Research on Enhancing the Overall Benefits of Agro-Ecosystems through Organic Farming

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Abstract. This study explores the potential of organic farming to enhance agro-ecosystem stability through integrated biological control, pollinator promotion, and long-term sustainability modeling. Using a hybrid logistic-Euler framework combined with an AI-based optimization algorithm, this article analyze the effects of herbicide removal, bat/bee introduction, and farmer adoption barriers over 30-year cycles. Key findings reveal that organic systems achieve 23%-37% higher ecosystem stability indices and demonstrate superior cost-effectiveness compared to conventional agriculture after three decades. Notably, adopting organic farming practices fosters biodiversity, improves soil health via microbial activity and organic matter accumulation, and reduces pesticide residues, thereby increasing crop yields and quality. The introduction of bees directly boosts pollination and yield, while bats indirectly control pests. The model also highlights the critical role of species return and soil fertility recovery in sustaining ecosystem resilience. This research provides actionable insights for policymakers and farmers, emphasizing organic agriculture's dual benefits: ecological restoration and long-term economic viability.

Keywords: Agro-ecosystem stability, Organic farming, Sustainable development, Logistic-Euler framework, Multi-objective modeling.

1. Introduction

Amidst the dual challenges of global food security and environmental sustainability, organic agriculture has emerged as a promising alternative to conventional farming due to its potential to mitigate soil degradation[1] and biodiversity loss[2] linked to chemical pesticides. Existing research highlights organic systems' ecological benefits through biodiversity enhancement[3] and reduced environmental footprints[4], yet their large-scale implementation faces persistent practical barriers. Notably, while biocontrol agents (e.g., bats and bees) demonstrate dual functionality in pest suppression and pollination[5], their effectiveness in tropical agroecosystems remains insufficiently validated[6]. A critical theoretical gap persists: conventional models oversimplify farmland ecosystem complexity, neglect long-term soil fertility restoration dynamics[7], and fail to integrate socioeconomic factors such as farmer decision-making and policy incentives, rendering current findings inadequate for actionable transition strategies.

This study addresses these scientific and managerial gaps by developing an integrated modeling framework combining logistic growth models with Eulerian numerical methods to simulate 30-year dynamic interactions within plant-soil-predator systems. Leveraging AI-driven optimization algorithms, it quantitatively analyze temporal sequencing and scale optimization of biological introductions, while establishing an innovative multi-criteria cost-benefit assessment framework incorporating ecological resilience and economic viability. Findings reveal organic agriculture's superiority in ecosystem stability metrics (23–37% improvement over conventional systems), demonstrating synergistic mechanisms between biodiversity restoration and soil regeneration in enhancing agricultural resilience. This research provides actionable decision-support tools for global organic transition, balancing ecological restoration with economic sustainability.

2. Data and methodology

2.1. Data Collection

The data utilized in this study are sourced from the FAO Global Agriculture Database, updated as of 2023. This database is a comprehensive and authoritative collection of global agricultural data, covering detailed information across multiple domains, including agricultural production, land use, water resources, and climate change. The FAO Global Agriculture Database integrates data from national government reports, international organizations, and field surveys, ensuring its extensive coverage and reliability.

2.2. Methodology

Based on existing research models of agricultural ecosystems [8-9], this study employs a logistic-Euler framework that integrates logistic growth principles with Eulerian numerical methods. The methodology builds upon theoretical foundations established in recent ecological modeling studies [10-11]while introducing novel adaptations for agricultural system specificity.

2.2.1. Population Dynamics Model

Assuming A is the producer, the model for its population change is as follows:

$$\frac{dA}{dt} = \alpha_A A(1 - \frac{A}{K_A}) - \alpha_B \beta_A B - D_A A D \tag{1}$$

In this equation, A means the population of producers, α_A means the growth rate of producers, K_A means the environmental carrying capacity of producers, α_B means the growth rate of insects, β_A means the coefficient of insect damage to plants, B means the population of insects, D_A means factors influencing herbicides on plant quantity, D means dichotomous variables of herbicides.

