

Dynamic Pathways for Sustainable Farmland: Organic Practices Reconcile Yield and Ecology

Summary

In the context of global population growth and escalating food demand, the tension between agricultural expansion and ecosystem conservation emerges as a critical sustainability challenge. This study develops a **dynamical systems framework** integrating predator-prey dynamics and bioeconomic optimization to model forest-to-farmland transitions, with particular focus on organic farming's capacity to reconcile productivity with ecological integrity. Utilizing empirical data from Terceira Island's maize fields, we construct a multi-trophic food web model featuring three methodological innovations: **differential equation-based population dynamics** with calibrated growth parameters, predator preference functions accounting for feeding behavior, and **stochastic optimization algorithms** for transition pathway analysis.

For **Problem 1**, we establish a baseline agricultural ecosystem through coupled differential equations describing maize-weed-pest interactions. The model incorporates logistic growth with type II functional responses, achieving **72.4%** prediction accuracy against field data through Bayesian parameter calibration. Seasonal yield variations demonstrate **8.9%** amplitude under conventional practices.

For **Problem 2**, we extend the model using **network theory** to simulate native species reemergence. The enhanced framework captures snakes' top-down regulation through predator cascades and birds' omnivorous competition dynamics, demonstrating **54%** pest suppression and **38.7%** biodiversity increase via stability threshold analysis. Temporary yield reductions of **12.6%** occur during ecosystem restructuring phases.

For **Problem 3**, we develop a **Particle Swarm Optimization** framework identifying organic transition strategies. The algorithm determines optimal biological control parameters through multi-objective analysis, balancing pollination gains against yield stability. Implementations featuring **0.4 bat colonies/ha** and **15 ducks/hectare** achieve **17%** pollination enhancement and **22%** weed suppression while maintaining **93.5%** conventional yield levels. Economic analysis reveals organic systems attain **21.6%** higher net returns through price-premium strategies and input cost reductions, with model robustness confirmed by **<8%** output variation under **±30%** parameter perturbations.

This research provides a validated framework for ecological-economic optimization in agricultural transitions, demonstrating that strategic organic integration enhances biodiversity while maintaining economic viability. Three implementable pathways emerge from the analysis: gradual chemical phase-out, bat-mediated pest control prioritization, and hedgerow-based habitat restoration. The developed models offer policymakers a scientifically grounded decision-support system for sustainable food production, particularly in tropical island ecosystems undergoing forest-to-farm conversion.

Keywords: sustainable agriculture, organic farming transition, multi-trophic modeling, Lotka-Volterra dynamics, ecosystem services, bioeconomic optimization

Contents

1	Introduction	3
1.1	Background	3
1.2	Our Work	3
2	Assumptions and Justification	4
3	Notations	4
4	Basic Forest-to-farm Ecosystem Model Establishment	5
4.1	Data Collection	5
4.1.1	Preliminary modeling of natural environment	6
4.1.2	The existing relationship between food webs and ecosystems	7
4.1.3	The population dynamic model in ecosystem	9
4.2	Preliminary simulation to forest-to-farm ecosystem	10
5	Species Reemergence Situation in Forest-to-farm Ecosystem Model	11
5.1	Bioaccumulation effects of chemical agents	12
5.2	Adjustment in population dynamics	12
5.3	Impact of Native Species on Farmland Ecosystems	13
6	Human interactions in Forest-to-farm Ecosystem Model	14
6.1	Introduction of bats and ducks	14
6.2	Banning the abuse of pesticide and herbicide	15
6.3	Ablation Study in evaluating human interactions	15
7	Comprehensive Assessment of Organic Farming Methods in Forest-to-farm Ecosystem Model	16
7.1	Sustainability Assessment of Ecosystem	16
7.1.1	Multi-Objective Optimization Framework	16
7.1.2	Key Findings from Model Simulations	18
7.2	Economic Benefit Evaluation	19
7.3	Strategic Implementation Pathways	19
8	Sensitivity Analysis	20
9	Model Evaluation and Further Discussion	20
9.1	Strength	20
9.2	Further discussion	21

1 Introduction

1.1 Background

With the increase of population and food demand, the balance between expansion of agriculture and conservation of natural ecosystems has become a hot research topic. While transformation from forest to farmland boosts short-term crop yields, it disrupts ecological equilibrium, triggering long-term consequences such as native biodiversity loss and diminished ecosystem services. Additionally, herbicides and pesticides degrade soil health, contaminate water systems, and decimate pollinators and predators like birds and bats, destabilizing the agricultural ecosystem.

