Modeling and Stability Analysis of Agricultural Ecosystems: A Comparative Study of Traditional and Organic Farming Practices

Hongyuan Niu[1], Jinming Zhang[2, *]

[1] School of Science, Harbin Institute of Technology, Weihai, China

[2] College of New Energy, Harbin Institute of Technology, Weihai, China

*Corresponding Author: 13053603599@163.com

Abstract

With the increasing concerns over ecological degradation caused by traditional agricultural practices, this study explores the dynamic relationship between human agricultural activities and the environment. We propose a comprehensive modeling framework to evaluate the evolution and stability of agricultural ecosystems under varying conditions. Using the Lotka-Volterra model, we simulate species interactions and ecosystem transitions from dense forests to agricultural systems. A stability evaluation model, enhanced by the Analytic Hierarchy Process (AHP), quantifies ecosystem robustness through a stability index (St). Our results reveal that the use of pesticides and herbicides slightly reduces ecosystem stability, while the reintroduction of native species such as eagles and rabbits improves stability. Furthermore, reducing herbicide use and introducing biological control agents-specifically bats and woodpeckers-significantly enhances ecosystem resilience. We also explore the feasibility of adopting organic farming through a multi-objective programming model that balances economic returns and ecological sustainability. The analysis demonstrates that organic farming outperforms traditional methods in crop health, biodiversity, and pest control. Finally, a sensitivity analysis is conducted to assess model robustness. This study provides a data-driven, multi-dimensional approach to support the sustainable transition from conventional to organic agriculture.

Keywords

Lotka-Volterra Model, Multi-objective Programming, Agricultural Ecosystem, Ecological Stability, Organic Farming.

1. Introduction

The intensification of traditional agricultural practices has led to a growing ecological imbalance, including soil degradation, biodiversity loss, and increased dependency on chemical fertilizers and pesticides[1]. As global awareness of environmental sustainability deepens, organic farming has emerged as a promising alternative, aiming to reduce chemical inputs while restoring the natural balance of ecosystems. However, transitioning from conventional to organic agriculture presents significant challenges, particularly in balancing economic profitability with long-term ecological stability[2].

Agricultural ecosystems are inherently complex and dynamic, shaped by the interactions between biotic and abiotic components, seasonal cycles, and human interventions[3]. The ecological consequences of farming practices-such as the use of pesticides and herbicides, species displacement, and habitat fragmentation-can fundamentally alter the structure and stability of these ecosystems[4]. Understanding and quantifying these effects is crucial for designing sustainable agricultural systems that maintain productivity while preserving ecological integrity[5].

This paper develops a series of mathematical models to analyze the ecological dynamics of agricultural ecosystems under different farming regimes. By constructing a food chain model based on the Lotka-Volterra equations, we simulate species interactions and assess the impact of external inputs such as chemicals and biological control agents. Furthermore, we propose a stability evaluation model using the Analytic Hierarchy Process (AHP) to calculate a comprehensive stability index (St), which quantifies ecosystem resilience under various scenarios. We also integrate multi-objective programming techniques to evaluate the trade-offs between economic returns and ecological sustainability in organic farming.

The study explores four key aspects of agricultural ecosystem development: (1) the ecological shift from forest ecosystems to chemically-managed agricultural systems; (2) the effects of native species return on ecosystem balance; (3) the impact of reducing herbicide use and introducing beneficial species such as bats and woodpeckers; and (4) the viability and ecological benefits of organic farming under different constraints. The models are further evaluated through sensitivity analysis, and recommendations are provided for optimizing agricultural policies and practices to enhance sustainability.

This study makes the following key contributions:

1) Ecosystem Transition Modeling: We construct a dynamic food chain model to simulate the ecological transformation from a dense forest ecosystem to a modern agricultural ecosystem, incorporating the effects of pesticides and herbicides on species interactions.

2) Stability Quantification Framework: A novel ecosystem stability evaluation index (St) is proposed, integrating the Lotka-Volterra model with Analytic Hierarchy Process (AHP), enabling quantitative comparison of ecosystem stability under various scenarios.

