Biodiversity and Economic-Ecological Assessment of Organic and Conventional Agriculture Based on the Lotka-Volterra Model

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Abstract. In this era, the pace of global agricultural intensification is accelerating. Under such circumstances, although traditional agricultural practices have increased crop yields, they have also brought about some major problems, such as the reduction of biodiversity and the deterioration of ecosystems. Now, for agriculture to achieve sustainable development, it is facing a significant challenge. The significant challenge is how to ensure profitability while simultaneously achieving effective ecological protection. To solve this problem, this paper conducts a study, adopts the extended Lotka-Volterra dynamic model, and combines the Shannon Diversity Index to construct a coupled analysis framework. This framework can capture the interactions among different species such as crops, weeds, trees, pests, and birds. At the same time, economic value and ecological value can also be evaluated. Subsequently, this paper simulated and compared the long-term dynamic changes of the traditional agricultural system and the organic agricultural system under different management systems. The results show that organic agriculture has significantly improved the diversity of species in the ecosystem. After approximately 15 years, organic agriculture surpassed traditional agriculture in both economic and ecological benefits. From these results, it can be seen that organic agriculture not only promotes the joint development of economic and ecological achievements, but also provides a better approach for sustainable agricultural management.

Keywords: Organic Agriculture, Conventional Agriculture, Shannon Diversity Index, GE Matrix.

1. Introduction

With the global population increasing and food demand rising, agricultural production systems are confronted with an inherent conflict between maximizing economic efficiency and preserving the ecological environment. This conflict arises from the emphasis of traditional agriculture on achieving high yields, which has led to excessive reliance on chemical inputs and, consequently, a marked decline in ecosystem biodiversity and the degradation of ecosystem services[1]. Enhancing the sustainability of agricultural ecosystems while ensuring economic viability has therefore become a central challenge in contemporary agricultural management and policy-making[2].

In recent years, scholars have undertaken extensive research on maintaining agricultural ecosystem diversity and balancing economic and ecological values. Ada M. Herrera investigated the application of the Shannon diversity index in dynamic multi-landscape systems, demonstrating the index's effectiveness in assessing the stability of community structures[3]. Y. Lin et al. conducted an in-depth analysis of chaotic dynamics in Lotka-Volterra models describing interspecies interactions and proposed corresponding control strategies[4]. Carrié et al. examined the effects of dispersal constraints and external disturbances on the recovery of farmland plant communities during the transition to organic agriculture, confirming the positive impact of organic practices on enhancing biodiversity[5].

Although many studies have laid the foundation for the management of diversity and economic value in agroecosystems, giving many theoretical bases and practical examples, most papers now focus on a single species or a particular ecosystem service. These studies do not take into account the complex interrelationships between different species, nor do they carefully analyze the balance between economic goals and ecological conservation. Another question is how traditional agriculture and organic agriculture have different impacts on biodiversity in the long-term development process, which is better, and there is a lack of systematic comparison with mathematical modeling and data analysis.

To address the aforementioned limitations, this study focuses on agricultural ecosystems and employs an extended Lotka-Volterra dynamic model to comprehensively account for interspecific interactions among multiple species—including crops, weeds, trees, pests, and birds—as well as the effects of chemical inputs, thereby constructing a dynamic system that integrates both ecological and economic coupling. By innovatively introducing a dual evaluation framework that combines the Shannon diversity index with assessments of ecological-economic value, this study systematically analyzes the long-term dynamics of biodiversity and the evolution of economic-ecological benefits under traditional and organic agricultural management regimes.

The main contributions of this paper are as follows: (1) For the first time, it integrates multi-species Lotka-Volterra dynamics with economic-ecological value assessments, proposing a quantitative analytical framework applicable to complex agricultural ecosystems; (2) Through comparative simulation experiments, it demonstrates the long-term advantages of organic agriculture in enhancing ecosystem diversity and achieving synergistic economic and ecological outcomes, thereby providing a theoretical foundation and practical references for the development of sustainable agricultural policies and management strategies.