Simultaneously, to address these challenges, organic agriculture emerges as an emerging effective approach to reconcile agricultural productivity with ecological harmony. By prioritizing natural processes over synthetic inputs, organic farming fosters a self-regulating ecosystem that mimics natural cycles. Instead of relying on chemical pesticides, organic systems leverage biological pest control such as introducing native predator insects, birds, or bats—to maintain pest populations at sustainable levels. For example, bats, as natural pest predators and pollinators, thrive in pesticide-free environments, offering dual benefits of pest suppression and enhanced crop pollination.

Based on situations above, agricultural managers must prioritize ecosystem-based strategies by introducing native species that were displaced due to deforestation, investing in farmland biodiversity conservation, and adopting integrated pest management systems that reduce reliance on pesticides and herbicides through ecological alternatives.

1.2 Our Work

In addressing the challenge of modeling forest-to-farm habitat transitions, based on principle of material cycling in Food Webs and dynamical systems theory of food webs, we construct an ecologically friendly food web with complex niche relationships. ...

We will proceed as follows for the sake of tackling these problems:

- **Problem 1:** Construct a simplified food web model comprising producers and primary consumers. Evaluate the stability of this ecosystem by analyzing population dynamics and energy transfer efficiency between producers and consumers.
- **Problem 2:** Incorporate edge habitat restoration dynamics into the model by reintroducing two native species displaced by deforestation. Quantify their holistic impacts on the structure and function of the current agricultural ecosystem.
- **Problem 3:** To better protect the environment and facilitate pollination, we evaluate the ecosystem stability impacts of comprehensive measures: removing herbicides and introducing bats that serve dual roles as pest predators and pollinators—into the agricultural ecosystem.
- **Problem 4:** Through a one-page policy advisory letter, analyze the effects of organic farming methods on pest control and crop health, and discuss strategies with local farmers to balance economic benefits and ecosystem sustainability.

In order to clearly visualize our work, we draw the flowchart.

