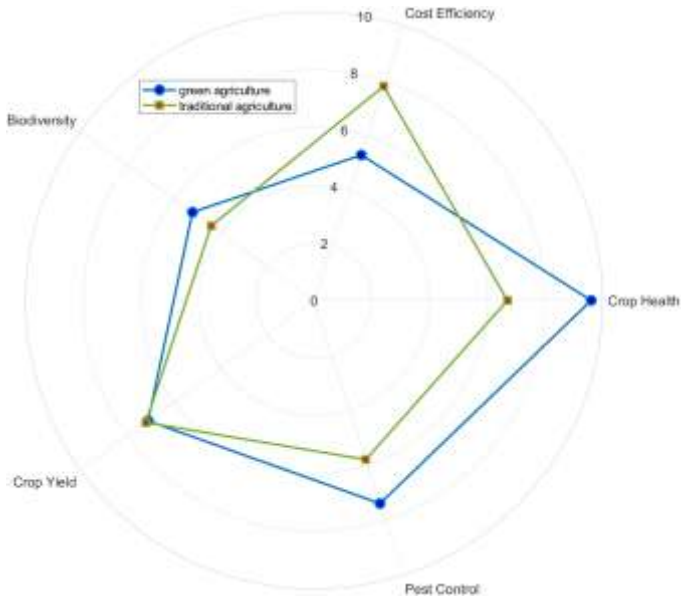


Figure 8. Comparison of two agricultural models

1. Crop health: The growth rate and health level of crops are improved. The positive feedback effect brought by the improvement of soil quality makes the growth environment of crops more suitable.

2. Pest control: Through biological control methods (such as introducing predatory insects, pest natural enemies, etc.), the population of pests is significantly lower than that under the use of chemical pesticides, and the damage to crops is reduced.

3. Crop yield: Using organic agricultural strategies, crops may face greater competitive pressure, leading to inhibited population growth and reduced yield.

4. Biodiversity: Organic agriculture increases the diversity of the ecosystem. The increase in diversity not only helps with pest control but also enhances soil fertility and provides more ecological services.

5. Cost-effectiveness: The cost of organic agriculture in the early stage is higher, but in the long-term development, the benefits brought by organic agriculture are greater.

Whether from the whole or part, organic agriculture is more beneficial to the maintenance and stability of the agricultural ecosystem compared with traditional agriculture.

5. Conclusion

In this paper the agricultural ecosystem model based on Lotka-Volterra can simulate the dynamic process of agricultural production, and the indexes influence and restrict each other, which provides a comprehensive framework for the management of agricultural ecosystem. The simulation process is close to the reality. The agriculture model clearly takes into account agricultural practices such as pesticide application and the transformation of organic agriculture, and can evaluate the ecological and economic impacts of different agricultural strategies. The model can adapt to a variety of scenarios, not only for small-scale organic farms, but also for large-scale agricultural systems. By using numerical methods such as Runge-Kutta, the classical model can stably deal with nonlinear and coupled differential equations and ensure reliable results. However, the interaction model assumes that species interactions follow Lotka-Volterra dynamics, but interactions in real ecosystems may be more complex, including mutually beneficial relationships or indirect effects. This simplification may affect the accuracy of the model. The empirical model lacks in-depth consideration of external factors. In reality, external factors such as natural disasters and species migration may have a significant impact on agricultural ecosystem. Hence we will continue to study the improvement of the accuracy of the model.

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