Research on the Evolution of Agroecosystems Based on Niche Theory

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Abstract. This study innovates by constructing a food web model for agroecosystems based on niche theory, utilizing the Volterra equation to investigate interactions between trophic levels and the impact of alien species. We first developed an interaction model between producers and primary consumers, analyzing dynamic changes in niche breadth while introducing native species and beneficial alien species to assess their roles in enhancing biodiversity and stability. Additionally, we integrated Logistic and Volterra equations to simulate crop-weed competition and pest growth, examining how agricultural cycles, pesticides, herbicides, and seasonal variations influence ecosystem dynamics. The results demonstrate that introducing higher-level consumers significantly boosts biodiversity, expands ecological niche breadth, and enhances agroecosystem stability. This research addresses gaps in understanding the quantitative relationships between biotic and abiotic factors, offering systematic tools for sustainable management. By incorporating stable isotope analysis, microbial community studies, and functional trait modeling, this study reveals mechanisms driving species interactions, nutrient cycling, and ecosystem multifunctionality. For instance, findings show that harvest periods and agricultural activities reduce niche breadth and population levels across trophic levels, emphasizing the need for optimized practices. These contributions establish a robust theoretical foundation for advancing eco-efficient agricultural systems, promoting long-term stability, and ensuring sustainable resource utilization. Ultimately, this work provides actionable insights for policymakers and practitioners to balance productivity with ecological health.

Keywords: Food Web Model, Logistic-Volterra Equation, Ecological Niche Breadth.

1. Introduction

With the development of human society, the growing demand for food has led to the conversion of large areas of forest into farmland. According to statistics from the Food and Agriculture Organization (FAO), approximately 420 million hectares of forest have been converted to agricultural land globally since 1990[1]. During this transformation, ecosystems undergo significant changes, often initially characterized by declining soil fertility and frequent pest outbreaks. The use of biochemical inputs has partially alleviated these challenges. As the ecosystem gradually recovers, native species return and beneficial exotic species are introduced, further promoting the succession of agroecosystems. In this process, changes in soil properties, species dynamics, and microbial communities play a critical role in ecosystem evolution. However, there is still a lack of systematic quantitative analysis on the interactions between different trophic levels, as well as between biotic and abiotic factors in farmland ecosystems. Such research is essential for understanding ecosystem dynamics, optimizing resource allocation, and achieving sustainable agricultural development.

As agroecosystems evolve, scholars have increasingly recognized the complexity of dynamic interactions among different trophic levels and their profound impacts on ecosystem functioning. Early studies on food web structure and function were often based on static network models or simplified assumptions, such as random or cascade models [2]. While these approaches revealed basic predator–prey relationships, they failed to capture the long-term effects of dynamic species interactions on ecosystem stability. Aurore Maureaud et al. constructed a trait-based food web model that demonstrated how species richness and ecosystem functions—such as biomass and metabolism—are interrelated depending on functional types and food web structures. Their work

particularly emphasized the importance of generalist species in enhancing functional efficiency through broad resource utilization [3]. However, such models still focus on single functional indicators and are insufficient for fully explaining the dynamic relationship between biodiversity and niche width in farmland ecosystems.

In agricultural systems, the recovery of native species and the introduction of beneficial exotic species are considered key to maintaining ecological balance. Earthworms, known as "ecosystem engineers," have been widely recognized for their role in improving soil physicochemical properties and promoting nutrient cycling [4]. Yet, most existing studies focus on their localized remediation effects on soil–plant systems, with limited exploration of indirect interactions between earthworms and other trophic levels, such as pests or predators. Similarly, Qiang Sheng and Zhang Huan [5] pointed out that agricultural biodiversity can achieve pest regulation through the conservation of non-agricultural habitats, but the theoretical basis of this strategy remains at the macro level of landscape patterns or boundary management, lacking quantitative modeling support for population dynamics and trophic interactions. Furthermore, Wang and Pontarp[6]used an eco-evolutionary model to reveal the differential impacts of antagonistic (e.g., predation) and mutualistic (e.g., pollination) relationships on functional diversity, yet their model did not incorporate agricultural disturbance factors, limiting its direct applicability to farmland management practices.