3) Species Reintroduction and Biological Control: The paper analyzes the impact of reintroducing native species (e.g., eagles and rabbits) and biological control agents (e.g., bats and woodpeckers) on ecosystem dynamics, revealing how biodiversity restoration enhances stability.

4) Optimization of Organic Farming Strategies: A multi-objective programming model is developed to evaluate the feasibility and sustainability of organic farming practices, considering factors such as yield, cost, biodiversity, and crop health.

5) Policy-Oriented Insights for Agricultural Sustainability: The study offers actionable insights for agricultural policy, highlighting the ecological and economic advantages of transitioning to organic farming and integrating biological control methods.

2. Methodology

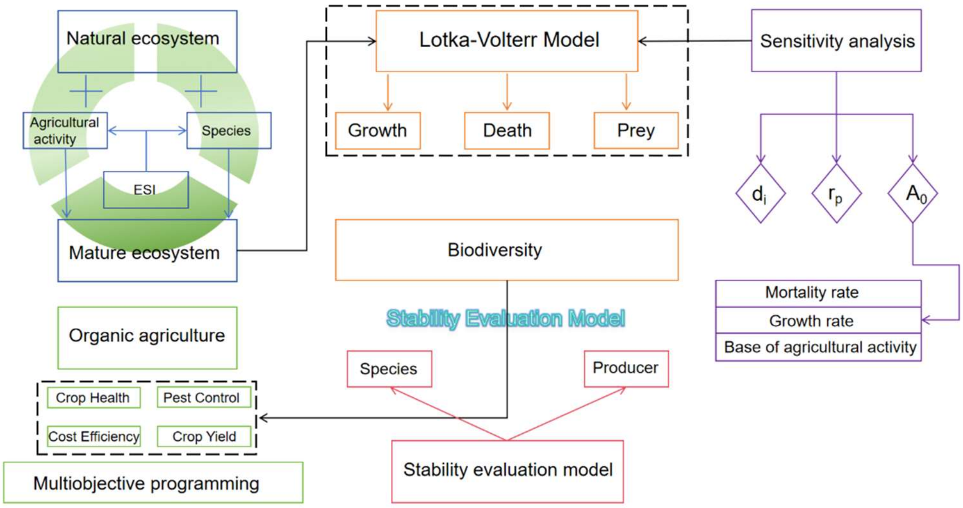

Figure 1. Overview of this work

The overview of this work is displayed in Figure 1.

2.1. Lotka-Volterra Model

As shown in the Figure 2, the changes in various indicators during the ecosystem's maturation process are depicted. Among them, human activities and arable land area gradually decrease, while forest area and ecosystem stability gradually increase, reflecting the transition from traditional agriculture to organic farming.

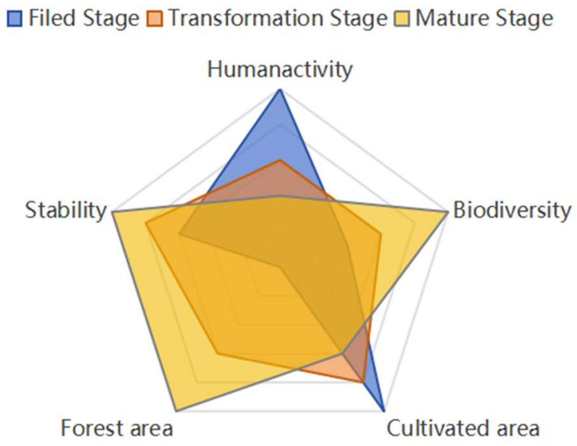

Figure 2. Transformation process

There is no human activity in the natural ecosystem, so the model is as follows:

(1) Crop dynamics:

$$\frac{dP}{dt}=r_P P(t)\left(1-\frac{P(t)}{K_P}\right)-\alpha_I I(t)P(t)-d_P P(t)-\varepsilon_{PW}P(t)W(t) \tag{1}$$

(2) Weed dynamics:

$$\begin{cases}\frac{dW}{dt}=r_W W(t)\left(1-\frac{W(t)}{K_W}\right)-\alpha_I I(t)W(t)\\ -d_W W(t)-\varepsilon_{PW}P(t)W(t)\end{cases} \tag{2}$$