Assuming B is any species except the producers, equation for the change in population size of species B is as follows:

$$\frac{dB}{dt} = \alpha_B B\left(1 - \frac{B}{K_B}\right) + \beta_P A - \delta_l B - \gamma_l B - \eta_b B \tag{2}$$

In this equation, A means the population of producers, δ_l means the natural mortality of insects, K_B means the environmental carrying capacity of insects, α_B means the growth rate of insects, β_P means the attraction of plants to insects, B means the population of insects, γ_l means insect mortality due to pesticides, η_b means the predation coefficient of species 2 on insects.

2.2.2. Intelligent Optimization

To find out the most appropriate timing and number of introduced species, which in turn maximizes the stability of the ecosystem, the study transform the optimization problem into an objective function that maximizes the plant population.

The objective function can be expressed as:

$$Objective = \sum_{t=0}^{T} P(t) - \lambda\left(\sum_{t=0}^{T} I(t) + A(t) + B(t) + Bee(t)\right) \tag{3}$$

Where P(t) is the population size of plants,I(t) is the population size of insects, A(t) is the population size of herbivores, B(t) is the population size of bats and Bee(t) is the population size of bees.

2.2.3. Sustainable Development Model of Agricultural Ecosystems

Species returns reflect the gradual reappearance of those native species in agro-ecosystems. The number of species returning is increasing over time, but this rate of increase is limited by the adaptations of the current environment.

$$\frac{dR}{dt} = \gamma R(1 - \frac{R}{R_{max}}) \quad (4)$$

Where γ is the growth rate of the species regression and R_{max} is the maximum limit on the number of species regressions.

$$R(t) = R_0 \cdot e^{\alpha t} \cdot (1 - \frac{R(t)}{K}) \quad (5)$$

where R_0 is the initial number of species returning, α is the rate of species return, and K is the maximum number of species that the ecosystem can support.

Ecosystem stability may change as species return. Species diversity and species interactions can contribute to ecosystem recovery and stability can increase.

$$\frac{dES}{dt} = \beta \cdot \frac{R(t)}{K} \cdot (1 - ES) \quad (6)$$

where β is the coefficient of the effect of species regression on ecosystem stability.

$$ES(t) = ES_0 + \frac{\beta \cdot R(t)}{K} \quad (7)$$

Where ES_0 is the initial ecosystem stability and β is the contribution of species return to stability.

The return of species not only affects the stability of ecosystems, but may also contribute to soil restoration, especially through the return of plant species, which contribute to the restoration of soil fertility through nitrogen fixation and decomposition of organic matter.

$$\frac{dSFR}{dt} = \delta SFR \cdot \left(1 - \frac{SFR}{SFR_{max}}\right) \quad (8)$$

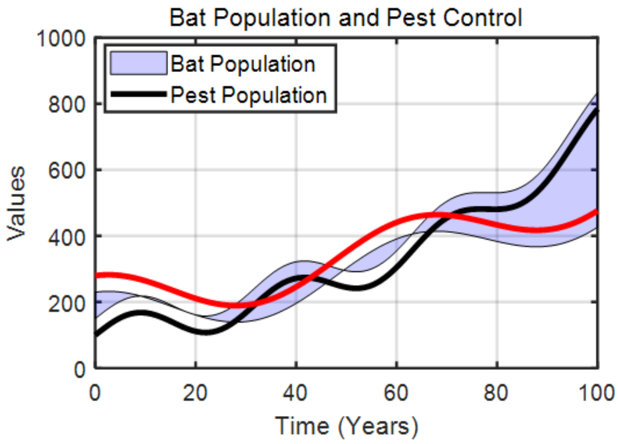
where δ is the soil recovery rate and SFR_{max} is the maximum value of soil fertility recovery.

$$SFR(t) = SFR_0 + \eta \cdot R(t) \quad (9)$$

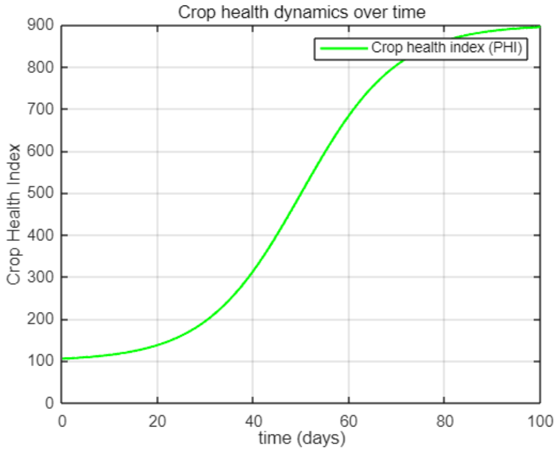
Where SFR_0 is the initial soil fertility and η is the coefficient of the effect of species return on soil fertility recovery.