2. Related Theories

2.1. The Lotka-Volterra model

The Lotka-Volterra model (Lotka-Volterra interspecies competition model) is an extension of the logistic model (logistic growth model)[6], According to the Logistic model, the following relationships apply：

$$\frac{dN}{dt} = RN\left(1 - \frac{N}{K}\right) \tag{1}$$

where N represents the population size of a species, R represents the population growth rate of a species, and K represents the environmental capacity of the population. $\frac{N}{K}$ can be interpreted as space that has been utilized, $(1 - \frac{N}{K})$ can be interpreted as unused space.

2.2. Shannon diversity index

The application of Shannon entropy in biodiversity assessment[7]：

$$SR = -\sum_{i=1}^{n} p_i \ln p_i \tag{2}$$

In this formula:

p_i is the proportion of individuals belonging to species i in the total number of individuals. n is the total number of species in the community. $\ln$ is the natural logarithm.

In ecological research, there is a very important indicator called the Shannon Diversity Index, which not only shows how many different species there are, but also reflects whether the number of these species is more evenly distributed. Generally speaking, if the value of this index is relatively large, it means that the species in this place are more and more diverse, and no organisms are particularly large or small; conversely, if the value is relatively small, it means that only a few organisms may account for the majority, and other species are relatively rare.

3. Experiments

In agricultural ecosystems, crops, weeds, trees, pests, birds, and external inputs (such as pesticides and herbicides) collectively form a complex network of interactions. The primary objectives of this study are to investigate the dynamics of multi-species interactions and analyze the balance between economic returns and ecological services.

We employed an enhanced Lotka-Volterra model (with extensions to the logarithmic growth model) to examine interactions among various species (crops, weeds, trees, pests, birds, and bats) in agricultural ecosystems, ultimately calculating the biodiversity index of the ecosystem.

The model incorporates economic factors in ecosystem utilization and maintenance, combining crop production value with forest ecological value (carbon sequestration function) to analyze how to balance agricultural economic returns with ecological services under different management strategies to achieve sustainable development[8-9].

Considering inter-species influences and chemical impacts, we derived the following system of differential equations:

The crop population (C) changes under natural growth, resource limitations, pest predation, and insecticide effects:

$$\frac{dC}{dt} = C\left(r_c - \frac{r_c C}{K_c} - a_{cp}P - \alpha_c S\right) \tag{3}$$

where r_c represents the crop growth rate, K_c the environmental carrying capacity for crops, a_{cp} the predation rate of pests on crops, and α_c the mortality rate of crops due to insecticide application. The weed population (W) responds to natural growth, resource constraints, pest predation, and herbicide effects:

$$\frac{dW}{dt} = W\left(r_w - \frac{r_w W}{K_w} - a_{wp}P - \alpha_w H\right) \tag{4}$$

where r_w is the weed growth rate, K_w the environmental carrying capacity for weeds, a_{wp} the predation rate of pests on weeds, and α_w the mortality rate of weeds due to herbicide application. The tree population (M) considers natural growth, resource limitations, and pest predation:

$$\frac{dM}{dt} = M\left(r_m - \frac{r_m M}{K_m} - a_{mp}P\right) \tag{5}$$

where r_m is the growth rate of the tree, K_m is the environmental holding capacity of the tree, and a_{mp} is the predation rate of the pest on the tree.

The pest population (P) accounts for nutrition provided by crops and weeds, natural mortality, bird predation, and pesticide effects:

$$\frac{dP}{dt} = P\left(e_{pc}a_{cp}C + e_{pw}a_{wp}W - r_p - a_{pb}B - \alpha_p S\right) \tag{6}$$

where e_{pc}, e_{pw} is the rate of nutrient conversion of pests from crops and weeds, r_p is the natural mortality rate of pests, a_{pb} is the predation rate of pests by birds, and $\alpha_p S$ is the kill rate of pests by insecticides.

The bird population (B) changes based on nutritional benefits from pest predation and natural mortality:

$$\frac{dB}{dt} = B\left(e_{bp}a_{pb}P - r_b\right) \tag{7}$$

where e_{bp} is the rate of nutrient conversion of birds from pests. a_{pb} is the predation rate of bird on pests, and r_b is the natural mortality rate of birds.