(3) Insect dynamics:

$$\begin{cases}\frac{dI}{dt}=r_I I(t)\left(1-\frac{I(t)}{K_I}\right)+\phi_I M(t)\mathrm{I}(t)-\alpha_B I(t)B(t)\\ -d_I I(t)+\alpha_I I(t)W(t)+\alpha_I I(t)P(t)\end{cases} \tag{3}$$

(4) Avian dynamics:

$$\frac{dB}{dt}=r_B B(t)\left(1-\frac{B(t)}{K_B}\right)+\phi_B M(t)-d_B B(t)+\alpha_B B(t)I(t) \tag{4}$$

The key indicators of the ecosystem can be used to analyze the changes in the ecosystem during the transition from forest to farmland, focusing on six key indicators.

(1) Crop dynamics:

$$\begin{cases} \frac{dP}{dt} = r_P P(t)\left(1 - \frac{P(t)}{K_P}\right) - \alpha_I I(t)P(t) \\ -\beta_{D_wP} D_w(t)P(t) - d_P P(t) - \varepsilon_{PW} P(t)W(t) \end{cases} \tag{5}$$

P is crop yield, r_P is the natural growth rate of crops.

K_P is environmental capacity of crops α_I is predation rate of insects on plants.

β_{D_wP} are effects of herbicides on crops, d_P is natural mortality of crops.

ε_{PW} is competition coefficient for crops and weeds.

(2) Weed dynamics:

$$\begin{cases} \frac{dW}{dt} = r_W W(t)\left(1 - \frac{W(t)}{K_W}\right) - \alpha_I I(t)W(t) \\ -\beta_{D_wW} D_w(t)W(t) - d_W W(t) - \varepsilon_{PW} P(t)W(t) \end{cases} \tag{6}$$

(3) Insect dynamics:

$$\begin{cases} \frac{dI}{dt} = r_I I(t)\left(1 - \frac{I(t)}{K_I}\right) + \phi_I M(t)\mathrm{I}(t) - \beta_{D_iI} D_i(t)I(t) \\ -\alpha_B I(t)B(t) - d_I I(t) + \alpha_I I(t)W(t) + \alpha_I I(t)P(t) \end{cases} \tag{7}$$

ϕ_I is attraction rate of marginal habitats to insects after maturation.

(4) Avian dynamics:

$$\frac{dB}{dt} = r_B B(t)\left(1 - \frac{B(t)}{K_B}\right) + \phi_B M(t) - d_B B(t) + \alpha_B B(t)I \tag{8}$$

2.2. Species Regression Models

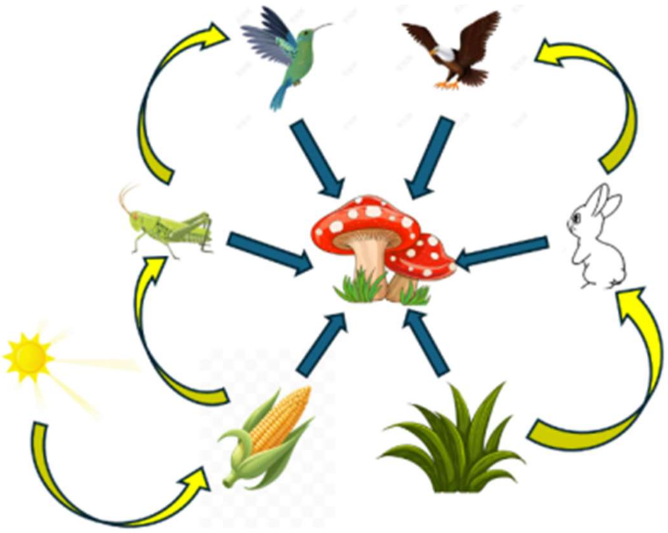

Figure 3. Biological chain structure

As time passes, marginal habitats gradually mature, and some species that were previously lost may reappear. These returning species interact with the existing species in the agricultural ecosystem, potentially altering the structure and stability of the ecosystem. As the agricultural ecosystem evolves, some beneficial species that had disappeared from farmland, such as predatory insects and pollinators, may return. Their return could have significant impacts on crop growth, pest control, and ecological balance[6]. Studying this process in depth is crucial to ensuring the sustainability of agricultural production.