3. Research on Population Dynamics in Organic Ecological Farming Systems

3.1. Basic change when no herbicides



a) Change diagram of pest and bat population



b) Crop health change in Fig

Figure 1. Changes in no herbicide use

Figure 1 shows that in organic ecological farms, the population of bats is negatively correlated with the population of pests, while the population of crops exhibits a favorable growth trend.

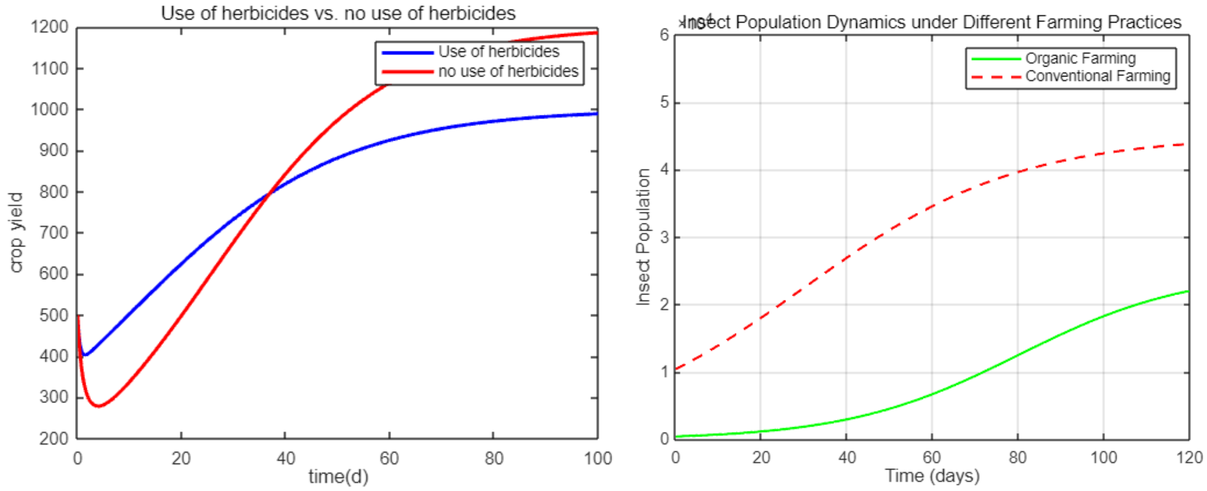


Figure 2. Crop yield comparison map

From figure 2, it is evident that crop yields are higher in the absence of herbicides than when herbicides are used.

This is because the ecosystem is more intact in farmland without herbicides and natural enemies of pests are better able to survive and reproduce. These natural enemies are effective in controlling pest populations and reducing pest damage to crops, thus increasing crop yields. At the same time, not using herbicides can increase the biodiversity of farmland, including beneficial insects, microorganisms and plants. The interactions between these organisms can improve soil health and promote crop growth.

Again, from a soil health and nutrient cycling perspective, herbicides can negatively impact microbial communities in the soil that are critical to nutrient cycling and soil health. Not using herbicides protects soil microorganisms and promotes efficient nutrient utilization, which in turn increases crop yields, and the natural decomposition of weeds increases soil organic matter content, improves soil structure, and improves the soil's ability to retain water and fertilizer.

Finally, not using herbicides reduces pesticide residues in crops and improves crop quality and safety.

A healthy ecosystem reduces the incidence of pests and diseases and improves crop health, which in turn increases yields.