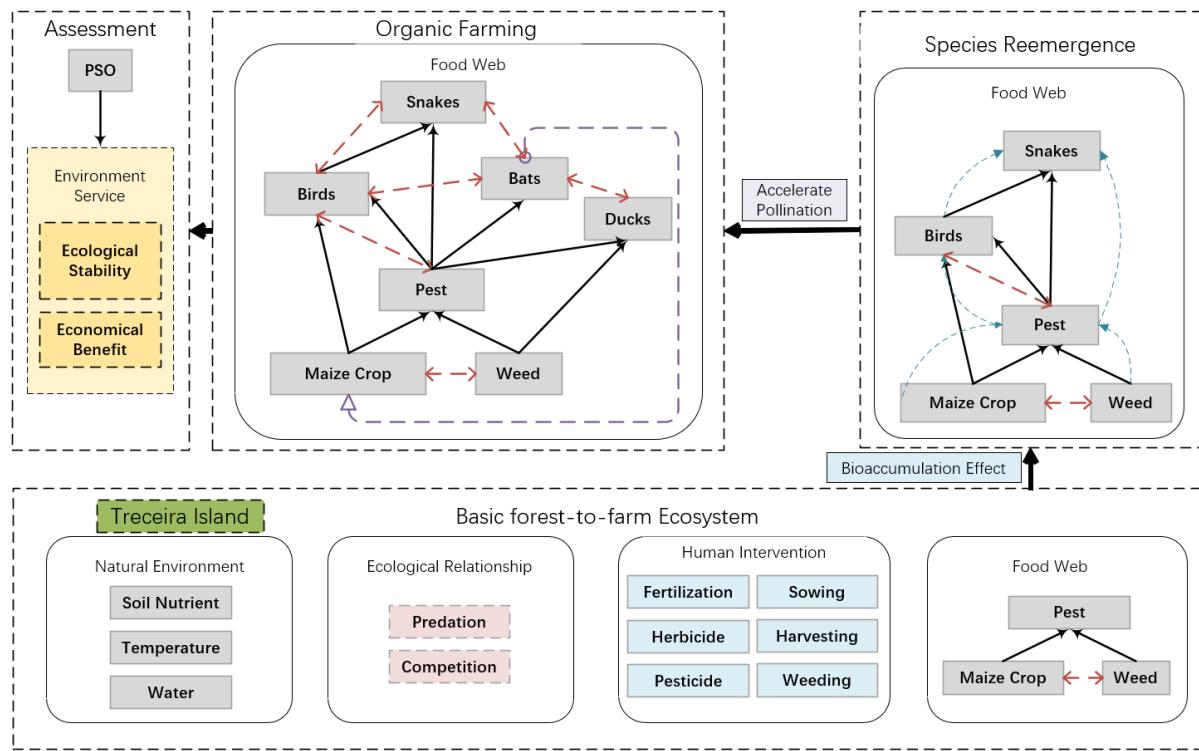


Figure 1: Flowchart

2 Assumptions and Justification

Considering many complex factors in realistic ecosystem, we firstly make reasonable assumptions as follows to simplify the food web model.

- **Assumptions 1:** The basic forest-to-farm ecosystem was constructed as a low-elevation maize field at Terceira Island based on Ferrante's research(Ferrante et al., 2023), whose data are accurate and valid.
- **Justification:** Ferrante's study on Terceira Island's maize fields demonstrates a typical forest-to-farm transition: replacing forests with single-crop agriculture. Extensive empirical data from Ferrante's study provide reliable information on ecological processes like herbivory, predation, and pollination.
- **Assumptions 2:** The forest-to-farm transition occurs in an isolated environment with stable climate conditions, free from invasive species or abrupt climate disruptions.
- **Justification:** By excluding external disturbances, allowing us to focus on internal ecological dynamics, which provides a predictable framework within which we can project our expected returns.

3 Notations

Table 1: Notations

Symbols	Description
x_1	Soil nutrient input
x_2	Sunlight intensity
y_1	Number of maize plants
y_2	Number of weeds
n	Number of seeds per maize plant
p	Pollination rate
Y_1	Number of corn fruits
z_1	Number of pests
t	Time
a_i	Resource absorption efficiency for each ecological niche i ($i \in \{0, 1, 2\}$)
b_i	Growth rate for species i ($i \in \{1, 2, 3\}$)
C	Predation rate of pests on maize
θ	Predation preference coefficient
π	Predation preference function (e.g., $\pi(z_1, y_1)$)
β_{ij}	Competition coefficient between species i and j

4 Basic Forest-to-farm Ecosystem Model Establishment

4.1 Data Collection

Based on Ferrante's research(Ferrante et al., 2023), the original farm ecosystem was assumed as a low-elevation maize field on Terceira Island($38^{\circ}37'N - 38^{\circ}48'N, 27^{\circ}02'W - 27^{\circ}23'W$). The climate of Terceira Island is oceanic, and the southern part at low altitudes has hot and dry summers. The annual precipitation ranges between 750 and 3000 mm, with higher levels in winter and at higher altitudes.