When modeling species regression, we used the Lotka-Volterra model to introduce two newly regressed species, rabbits and eagles, and analyzed the dynamics between them and their impact on ecosystem stability.

$\mathrm{N(t)}$: Population density of existing species.

$\mathrm{N_2(t)}$: Population density of rabbits and eagles.

$\mathrm{P(t)}$: The population density of the crop.

The regression of these two species can be described by the following equation:

$$\frac{dN}{dt} = r_1 N\left(1 - \frac{N}{K_1}\right) - a_{12} N N_2 \tag{9}$$

$$\frac{dN_2}{dt} = r_2 N_2\left(1 - \frac{N_2}{K_2}\right) + a_{21} N N_2 \tag{10}$$

r_1 and r_2 are the intrinsic growth rates of species N and $\mathrm{N_2}$, respectively. K and K_2 are the carrying capacities of species N and N_2, respectively. a_{12} represents the predation effect of predatory insects on the pest population, while a_{21} represents the impact of pests on the predatory insect population.

Therefore, we adjust the dynamic equations for two species:

(1) Eagle dynamics:

$$\frac{dE}{dt} = r_E E(t)\left(1 - \frac{E(t)}{K_E}\right) - d_E E(t) + \alpha_E E(t) R(t) \tag{11}$$

(2) Rabbit dynamics:

$$\begin{cases} \dfrac{dR}{dt} = r_R R(t)\left(1 - \dfrac{R(t)}{K_R}\right) - \varepsilon_{RI} R(t) I(t) - d_R R(t) - \alpha_E R(t) E(t) \\ -\beta_{D_i R} D_i(t) I(t) + \alpha_R R(t) P(t) + \alpha_R R(t) W(t) \end{cases} \tag{12}$$

2.3. Effects on the Ecosystem after the Introduction of Bats after Herbicide Removal

The stability of the ecosystem may be affected after gradually discontinuing the use of herbicides. Reducing herbicide use may lead to an increase in weed populations or a rise in pest numbers. Our goal is to analyze the dynamic equilibrium between producers and consumers after stopping the use of herbicides[7].

Introducing bats can promote ecological balance: Bats can prey on insects and engage in pollination activities, which play a positive role in ecosystem restoration. We need to establish a model to simulate the role of bats in the ecosystem and analyze their interactions with insects, plants, and other predators, as well as how these interactions affect the overall stability of the ecosystem.

Introducing other species: Select another species that is beneficial for ecological restoration (such as certain bird species or other insect predators) and compare its role in promoting ecological balance with that of bats. Based on the comparison results, we can further understand the contributions of different species to ecosystem restoration and provide guidance for ecological management.

After the introduction of bats, they can play a role in the ecosystem to capture pests, control the increase in insect populations, and promote plant pollination and improve plant reproduction. Therefore, the interaction between bats and other species needs to be considered when building the model.

Avian dynamics:

$$\begin{cases}\dfrac{dB}{dt} = r_B B(t)\left(1 - \dfrac{B(t)}{K_B}\right) + \phi_B M(t) \\ -d_B B(t) + \alpha_B B(t) I(t) - \varepsilon_{BF} B(t) F(t)\end{cases} \tag{13}$$

Bat Dynamics: (Bats eat insects and help plants spread)

$$\frac{dF}{dt} = r_F F(t)\left(1 - \frac{F(t)}{K_F}\right) - d_F F(t) - \varepsilon_{BF} B(t) F(t) + \alpha_F F(t) I(t) \tag{14}$$

Here we choose a bird that can prey on insects and thus control the insect population. This bird is assumed to be a woodpecker.