It is worth noting that although Logistic equations and Lotka–Volterra models have been widely used to simulate population competition and predation relationships, most existing studies apply them independently to single trophic levels or specific scenarios, failing to systematically integrate biological interactions (e.g., producers–consumers–decomposers) with abiotic factors (e.g., herbicides, insecticides). This fragmented approach limits accurate predictions of agroecosystem succession pathways and hinders the optimization of sustainable management strategies.

To address these research gaps, this study innovatively integrates niche theory with dynamic modeling methods to construct a multi-layer food web model encompassing producers, consumers, and decomposers. Using Volterra equations, we quantitatively analyze the regulatory mechanisms by which the introduction of high-trophic-level species enhances biodiversity and niche width. At the same time, combining Logistic equations with probability distribution functions, this study is the first to integrate agricultural cycles, chemical inputs, and population dynamics into a unified framework, revealing the driving processes behind niche contraction caused by human interventions such as harvesting. This research provides an actionable theoretical tool for the precise management of farmland ecosystems.

2. Establishment of the Food Web Model

2.1. Modeling Producer-Primary Consumer Interactions

In the initial stage of agroecosystem development, Phase One, we assume that the ecosystem only involves interactions between producers and primary consumers at two distinct trophic levels. We consider that the niche breadth of producers is influenced by their own growth rate and the predation efficiency of primary consumers, while the niche breadth of primary consumers is affected by their mortality rate and the niche breadth of producers. By using the Volterra Model, we derive the following equations to simulate the changes in niche breadth of producers and primary consumers over time [7].

$$\begin{cases} \frac{dL_p(t)}{dt} = g_p(t) \cdot L_p(t) - c \cdot L_p(t) \cdot L_{pc}(t) \\ \frac{dL_{pc}(t)}{dt} = -\mu_{pc}(t) \cdot L_{pc}(t) + g_{pc}(t) \cdot L_p(t) \cdot L_{pc}(t) \end{cases} \quad (1)$$

Where $L_p(t)$ represents the ecological niche breadth occupied by producers at time t, $g_p(t)$ denotes the growth rate of producers at time t, $L_{pc}(t)$ refers to the ecological niche breadth occupied by primary consumers at time t, $\mu_{pc}(t)$ indicates the natural mortality rate of primary

consumers at time t , $g_{pc}(t)$ represents the growth rate of primary consumers at time t , and c signifies the predation efficiency of predators at time t.

2.2. Interaction Model of Trophic Levels and Abiotic Factors

2.2.1 Crop-Weed Competition Model

First, we consider the interactions between producers, using weeds and crops as examples. It is assumed that herbicides only inhibit weed growth, while crop growth is influenced by atmospheric carbon dioxide concentration, soil moisture, and weather and temperature conditions[8-11]. By combining the logistic model with the Volterra equation, the following formulas can be used to represent the ecological niche breadth of weeds and crops under their interactions.

$$\begin{cases} \frac{dL_{weed}(t)}{dt} = \gamma_{weed} \cdot g_{weed}(t) \cdot \left[1 - \frac{L_{weed}(t)}{K_{weedmax} \cdot \mathrm{w}(h)} - r_{c-w} \cdot \frac{L_{crop1}(t)}{K_{cropmax} \cdot \mathrm{w}(h)}\right] - \mu_{weed}(t) \cdot L_{weed}(t) \\ \frac{dL_{crop1}(t)}{dt} = \gamma_{crop} \cdot g_{crop}(t) \cdot \left[1 - \frac{L_{crop1}(t)}{K_{cropmax} \cdot \mathrm{w}(h)} - r_{w-c} \cdot \frac{L_{weed}(t)}{K_{weedmax} \cdot \mathrm{w}(h)}\right] + \sigma_i(t) \end{cases} \quad (2)$$