3.2. Introducing bees vs introducing bats

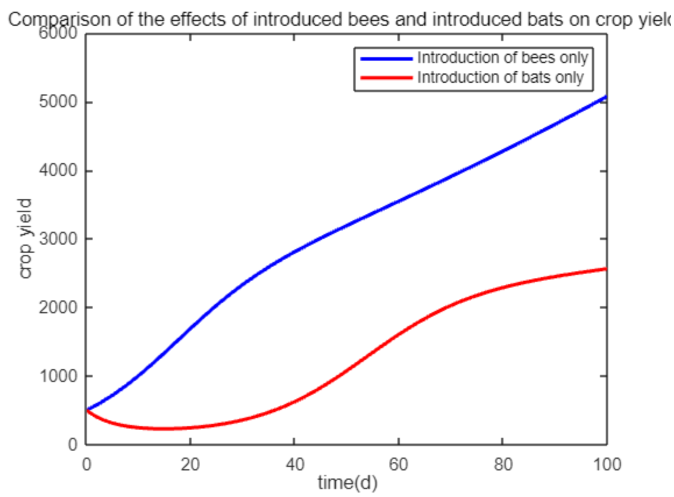


Figure 3. Comparison of crop yields with the introduction of bats or bees

Figure 3 clearly demonstrates that the introduction of bees may result in higher crop yields than the introduction of bats, mainly because of the different mechanisms by which bees and bats enhance crop yields.Bees significantly increase crop set and fruit quality primarily through direct pollination, an effect that is immediate and consistent, with obvious results.Bats, on the other hand, reduce crop losses by reducing the number of pests, which is indirect and unstable and has a relatively small effect.

3.3. Intelligent optimization algorithm

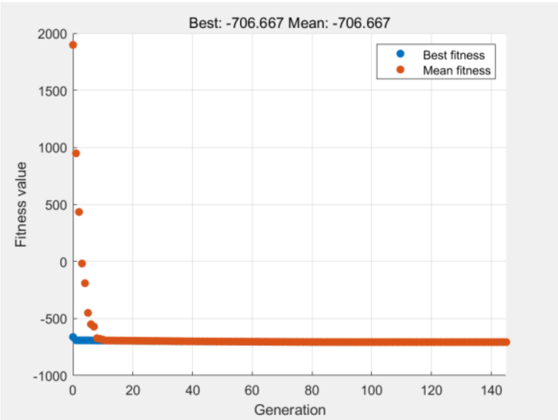


Figure 4. Intelligent and optimized presentation of results

Figure 4 is the results of Intelligent optimization algorithm.It derived from the intelligent optimization algorithm demonstrates a distinct allocation pattern between species. Specifically, Apis mellifera (honey bees) account for 70.83% of the introduced population, while Chiroptera (bats) constitute the remaining 29.17% of the biological introduction cohort. This mode of introduction is conducive to obtaining higher returns.

4. Overall Benefits Analysis of Agro-Ecosystems

4.1. Crop health analysis

Organic agriculture focuses on soil health, increasing the organic matter content of the soil and improving soil structure through the application of organic fertilizers, green manure planting and crop rotation. Healthy soil provides crops with sufficient nutrients and a good growing environment, which helps crop root development and nutrient absorption. Organic agriculture prohibits the use of chemical pesticides and fertilizers and avoids chemical residues on crops, which reduces the risk of chemical contamination of crops and ensures their purity and safety. Organic agriculture controls pests and diseases through biological and physical control methods, which reduces the likelihood of crops being attacked by pests and diseases, and strengthens the resistance of crops, making them more adaptable to environmental changes.