Woodpecker dynamics:

$$\begin{cases}\dfrac{dZ}{dt} = r_Z Z(t)\left(1 - \dfrac{Z(t)}{K_Z}\right) - d_Z Z(t) \\ -\varepsilon_{BZ} B(t) Z(t) + \alpha_Z Z(t) I(t) - \varepsilon_{FZ} F(t) Z(t)\end{cases} \tag{15}$$

2.4. Factors Influencing Organic Agriculture

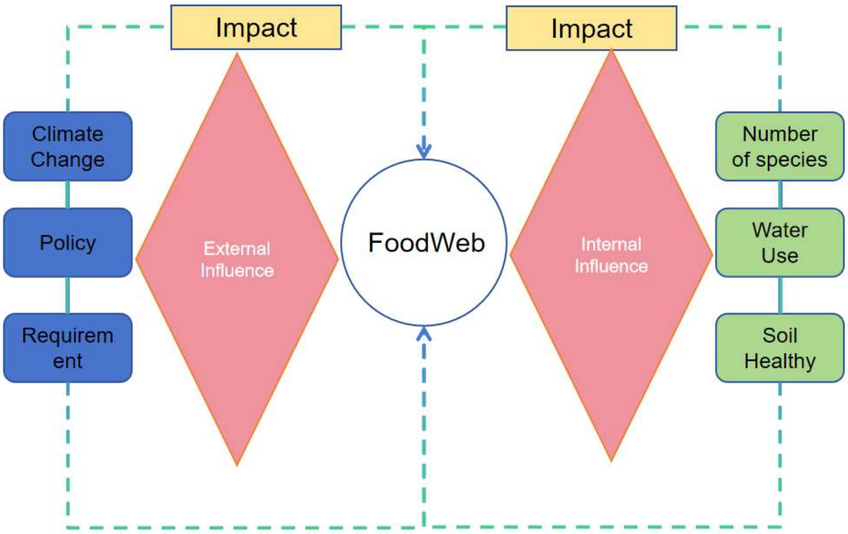

Figure 4. Factors influencing organic agriculture

Organic farming, as part of green agricultural methods, is receiving increasing attention in modern agriculture. Compared to traditional agriculture, organic farming focuses more on utilizing natural mechanisms rather than relying on chemicals such as pesticides and fertilizers. During the transition to organic farming, farmers not only need to focus on crop yield but also must assess its impact on the entire ecosystem, including soil, water, and biodiversity.

1) Cost constraints

In the transition from traditional agriculture to organic agriculture, there is an upper limit to farmers' investment expectations, and the cost cannot be higher than this upper limit.

$$C_o \leq C_{max} \tag{16}$$

C_{max} is the cost expectation of farmers.

2) Market demand constraints

Due to the higher price of organic food, there is an upper limit on the demand for organic food, and the organic crops produced should be below this upper limit.

$$Y_o \leq D_{max} \tag{17}$$

D_{max} is the upper limit of market demand.

3) Crop yield constraints

Farmers have a lower limit on the yield of organic crops, and the yield of organic agriculture cannot be lower than this lower limit.

$$Y_o \geq Y_{min} \tag{18}$$

Y_{min} is the lower limit of farmland yield.

4.Sustainability constraints

Organic agriculture emphasizes environmental sustainability, but there is a constraint on ecological diversity, and the number of species should not be lower than that of traditional ecosystems.

$$\text{Biodiversity} \geq \text{Biodiversity}_{min} \tag{19}$$

$\text{Biodiversity}_{min}$ is the minimum number of species.

3. Results

Analytic Hierarchy Process (AHP) is a method for dealing with multi-criteria decision-making. It simplifies the decision-making process by breaking down complex decision-making problems into multiple layers.

In this model, the target layer is the comprehensive stability index of the ecosystem, and the decision-making layer is EA, RC, RD, CQ, N, P. The Objective and Criterion is displayed in Figure 5.

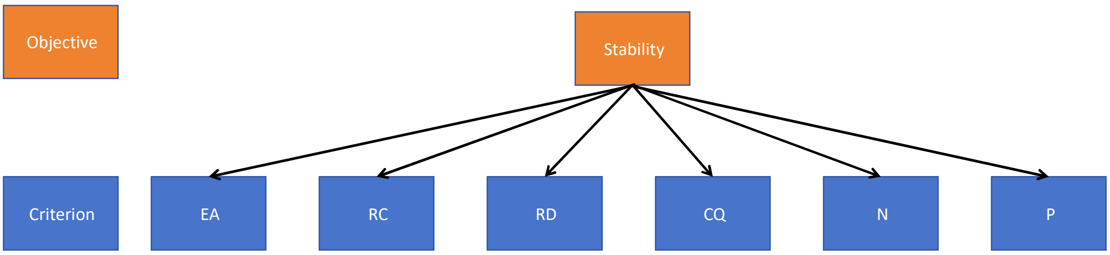

Figure 5. Objective and Criterion

The judgment matrix is displayed in Table 1:

Table 1. Judgment matrix

Matrix	EA_t	RC_t	RD_t	CQ_t	N	P
EA_t	1	1/3	1/3	2	1/5	1/7
RC_t	3	1	1	5	1/4	1/3
RD_t	3	1	1	5	1/4	1/3
CQ_t	1/2	1/5	1/5	1	1/9	1/5
N	5	4	4	9	1	2
P	7	3	3	5	1/2	1

The result of the calculation is:

$$St = \omega_a EA_t + \omega_b RC_t + \omega_c RD_t + \omega_d CQ_t + \omega_e N + \omega_f P \tag{20}$$

$$\omega_a = 0.0529 \quad \omega_b = \omega_c = 0.1234 \quad \omega_d = 0.0338 \quad \omega_e = 0.3934 \quad \omega_f = 0.2732 \tag{21}$$

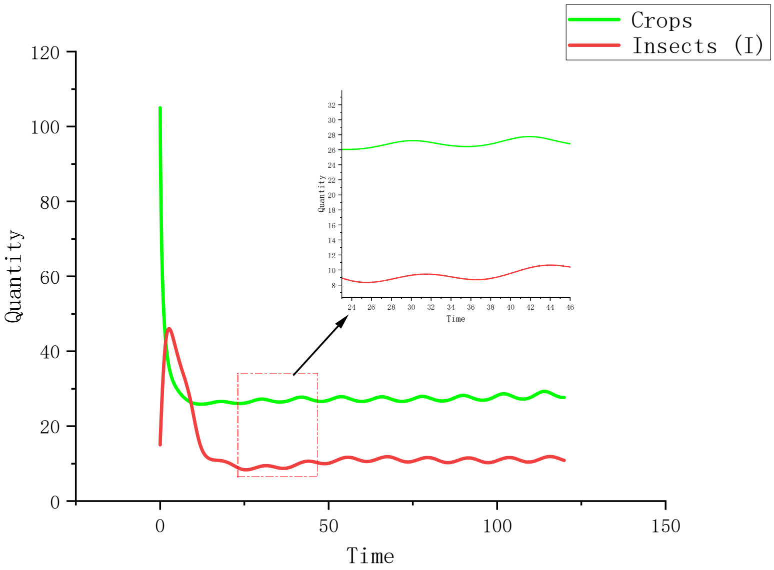

Figure 6. Crops and insect populations change over time

Figure 6 depicts the dynamic changes in crop and insect populations over time. The horizontal axis represents the time in months, while the vertical axis represents population size (assuming the unit for both crop and insect populations is "unit of quantity"). At the beginning of the formation of the agricultural ecosystem, the ecosystem is unstable, and the populations of crops and insects fluctuate dramatically. Due to an abundance of food, insects heavily prey on crops, causing a rapid decline in crop numbers, which in turn leads to a sharp decrease in insect populations. As the ecosystem gradually matures, both the insect and crop populations stabilize and undergo seasonal variations over time.

Figure 7 shows the variation in pesticide levels over a period of time. If no additional pesticides are applied, the pesticide concentration gradually decreases over time.