The insecticide concentration (S) considers application and degradation rates:

$$\frac{dS}{dt} = u_s - \lambda_s S \tag{8}$$

where u_s is the rate of application of the insecticide and λ_s is the rate of whitening degradation of the insecticide.

The herbicide concentration (H) accounts for application and degradation rates:

$$\frac{dH}{dt} = u_h - \lambda_h H \tag{9}$$

where u_h is the rate of herbicide application and λ_h is the rate of herbicide whitening degradation.

To evaluate ecosystem biodiversity, we utilized a species richness index derived from information theory, designed to measure both the richness and evenness of species diversity. This index reflects the uncertainty and complexity of information within the system by considering the distribution of species populations. The formula for this index is:

$$SR = -\sum_{i=1}^{n} p_i \ln p_i \tag{10}$$

where p_i is the proportion of the i-th species' population relative to the total population of all species in the ecosystem, n is the total number of species, and SR represents the diversity index. The higher the index, the more evenly species are distributed, indicating higher biodiversity in the ecosystem; conversely, a lower index suggests that certain species may dominate, resulting in lower biodiversity.

In this model, benefits include both crop economic value and tree ecological value. Crop economic value is represented by the product of quantity and unit price, specifically the crop yield per unit area multiplied by the market price. Trees possess more complex ecological functions, particularly carbon sequestration, where they absorb carbon dioxide through photosynthesis and convert it to organic matter, playing a significant ecological role in mitigating climate change and reducing greenhouse gas emissions[10-11]. Therefore, in assessing tree ecological value, we include their carbon sequestration function, quantifying their contribution to ecosystem services, thereby highlighting their important role in environmental protection and sustainable development.

$$TR = CV + TEV \tag{11}$$

where TR represents total revenue, CV crop value, and TEV tree ecological value.

$$CV = AY * CP \tag{12}$$

where AY represents agricultural yield and CP crop price.

$$TEV = NT * CPT * CHC \tag{13}$$

where NT represents the number of trees, CPT the amount of CO_2 absorbed per tree, and CHC the unit price for human treatment of CO_2.

Costs include both farmland planting management costs and ecological value losses due to tree reduction from land conversion. Farmland planting management costs typically encompass expenditures for agricultural activities such as tillage, fertilization, irrigation, and pest control, which directly affect crop production efficiency and economic returns[12]. Conversely, during farmland conversion, forest ecosystem area decreases, leading to tree reduction and loss of related ecological services provided by forests.

$$TC = DEC + EOC \tag{14}$$

where TC represents total cost, DEC direct economic cost, and EOC environmental opportunity cost.

$$DEC = FA * UCFA \tag{15}$$

where FA represents farmland area and UCFA the cost per unit of farmland.

$$EOC = \frac{FA}{TAT} * CPT * CHC \quad (16)$$

where TAT represents the area required for a single tree.

During model construction, data collection relied on multiple authoritative databases: the National Agricultural Statistics Service (NASS) of the United States Department of Agriculture (https://www.nass.usda.gov/index.php) Crop yield statistics from 2018 to 2023 were used to calibrate the baseline yield parameters for conventional and organic agriculture in the model. The 2023 high-resolution cropland distribution data (spatial resolution of 30 meters) from CropScape - Cropland Data Layer (https://nassgeodata.gmu.edu/CropScape/) was used to define cropland boundaries and crop planting patterns. Global Forest Watch (Global Forest Watch, https://www.globalforestwatch.org/) 2024 updated vegetation cover dataset was used to extract tree carbon sink coefficients. Data from the FAO FAOSTAT database (https://www.fao.org/faostat/en/#data/FO) on global pesticide usage, organic agriculture area share, and crop market prices were used for initial chemical input concentration settings and economic benefit calibration.

Through the dynamic ecosystem experiments and economic analyses described above, we derived biodiversity indices and economic-ecological values for conventional and organic agricultural systems. Our findings demonstrate that organic agriculture maintains significantly higher biodiversity than conventional agriculture, with this disparity progressively widening over time. The economic and ecological returns of organic agriculture surpass those of conventional agriculture at approximately year 15, establishing a critical temporal threshold for sustainable agricultural investment decisions.

4. Results

Through experimental studies on changes in the population sizes of all species in the ecosystem, we calculated the dynamic changes in biodiversity indices for conventional agriculture and organic agriculture. The results are shown in Figure 1.