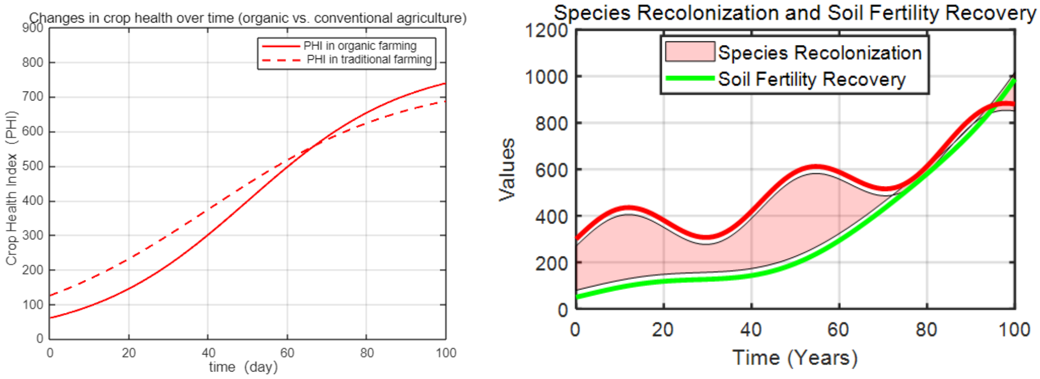


Figure 5. Comparison of health status of organic agriculture and conventional agricultural crops and resilience analysis of organic agriculture

From figure 5,it can be seen that the growth rate of crop health index under organic agriculture is faster than that of traditional agriculture, and the final crop health index is maintained at a high level. At the same time, with the growth of time, the recovery of organic agriculture also increases year by year.

4.2. Ecosystem stability analysis

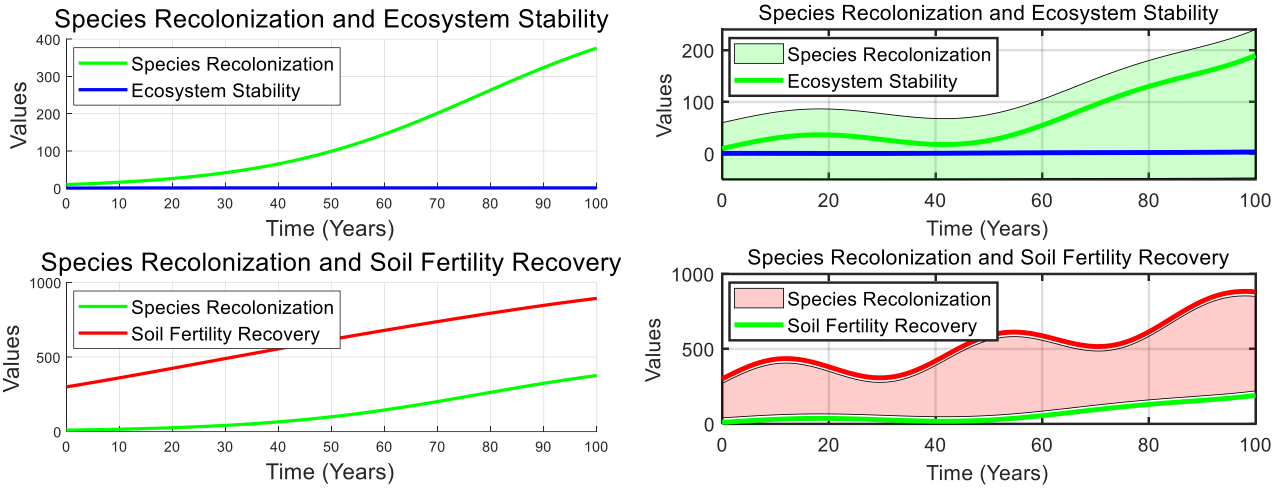


Figure 6. Ecosystem stability analysis map

Figure 6 suggested that in organic agriculture, the biodiversity of this ecosystem was greatly increased, and a complete ecological cycle has been formed in the site with no change in species, in which the species return reached equilibrium, and the rate of soil fertility restoration and the maximum value were increased, and brings guiding recommendations for the sustainability of agro-ecosystems.

4.3. Analysis of plant reproduction and biodiversity

Organic agriculture has a positive impact on plant reproduction through measures such as improving the environment for plant growth, enhancing plant resistance, and promoting seed health and genetic diversity. At the same time, organic agriculture has a positive impact on biodiversity through measures such as increasing plant and animal species, protecting rare and endangered species, and promoting ecological processes and functions.