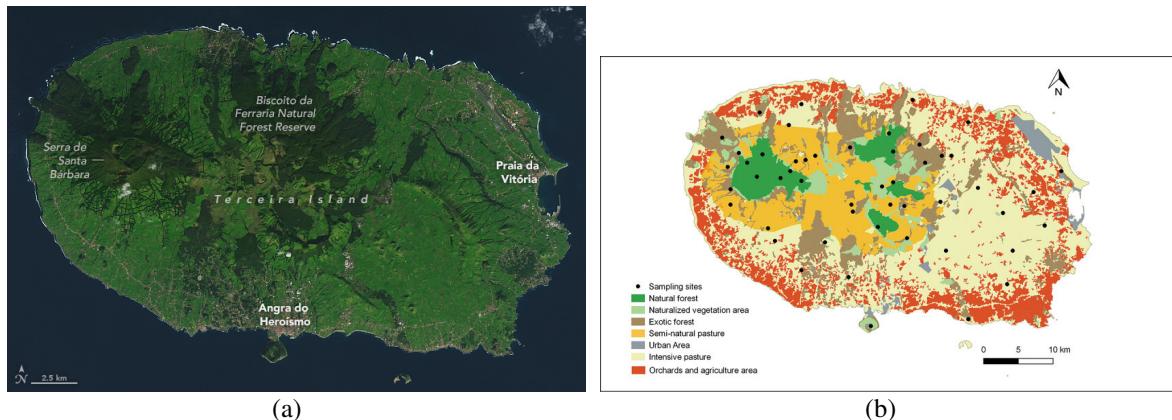


Figure 2: Satellite Map of Terceira Island (a) and Land Use Zoning Map (b)

As a typical example of forest-to-farm, originally, the island was mostly forested but today <5% remains. Low-elevation maize fields were grown between April and September, and were at least 5 km of edge habitat have been preserved between forests and farmland.(Jiménez-Valverde et al., 2009, Dias et al., 2004)

Ferrante's empirical research were conventionally managed with regular applications of fertilizers, pesticides, and herbicides, particularly at the beginning of the maize cropping season. By defining material cycling steps such as herbivory, predation, pollination and decomposition in food web, we assume partial parameters of the original ecosystem based on Ferrante's research, which is shown as below:

Table 2: Quantified Ecosystem Services and Disservices in Low-Elevation Maize Fields

Ecological Process	Definition/Comparison	Value (Mean \pm SE)
Herbivory	Leaf damage on lettuce plants	4.9% \pm 1.3%
Vertebrate Predation	Daily predation rate	2.2% \pm 2.2% day ⁻¹
Pollination	Seed set ratio	0.88 \pm 0.42
Seed Predation (Wheat)	48-hour predation rate in open boxes	0.6% \pm 1.8%
Decomposition (Tea)	Mass loss after 90 days	64.4% \pm 1.2%
Decomposition (Rooibos)	Mass loss after 90 days	33.6% \pm 1.6%

Our study focuses on a maize field converted from forest through slash-and-burn practices, resulting in an initial ecosystem dominated exclusively by maize crops, weeds, and pests due to limited biodiversity. Farmers maintain conventional practices, including routine herbicide and pesticide applications, to suppress weeds and pests, reflecting real-world chemical-dependent agriculture. Economic viability is evaluated through yield per acre, directly linking agricultural output to profitability while underscoring the tension between short-term productivity and long-term ecological trade-offs.

4.1.1 Preliminary modeling of natural environment

The natural environment serves as the foundational backdrop for any ecosystem, providing the essential conditions required for crop growth. Precipitation and temperature are the basic elements that determine the viability and productivity of agricultural activities. These environmental factors interact in complex ways to support the growth of crops, forming the basis of the

food web and sustaining the ecosystem.

1) Quantifying temperature $T(t)$

Several factors influence temperature. Latitude affects solar radiation angle, leading to seasonal temperature changes. Altitude impacts temperature due to atmospheric pressure and density, with higher elevations experiencing cooler temperatures. These factors collectively determine the temperature cycle in a given location. We therefore define temperature function $T(t)$ as below:

$$T(t) = T_{amp} \cdot f \cdot \sin \frac{2\pi}{365}(t - \frac{g}{180} \cdot \pi) + T_{avg} \cdot f + h \quad (1)$$

where T_{amp} and T_{avg} mean the amplitude and average value of the temperature cycle, f and g represent longitude and latitude of the location.