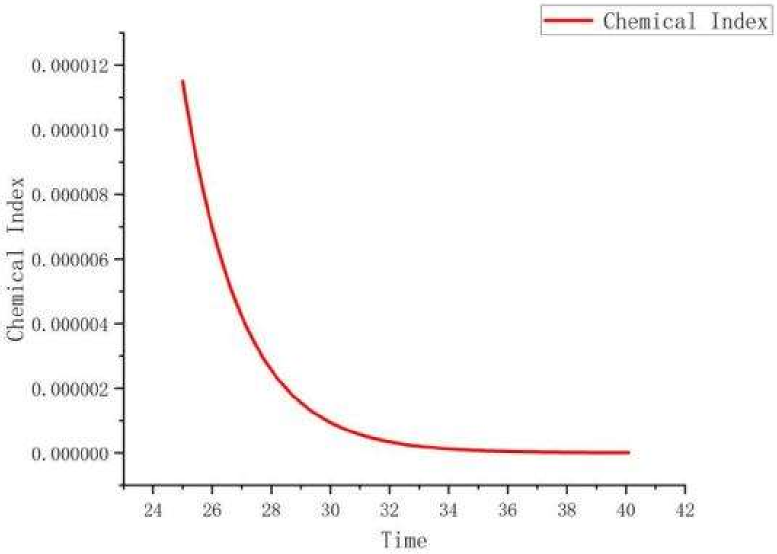

Figure 7. Pesticide concentration changes with time

The changes in crop growth are significantly influenced by seasonal factors, especially conditions such as temperature, precipitation, and sunlight, which affect plant growth.

The final model can be represented as:

$$Maximize\ Z = \delta M_0 Y_0 + C_0 + \varepsilon(\alpha \text{Pest Control} + \beta \text{Crop Health} + \gamma \text{Biodiversity} \quad (22)$$

The organic farming versus conventional farming is displayed in Figure 8:

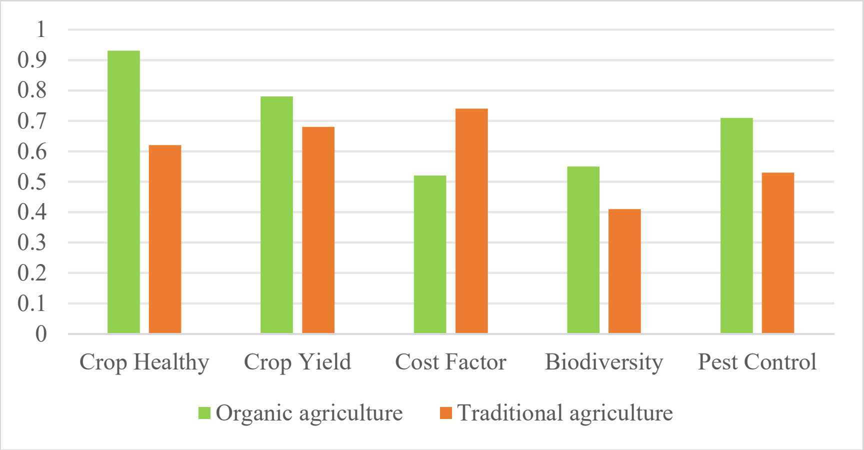

Figure 8. Organic farming versus conventional farming

4. Conclusion and Future Work

This paper presents a comprehensive modeling framework to investigate the dynamic balance between human agricultural activities and ecosystem stability under different farming practices, with a specific emphasis on the transition from traditional to organic agriculture. Through the construction of food chain models based on the Lotka-Volterra equations and the integration of the Analytic Hierarchy Process (AHP) to evaluate ecosystem stability, we quantitatively assessed how species interactions, chemical inputs, and ecological interventions influence the resilience of agricultural ecosystems. Our findings suggest that the use of pesticides and herbicides leads to a noticeable decline in ecosystem stability, while the reintroduction of native species such as eagles and rabbits significantly improves stability. Moreover, the incorporation of biological control agents-particularly bats and woodpeckers-not only enhanced the ecological balance but also demonstrated that their combined presence yields the highest stability index observed in our simulations. The multi-objective optimization model further showed that organic farming surpasses conventional methods in crop health, biodiversity, pest control, and long-term sustainability, with the greatest performance improvement observed in crop health.

Despite these insights, the current model has certain limitations that point to potential directions for future work. Notably, it simplifies the impact of external environmental and socio-economic variables such as climate change, market fluctuations, and agricultural policy incentives, which can significantly alter ecosystem responses. To address this, future research should integrate these complex external factors, along with improved datasets derived from real-world regional data, to enhance the model's predictive accuracy and applicability. In addition, incorporating dynamic economic feedback mechanisms and spatial analysis tools such as GIS or remote sensing could help contextualize ecological changes across landscapes. Furthermore, there is a need to develop early-warning systems within the model framework to assess the risk of pest outbreaks or ecological degradation, especially under organic farming systems. By refining these aspects, the model can evolve into a robust decision-support tool for sustainable agricultural planning and biodiversity conservation in the face of growing environmental challenges.

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