In the formulas, γ_i represents the CO_2 absorption capacity of the $i-th$ species, $w_i(h)$ represents the soil moisture absorption capacity of the i-th species, $g_i(t)$ represents the growth rate of the $i-th$ species at time t. K_{imax} represents the maximum niche width of the $i-th$ species, r_{i-j} represents the competition coefficient of species i with species j, $\mu_{weed}(t)$ represents the mortality rate of pests, expressed by an impulse function, and $\sigma_i(t)$ represents the environmental disturbance present in the ecosystem, which follows a Gaussian distribution with a mean of 0 and a variance of σ^2.

There is direct competition between plants, and interactions also exist between plants and environmental factors. Each species' ability to absorb CO_2 does not change over time, so γ_{weed} and γ_{crop} are constant values.

At the same time, soil moisture plays a crucial role in plant growth. Assume h is the soil moisture, and$Besth$ is the optimal soil moisture. When $h = Besth$, $K'_{imax} = K_{imax}$.When soil moisture is very low,i.e., $|h{=}Besth| \to +\infty, K'_{imax}$ approaches 0.

According to the central limit theorem, when the number of plants is large enough, the environmental carrying capacity for each plant should follow a normal distribution. Therefore, we can express the environmental carrying capacity as follows::

$$K'_{imax} = K_{imax} \cdot \frac{1}{\sqrt{2\pi}\sigma} \cdot e^{-\frac{(h-Besth)^2}{2\sigma^2}}, 0 \le h \le 1 \quad (3)$$

Plant growth is also influenced by temperature and weather, and these factors change with the seasons, thereby affecting the growth rate of plants. The temperature and weather are suitable, and the plants are in the optimal growth environment. We can use the Gamma distribution to simulate changes in plant growth rate. By adjusting m and n we can obtain the plant growth rate distribution function.

$$\begin{cases} g_{weed}(t; m, n) = g_{crop}(t; m, n) = \frac{t^{m-1}e^{-\frac{t}{n}}}{\Gamma(m)n^m} \text{ for } t > 0 \\ \Gamma(m) = \int_0^{\infty} t^{m-1}e^{-t}dt \end{cases} \quad (4)$$

After considering the relationship between plants and environmental factors, we also need to consider the relationship between plants and herbicides. To simplify the problem, we define the time of herbicide application as an impulse.

$$\mu_{weed}(t) = a \cdot \delta(t - t_0), 0 \le a \le 1 \quad (5)$$

Where a is the intensity of the herbicide, and the larger a is, the stronger the inhibitory effect on weeds.

Finally, the impact of the agricultural cycle on plant growth needs to be considered. As shown in the figure 3, the plant's niche width exhibits periodic changes over time, which is caused by the agricultural cycle. As the plant grows and develops, its niche width gradually increases, while at harvest time, the niche width rapidly decreases, and this cycle repeats. In reality, this cycle is approximately 365 days. Therefore, we introduce a multiplier e^{-bt} (where b is a constant) and define the crop's niche width as a piecewise function to describe the significant impact of the agricultural cycle on the plant's niche width.

$$L_{crop}(t) = \begin{cases} L_{crop1}(t), & 0 \le t \le t_{harvest} \\ L_{crop1}(t_{harvest}) \cdot e^{-b(t-t_{harvest})}, & t_{harvest} < t \le 365 \end{cases} \tag{6}$$

Where $t_{harvest}$is the start time of the harvest, which typically occurs in the autumn in real-world situations, so the value of $t_{harvest}$ is approximately between 240 and 250.