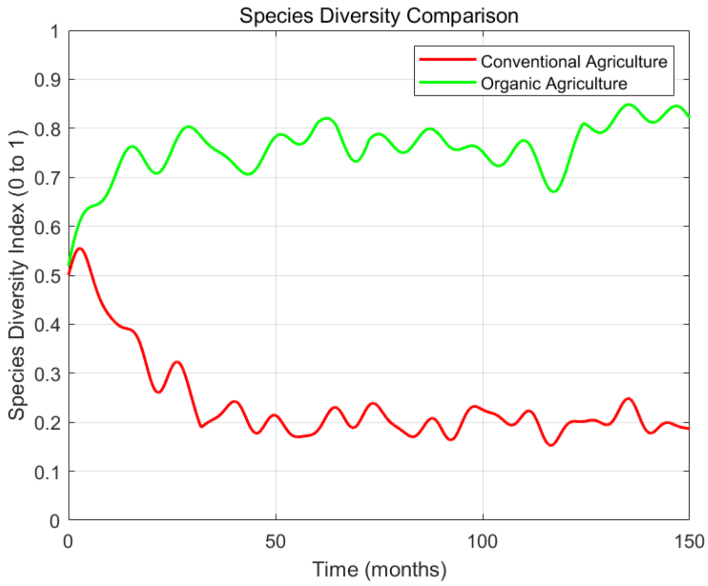


Figure 1. Comparison of changes in species diversity over time under traditional and organic farming models

The graph shows the diversity index of species for conventional agriculture (red line) and organic agriculture (green line) over 150 months (12.5 years). The index goes from 0 to 1 with more value indicating more diversity of species in the ecosystem.

The conventional agriculture diversity index (red line) starts at a moderate level of approximately 0.55 and then quickly declines in the first 20 months to about 0.3. It rebounds slightly around month

30 to about 0.35 before stabilizing at a low level of around 0.2 for the remainder of the period: more or less constant thereafter with only minor fluctuations.

The organic agriculture (green line) starts at about the same level of diversity 0.5, and then it increases steadily during the first 15-20 months going above 0.7. It then varies between 0.7-0.85 for diversity level thus maintaining very high levels of diversity throughout the entire period. In the last stage (months 120-150), it stabilizes at around 0.8.

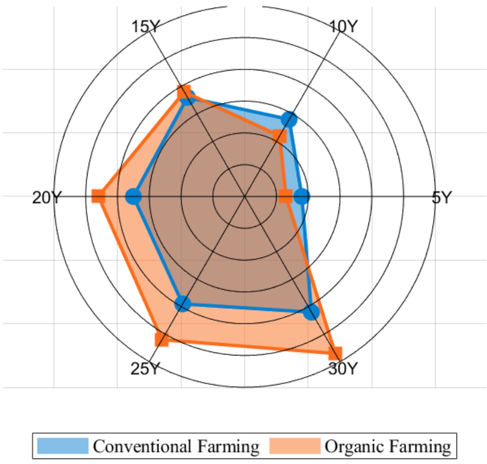
The factors that explain it are numerous. In Conventional Agriculture, the chemical pesticides treatment increased the death rate among non-target organisms—pollinators and natural predators. Monoculture land use limits Habitat Diversity, while Chemical pesticides lead to Resistance among the Pests; this also disrupts the natural predator-pest balance. Soil biodiversity was reduced, totally affecting the food web.

In organic farming, since there is no use of chemical pesticides, it offers a safe environment for the existence of beneficial organisms. Different practices under this management such as crop rotation and intercropping further increase habitat diversity. Slowly over time, with the natural enemies of the pests coming in, an ecological balance is created. Organic inputs enhance soil biodiversity.