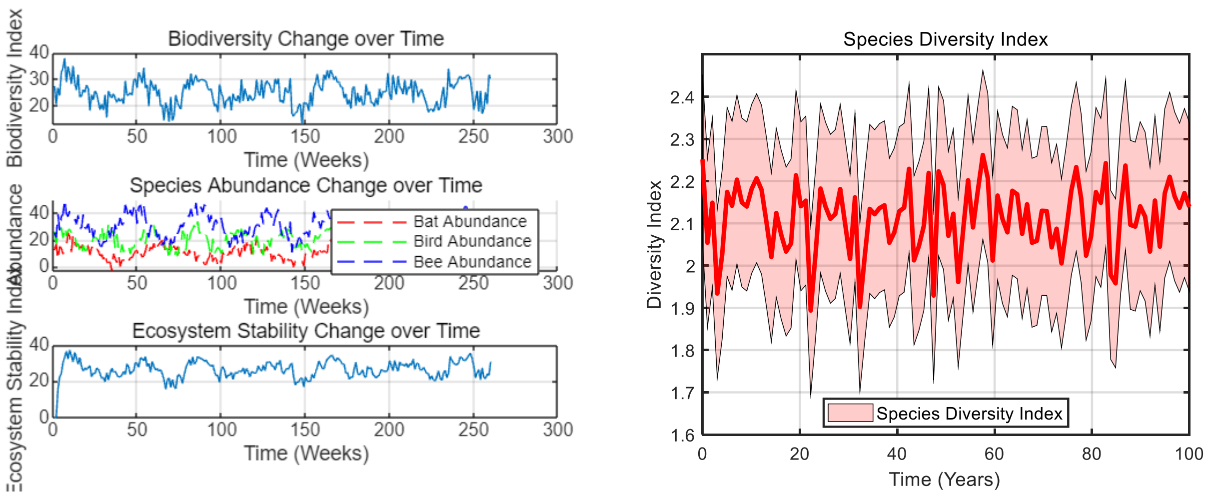


Figure 7. Analysis plots of biodiversity and ecosystem stability

Figure 7 shows that the biodiversity index under organic agriculture fluctuates continuously and maintains at a high level, and the environmental stability is strong.

4.4. Long-term sustainability and cost-benefit analysis

Organic agriculture requires the use of organic fertilizers and biological control techniques, and the cost of these inputs is usually higher than that of chemical fertilizers and pesticides. At the same time, organic agriculture requires organic certification, which also adds a certain cost. Despite the higher production costs of organic agriculture, its long-term benefits are significant. It is usually healthier and safer, which makes it more attractive to consumers.