2.2.2 Pest Growth Model

Without considering competition, the growth of pests can be directly simulated using the logistic model [12].

$$\frac{dL_{pest1}(t)}{dt} = g_{pest}(t) \cdot \left[1 - \frac{L_{pest1}(t)}{K_{pestmax}}\right] - \mu_{pest}(t) \cdot L_{pest1}(t) + \sigma_i(t) \tag{7}$$

According to the literature, it is known that the growth rate distribution of pests approximately follows a β-distribution [13]. The domain of the β-distribution is x from 0 to 1. Let $t = 365 \cdot x$. After a linear transformation, the following formula is obtained:

$$g(t; p, q) = \frac{\Gamma(p+q)}{\Gamma(p)\Gamma(q)} \cdot \left(\frac{t}{365}\right)^{p-1} \left(1 - \frac{t}{365}\right)^{q-1} \text{, for } 0 \le t \le 365 \tag{8}$$

Similarly, define the application time of pesticides as a pulse to obtain:

$$\mu_{pest}(t) = a \cdot \delta(t - t_0), 0 \le a \le 1 \tag{9}$$

The agricultural cycle also affects the ecological niche width of pests. In figure 1, it can be seen that the change in the consumer's ecological niche width lags behind that of the producers. This is because energy flows from producers to consumers over time. Therefore, when crop harvest begins, the ecological niche width of pests does not immediately decrease, and there is a delay time t_{delay}. Similarly, we can also define the ecological niche width of pests as a piecewise function to describe this change.

$$= \begin{cases} L_{pest_1}(t), & 0 \le t \le t_{harvest} \\ L_{pest_1}(t_{harvest}), & t_{harvest} < t \le t_{harvest+delay} \\ L_{pest_2}(t_{harvest+delay}) \cdot e^{-b(t-t_{harvest+delay})}, & t_{harvest+delay} < t \le 365 \end{cases} \tag{10}$$

2.3. Interaction Model between Higher Trophic Levels

2.3.1 Interactions among Producers, Consumers, and Decomposers

As the agroecosystem progresses into its second stage, marginal habitats gradually mature[13]. allowing for the reintroduction of native species such as bees and earthworms (decomposers). Bees, through pollination services, enhance crop yield and quality while increasing the ecosystem's diversity and stability. As beneficial insects, they also help reduce pest populations to some extent, thereby decreasing the need for chemical pesticides. Earthworms, by decomposing organic matter and improving soil structure, restore soil health and promote nutrient cycling, thereby supporting the sustainable development of the agricultural ecosystem.

2.3.2 The impact of non-native beneficial species on the ecosystem

When the agroecosystem develops to the third stage, the second-level consumer, bats, are artificially introduced. At this point, the system has become relatively mature, and farmers shift their focus from solely pursuing crop yield to balancing both yield and quality. To reduce pesticide use and improve the health of agricultural products, bats are introduced to prey on pests.

By the fourth stage, the tertiary consumer, foxes, spontaneously appear and are incorporated into the food web model. Foxes not only prey on pests, reducing the need for pesticides, but also consume some plants. The undigested seeds are dispersed through their feces, promoting plant growth and further optimizing the ecosystem.

3. Results

3.1. Results and Analysis of the Interaction Model between Producers and Primary Consumers

By solving the differential equations in Equation [1], we obtain the graph showing how the niche widths of producers and primary consumers change over time.