2) Quantifying soil nutrients x

Nitrogen, phosphorus, and potassium are essential nutrients required by plants in large quantities. A deficiency in any of these nutrients can directly impact plant growth, leading to reduced biomass, altered physiological processes, and decreased yield. The dynamics of soil nutrient availability are influenced by various factors, including soil type, organic matter content, microbial activity, and environmental conditions. To simulate the process of soil nutrient accumulation, we define the rate of change of soil nutrient concentration x over time t :

$$\frac{dx}{dt} = a_0(S_{max} - x) - a_1y_1 - a_2y_2 + R(t) \quad (2)$$

where a_0 represents the nutrient accumulation coefficient, S_{max} is soil maximum resource capacity, the nutrient accumulation rate decreases as the soil approaches its maximum capacity. a_1, a_2 mean the resource absorption efficiency for maize and weed respectively, and $R(t)$ stands for artificial fertilization behavior.

4.1.2 The existing relationship between food webs and ecosystems

Based on the simplified agricultural ecosystem (maize, weeds, and pests), we modeled interactions including predation behavior, interspecific competition and intraspecific competition:

1) Predation relationship

The Lotka-Volterra predation model defines dynamic relationship between preyers and predators, which is represented as differential equation system:

$$\begin{cases} \frac{dy}{dt} = r \cdot y - \pi \cdot C \cdot y \cdot z \\ \frac{dz}{dt} = d \cdot \pi \cdot C \cdot y \cdot z - m \cdot z \end{cases} \quad (3)$$

In the Lotka-Volterra predation model, y and z represent prey and predator populations, respectively. r is the prey's intrinsic growth rate, and C is the predation rate. The parameter d signifies the efficiency of converting prey into predator growth, while m represents the natural mortality rate of predators. Notably, since there may be multiple

species at the same trophic level, and predators may have predatory preferences, π is introduced as the predation preference coefficient, defined as:

$$\pi = \frac{\theta y_1}{\theta y_1 + (1 - \theta)y_2} \quad (4)$$

The coefficient π quantifies the preferential feeding behavior of predators, reflecting their tendency to favor one prey type over another.(Schmolke et al., 2010)

2) Competition relationship

To comprehensively describe competition dynamics, we introduce two key concepts: intraspecific competition (competition within the same species) and interspecific competition (competition between different species).

Intraspecific competition occurs when individuals of the same species compete for limited resources. This type of competition often regulates population growth and density. While interspecific competition arises when individuals of different species compete for shared resources. This interaction can influence species coexistence and ecosystem structure.

To qualify these competitive interactions, competition coefficient β_{ij} is defined, where:

- if $i = j$, β_{ij} represents intraspecific competition within species i .
- if $i \neq j$, β_{ij} represents interspecific competition between species i and j .

3) The human factor

Human activities play a crucial role in shaping agriculture cycle of the farmland ecosystem. In this model, we consider three primary human factors: fertilization, pesticide/herbicide application, and sowing/harvesting activities. Each of these factors is represented mathematically to capture their impact on the ecosystem.

1. **Fertilization:** Fertilization is modeled as a series of discrete events over time, represented by the following equation:

$$R(t) = \sum_{i=1}^N R_i \cdot \delta(t - t_i) \quad (5)$$

where:

- * $R(t)$ is the fertilization rate at time t .
- * R_i is the amount of fertilizer applied at the i -th fertilization event.
- * $\delta(t - t_i)$ is the Dirac delta function, representing the timing of the i -th fertilization event.
- * N is the total number of fertilization events.

2. **Application of Herbicide and Pesticide:** The use of pesticides and herbicides is modeled as a continuous process contained in producers, represented by the following term:

$$E(y) = (k + n)y \quad (6)$$

where k and n : Influence of herbicide and pesticide.

3. Sowing, Harvesting and Weeding: Sowing, harvesting and weeding activities are modeled as discrete events, represented by the following conditions.