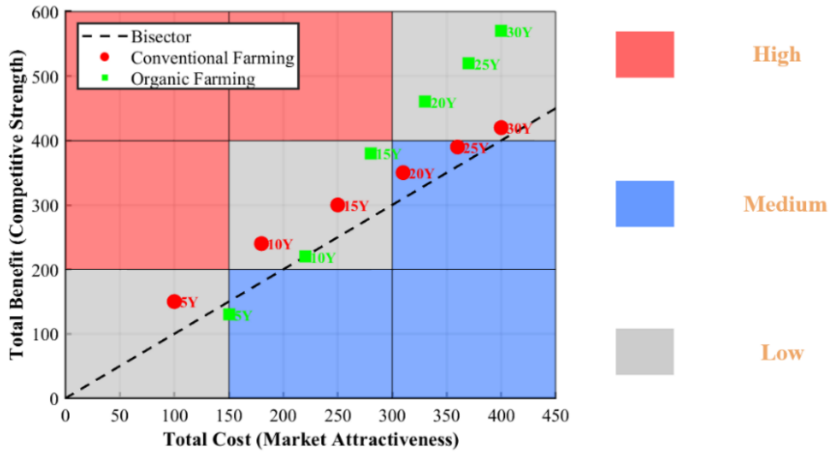
The variations seen in both setups mirror typical reactions to seasonal shifts and environmental elements. The organic setup exhibits bigger swings yet retains great diversity, pointing to a more lively and resilient ecosystem. The conventional setup's minor variations at lower levels hint at a simple system with little way of reacting to outside changes.

These results have been validated by field observations: organic agriculture allows biodiversity to flourish at ever higher levels because of more diversified habitats and lower chemical inputs, though the management of pests could be a better initial situation. Conventional agriculture may provide higher short-term yields but depletes the biodiversity of agricultural ecosystems in the long run.

From the above computations of the economic benefits of conventional agriculture and organic agriculture, we obtained the following two result graphs. As shown in Figure 2.



(a) Radar chart of the economic benefits of traditional and organic agriculture



(b) Conventional Farming vs. Organic Farming GE Matrix

Figure 2. Time Dimension Indicator Radar Chart and Cost-Benefit Competitiveness Scatter Analysis

Based on Figure 2, it can be seen that implementing organic agriculture in the current region, although initially the total economic benefits are lower than the total costs, after 10 years, the total economic benefits start to exceed the total costs. With time, the total economic benefits significantly surpass the costs. On the other hand, in conventional agriculture, although the initial total economic benefits are higher than the total costs and greater than those of organic agriculture, the growth of total economic benefits slows down over time. Around 15 years, the total economic benefits of conventional agriculture are surpassed by organic agriculture.

The dashed line in the graph represents the boundary where total economic benefits equal total costs. Conventional agriculture is gradually approaching this boundary with time, indicating that the total economic benefits of conventional agriculture will fall below the total costs, resulting in losses. In the GE matrix, conventional agriculture consistently falls within the medium and low levels, while organic agriculture starts in the low level, progresses to the medium level, and eventually reaches the high level. This also indicates that in the long run, the cost-benefit level of organic agriculture is superior to that of conventional agriculture.

5. Conclusions

In this study, we conducted a mathematical analysis of biodiversity and the economic-ecological value of conventional and organic agricultural systems. Our results indicate that organic agriculture exhibits higher biodiversity compared to conventional agriculture, and this difference becomes more pronounced over time. After approximately 15 years, organic agriculture yields higher economic and ecological returns than conventional agriculture, identifying a time threshold for sustainable agricultural investment decisions. In the following years, the gap between the total benefits and total costs generated by organic agriculture continues to widen, indicating increasing returns on investment over time. When extending the time horizon further, this gap narrows and eventually leads to losses in conventional agriculture. These findings provide strong evidence for the significant economic and ecological advantages of organic agricultural systems. The commitment to biodiversity conservation over time, alongside improved economic viability, demonstrates that organic agriculture is a more efficient and resilient production system. An integrated assessment of biodiversity and economic indicators offers valuable insights for agricultural policies under diverse ecological contexts.

Although this study provides strong evidence for the advantages of organic agriculture, there are still some limitations. The current model simplifies real-world complexity, such as local differences in climate, soil, and management practices. Some important ecological functions, like pollination and water regulation, are not fully considered. In future work, we plan to incorporate more diverse species, ecosystem services, and spatial data, and to analyze the effects of climate change and policy incentives. This will help improve the model's accuracy and provide more practical guidance for sustainable agriculture.

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