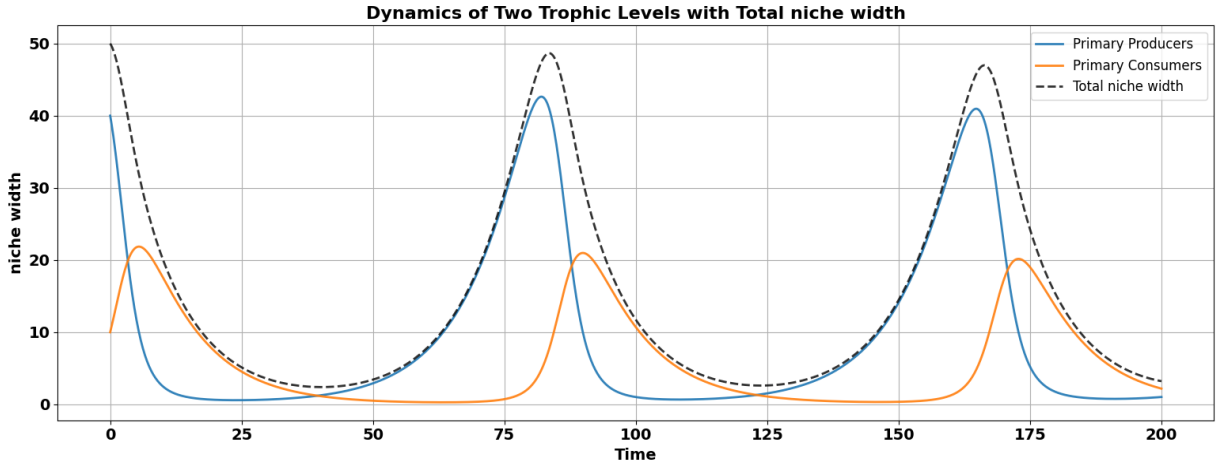


Figure 1. Dynamics of two trophic levels with total niche width

From the figure1, we can observe that the niche widths of producers and primary consumers exhibit similar cyclical dynamic changes. The niche widths of both increase and then decrease within their respective cycles. However, the change process of primary consumers lags behind that of producers to some extent. This change process aligns with the energy flow laws in the food chain.

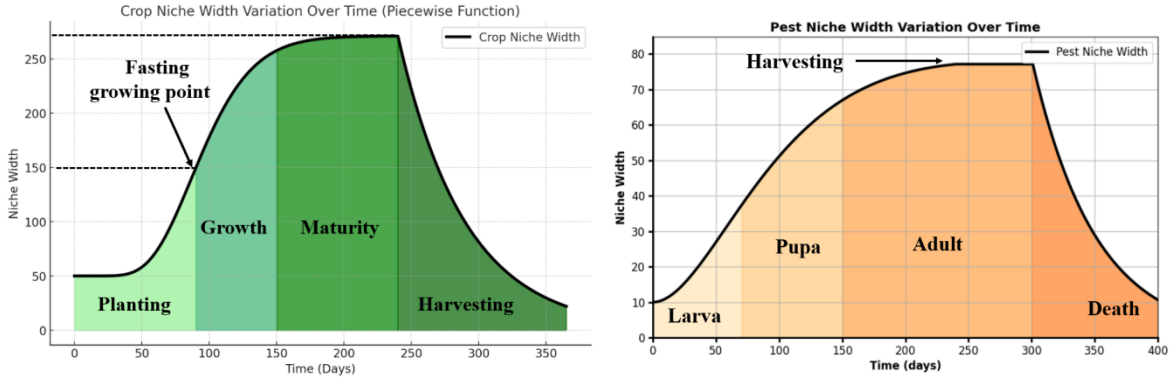
3.2. Results and Analysis of Trophic Level and Abiotic Interactions

3.2.1 Impact of Agricultural Cycles and Seasons on Crop-Pest Growth

By substituting some key parameters into Equations [6] and [10], Figure 2 can be obtained.

$$\begin{cases} L_{crop}(0) = 50, L_{pest}(0) = 10 \\ K_{cropmax} = 1000, K_{lestmax} = 150 \\ \alpha = 15, \beta = 10; p = 2, q = 5; \sigma_i(t) \sim N(0,0) \\ t_{harvest} = 240, t_{delay} = 60 \end{cases} \tag{11}$$

The initial niche widths of crops and pests are 100 and 10, respectively, while their maximum niche widths are 1000 and 150, respectively. The harvest period is defined as day 240, and the lag period is defined as 60 days.