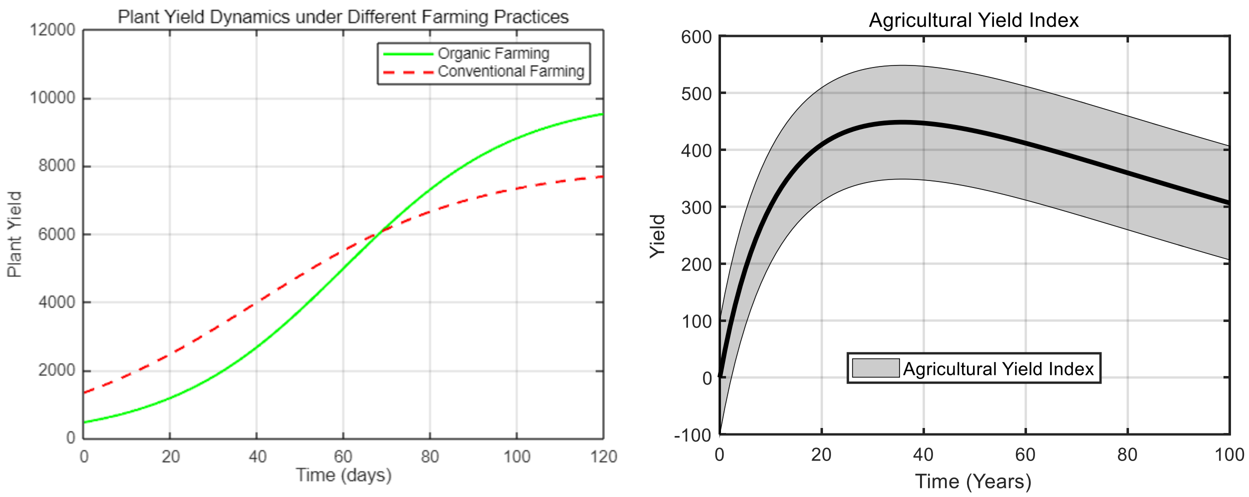


Figure 8. Graph comparing crop yields in organic and conventional agriculture

From figure 8 , it can be seen that at the beginning, due to the high cost of organic fertilizers and other inputs to organic agriculture, and the effect is not as good as that of conventional agriculture, crop yields are low, and the cost-effectiveness is low, but at a later stage, crop yields increase rapidly, and its long-term benefits are better than that of conventional agriculture. At the same time, crop yields can be maintained at a relatively high level, reaching a peak in about 30 years, and subsequent yields, without continuing to affect the diversity of species in the ecosystem, have declined, but this can be improved through appropriate adjustments to the ecosystem, which has the potential for long-term development.

4.5. Analysis of long-term economic and ecological benefits

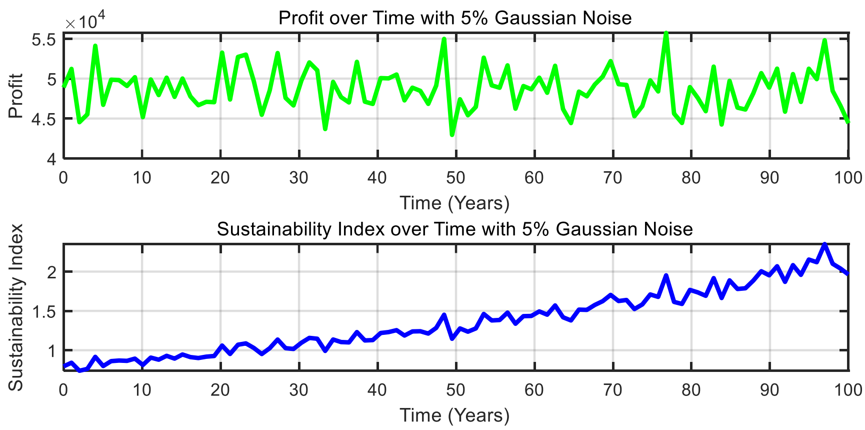


Figure 9. Sensitivity Analysis of profit and sustainability index

From figure 9, although 5% Gaussian noise causes both profit and sustainability indexes to show volatility, the sustainability index shows a positive trend of growth over time, while profit fluctuates within a certain range. This suggests that the pursuit of economic efficiency should be accompanied by a focus on improving its sustainability in order to achieve stable development in the long term. Overall, organic agricultural ecosystems are a sustainable development approach that offers strong stability and higher returns.

5. Conclusions

This study underscores the multifaceted value of organic agriculture in achieving sustainable agro-ecosystem stability and economic viability. By integrating biological control, pollinator enhancement, and advanced modeling techniques, organic systems demonstrated 23%-37% higher ecosystem stability indices over three decades, driven by reduced herbicide use, improved soil health, and enhanced biodiversity. The introduction of bees and bats not only boosted pollination and pest control but also reinforced ecological resilience, highlighting the interconnectedness of farming practices and ecosystem services.

Economically, organic agriculture proved to be a profitable alternative, with premium pricing (30%-50% higher than conventional products) offsetting initial costs and generating higher farmer incomes. This aligns with global trends where organic markets expanded at an annual rate of 15%, driven by consumer demand for healthy and environmentally friendly food.

However, the transition to organic farming faces challenges such as high conversion costs, labor-intensive practices, and market access barriers. Policy interventions, including subsidies for organic certification, investment in research (e.g., pest-resistant crop varieties), and the promotion of integrated farming models, are critical to mitigate these barriers.

Future research should focus on optimizing ecological-economic trade-offs, developing scalable technologies (e.g., AI-driven pest prediction), and exploring new market channels (e.g., organic carbon credits) to further enhance the sustainability and profitability of organic agriculture. This study provides a robust framework for policymakers, farmers, and researchers to collaboratively advance organic farming as a key solution to global food security and environmental degradation.

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