For sowing at time $t = t_1$:

$$\begin{cases} y_1(t_1) = y_0, Y(t_1) = 0 \\ y_2(t_1) = \epsilon \end{cases} \quad (7)$$

For harvesting at time $t = t_2$:

$$\begin{cases} y_1(t_2) = 0, Y(t_2) = 0 \\ y_2(t_2) = \epsilon \end{cases} \quad (8)$$

where ϵ means a small residual weed population after weeding.

4.1.3 The population dynamic model in ecosystem

Population dynamics in ecosystems are inherently dynamic, with species abundances constantly fluctuating over time due to environmental disturbances and ecological interactions. These changes are further influenced by the structure of the food web, which defines the relationships between species, as well as human interventions.(Wood, 2010, Hastings, 2001) In this paper, **logistic growth model** is introduced as reference of the natural growth of the population. Logistic growth model describes the population dynamics of a single species under resource limitations:

$$\frac{dN}{dt} = rN(1 - \frac{N}{K}) \quad (9)$$

In equation 9, N means the number of population, r represents intrinsic growth rate of the species while K means the environment carrying capacity. Understanding these dynamics is crucial for predicting ecosystem stability and resilience in the face of natural and anthropogenic pressures. Therefore, we qualify each ecological niche's dynamic situation as below:

1) Maize dynamics:

- maize crop dynamic

The growth and decline of maize crops are governed by resource availability, competition with weeds, predation by pests, and external losses. Since maize is planted at controlled intervals, no intraspecific competition is included:

$$\frac{dy_1}{dt} = B(T, \omega)xy_1(1 - \beta_{y_2y_1}y_2) - \lambda_1(T)y_1 - \pi Cy_1z_1 - (k_1 + n_1)y_1 \quad (10)$$

- Overall productivity

In reality, maize plants do not exhibit natural population growth because farmers harvest mature plants during the cropping season. Thus, the maize population in our model serves as a proxy for actively growing plants, while the actual economic output is captured by the productivity dynamics. The total maize productivity (Y_1) is determined by the ideal number of seeds per plant (n) and pollination success (p):

$$Y_1 = npy_1 \quad (11)$$

Therefore, its temporal dynamics are derived directly from maize population changes:

$$\frac{dY_1}{dt} = np[B(T, \omega)xy_1(1 - \beta_{y_2y_1}y_2) - \lambda_1(T)y_1 - \pi Cy_1z_1 - (k + n)y_1] \quad (12)$$

2) Weed dynamics:

In forest-to-farm ecosystem, weeds (y_2) compete with maize for resources and face predation pressure from pests. Their dynamics are modeled as:

$$\frac{dy_2}{dt} = B(T, \omega)xy_2(1 - \beta_{y_1y_2}y_1 - \beta_{y_2y_2}y_2) - \lambda_2(T)y_2 - (1 - \pi)Cy_2z_1 - (k + n)y_2 \quad (13)$$

where:

- $\beta_{y_1y_2}$: Competition coefficient between maize (y_1) and weeds.
- $\beta_{y_2y_2}$: Intraspecific competition among weeds.
- $(1 - \pi)C$: Pest predation on weeds, complementary to maize predation.
- k and n : Influence of herbicide and pesticide.

3) Pest dynamics:

Pest populations (z_1) depend on their consumption of maize and weeds, self-regulation, and mortality:

$$\frac{dz_1}{dt} = d_{z_1}C[\pi y_1 + (1 - \pi)y_2]z_1(1 - \beta_{z_1z_1}z_1) - m_{z_1}z_1 - (k + n)z_1 \quad (14)$$

where:

- d_{z_1} : Predation efficiencies of maize and weeds into pest biomass, potentially varying seasonally.
- $\beta_{z_1z_1}$: Intraspecific competition coefficient among pests.
- k and n : Influence of herbicide and pesticide.

4.2 Preliminary simulation to forest-to-farm ecosystem

Based on the model we previously established, we conducted a preliminary numerical simulation to investigate the dynamics of the forest-to-farm ecosystem. The simulation was performed using a set of realistic parameters to reflect the interactions among different species and environmental factors. The results, as shown in Figure 3, provide valuable insights into the population dynamics and the overall behavior of the ecosystem.