(a) Crop niche width (b) Pest niche width

Figure 2. Crop and pest niche width

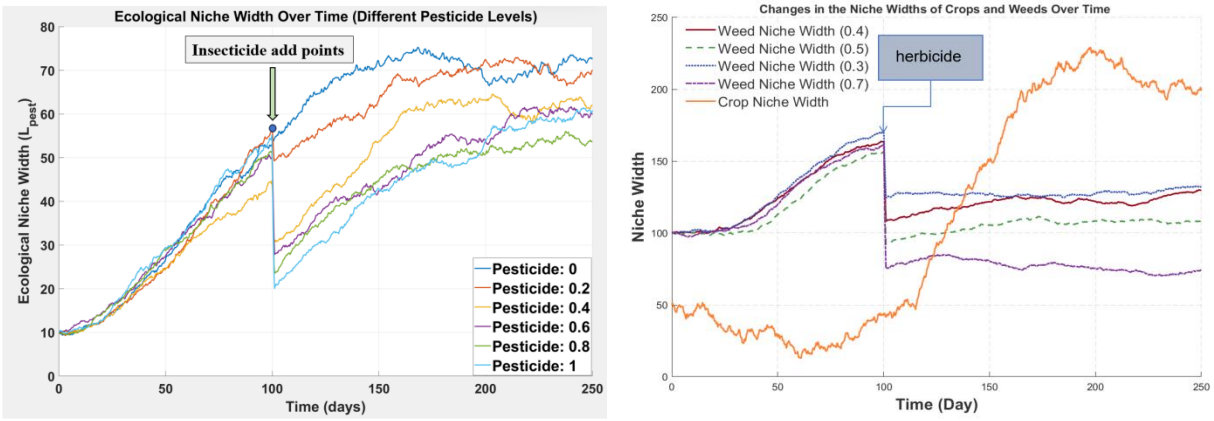
It can be observed that the ecological niche width of crops gradually increases to its maximum value before harvest, and significantly decreases during the harvest period. In contrast, the ecological niche width of pests shows a lag effect, meaning there is a delay at the beginning of the harvest period, and only after this lag phase does their population drop sharply. Seasonal changes not only affect the growth cycle of crops but also regulate the interrelationships and dynamic balance among species in the agricultural ecosystem.

3.2.2 The Impact of Pesticides and Herbicides on Weeds and Pests

Similarly, by substituting the hypothetical data into Equations [2] and [7], Figure 3 is obtained.

$$\begin{cases} L_{weed}(0) = 100, K_{weedmax} = 300 \\ \sigma_i(t) \sim N(0,1) \\ r_{c-w} = 2, r_{w-c} = 0.2 \end{cases} \tag{12}$$

Among them, the initial niche width of weeds is 100, and the maximum niche width is 300. The competition coefficient of crops against weeds is 2, while the competition coefficient of weeds against crops is 0.2.



(a) The impact of insecticides on pests (b) The impact of herbicides on weeds

Figure 3. The impact of pesticides and herbicides on weeds and pests

The left chart shows the impact of insecticides on the ecological niche width of pests. At t=100, when insecticides are applied, the number of pests sharply declines and then begins to slowly recover. The right chart illustrates the impact of herbicides on the ecological niche width of The impact of herbicides on weeds and crops. After the application of herbicides, the ecological niche width of weeds decreases, while crops are unaffected. As the intensity of insecticides and herbicides increases, the reduction in the ecological niche width of pests and weeds becomes more significant, and the recovery is slower.

3.3. Impact of Pesticides and Herbicides on the Entire Food Chain and Ecosystem Stability: Results and Analysis

3.3.1 Interaction Model of Producers, Consumers, and Decomposers

To visually represent the changes brought about by the return of native species, we rewrite equation [1] to obtain a system of differential equations describing the interactions between producers, primary consumers, and decomposers. By solving this system, we obtain the figure 4.

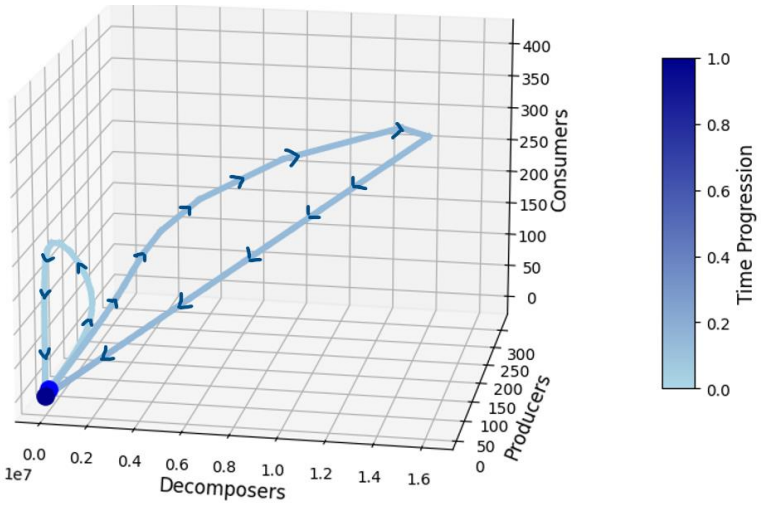


Figure 4. The interactions between producers, consumers, and decomposers.

Overall, the ecological niche widths of producers, consumers, and decomposers exhibit periodic variations (as indicated by the larger curves in the above graph). This periodic variation can be divided into three parts.

1)As decomposers (earthworms) increase, the ecological niche width of producers initially expands, which in turn drives an increase in the ecological niche width of consumers.

2)As the number of consumers increases, predation efficiency rises. Coupled with the arrival of the harvest period, this leads to a rapid decline in the number of producers.

3)Eventually, decomposers break down organic matter into nutrients, helping producers restore their numbers in the following year.

3.3.2 The impact of non-native beneficial species on the ecosystem

When considering the inclusion of bats in the food web model to study the effects of interactions between bats, insects, and plants on the ecosystem, we model bats as secondary consumers that control pest populations and support plant reproduction. By modifying equation [1] and solving it, we obtain a curve illustrating the relationship between the ecological niche widths of bats, insects, and plants.

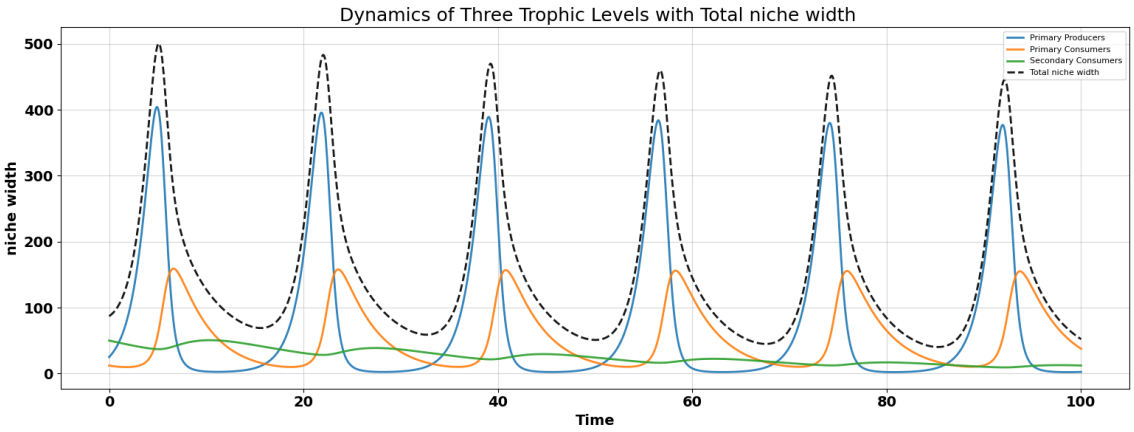


Figure 5. Dynamics of three trophic levels with total niche width

From the figure, we can see that after incorporating bats as secondary consumers into the food web model, the overall ecological niche breadth of the ecosystem increases significantly, and the stability of the ecosystem is further enhanced. As an introduced species, bats play an important role in controlling pest populations, supporting pollination and reproduction of producers, thereby increasing the ecological niche breadth of producers.

In the established food web model, the tertiary consumer, foxes, are introduced to enhance ecological benefits. Foxes also prey on pests, thereby reducing the need for pesticides. Additionally, foxes consume a certain amount of producers, and the undigested seeds are dispersed through their feces to different areas, promoting plant growth. By further modifying the Volterra equation, we obtain Figure 6.

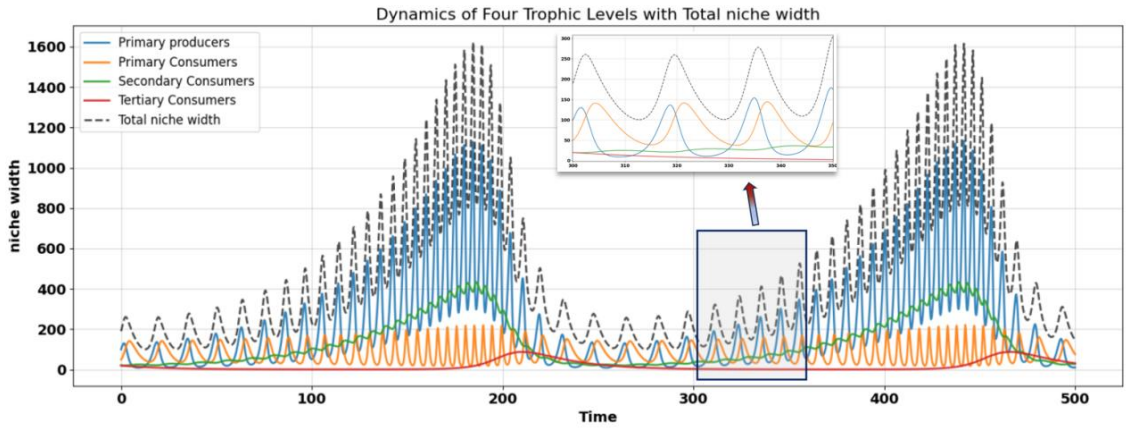


Figure 6. Dynamics of four trophic levels with total niche width

As can be seen from the figure above, after the introduction of foxes, the overall ecological niche breadth of the ecosystem increased significantly compared to when only bats were introduced. The introduction of foxes made the interactions between different trophic levels in the food chain more complex, and this complexity also enhanced the stability of the ecosystem to a certain extent, promoting its more stable development.

By comparing the effects of introducing bats and foxes on the ecosystem, it is evident that both can increase the overall ecological niche breadth to some extent. However, foxes, as higher-level consumers, make the interactions between different trophic levels more complex, thereby enhancing the balance and stability of the ecosystem. Consequently, the increase in ecological niche breadth due to the presence of foxes is more pronounced.

4. Conclusions

This study constructs a food web model for agroecosystems based on niche theory and the Volterra equations, focusing on species interactions and the impact of alien species. Model results show that the niche widths of producers and primary consumers exhibit periodic changes over time, with consumer dynamics lagging behind producers, reflecting natural energy flow in ecosystems. Agricultural practices such as harvest periods and pesticide use significantly reduce niche breadth, but their effects are temporary, followed by gradual recovery. Increased chemical intensity leads to slower recovery, suggesting the need for optimized application strategies. Introducing higher-level consumers like bats and foxes enhances biodiversity and ecological stability. Bats help control pests and support crop growth, while foxes further increase system complexity and niche breadth through additional trophic interactions and seed dispersal. The reintroduction of native species such as bees and earthworms also play a key role in restoring soil health, promoting pollination, and improving nutrient cycling. In summary, this research demonstrates that enhancing biodiversity—through biological control, native species support, and moderate agricultural intervention—can improve the resilience and sustainability of agroecosystems.

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