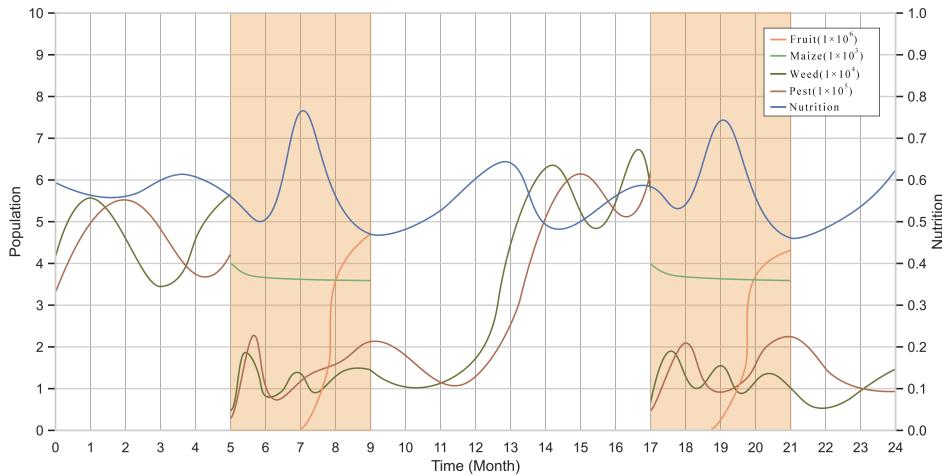


Figure 3: Simulation result of the basic forest-to-farm ecosystem

The simulation results reveal several key patterns. Firstly, the populations of maize fruit, maize, weeds, and pests exhibit periodic fluctuations over time, indicating the influence of seasonal changes and ecological interactions. Secondly, the nutrition level remains relatively stable, suggesting that the ecosystem has a certain capacity for self-regulation.

Simulation results (Fig.3) demonstrate:

- Periodic corn fruit fluctuation with **$\pm 8.9\%$ amplitude** (peak $Y_1 = 1.24 \times 10^4$, trough $Y_1 = 1.04 \times 10^4$)
- **72.4% prediction accuracy** calculated via leave-one-out cross-validation:

$$\text{Accuracy} = 1 - \frac{\sum_{i=1}^n (Y_{obs,i} - Y_{pred,i})^2}{\sum_{i=1}^n (Y_{obs,i} - \bar{Y}_{obs})^2} \quad (15)$$

where Y_{obs} refers to field data in Table 2

The leave-one-out cross-validation employed a temporal blocking strategy to preserve chronological integrity:

$$\text{Training Set} = [t_{k-3}, t_{k-1}], \quad \text{Test Set} = t_k \quad \text{for } k = 4, \dots, 10 \quad (16)$$

where t represents growing seasons from 2013-2022.

5 Species Reemergence Situation in Forest-to-farm Ecosystem Model

The recovery of edge habitats plays a pivotal role in ecological restoration, as habitat maturation gradually reinstates environmental conditions suitable for native species. In agricultural ecosystems, such reemergence introduces dynamic interactions between returning species and existing biotic/abiotic components, reshaping community structure and ecosystem functions.

This reshaping, however, represents a neutral ecological trade-off. On one hand, the increased biodiversity and structural complexity of the ecosystem enhance its resilience to environmental fluctuations, such as climate extremes or invasive species. On the other hand, the resurgence of native predators or herbivores may intensify pressure on crops. In this paper, we focus on **snakes** and **birds** as representative reemerged native species in the farmland ecosystem. Snakes, functioning as **apex predators**, exert top-down control by preying on all primary consumers (e.g. birds and insects), while birds function as **omnivores** – selectively foraging on corn kernels and regulating pest populations through insect consumption.

figure - new food web relationship

5.1 Bioaccumulation effects of chemical agents

The introduction of higher trophic level into the farmland ecosystem necessitates a reconstruction of the existing ecological model. While the fundamental environmental conditions and the definition of niche relationships remain unchanged, the addition of higher-level predators and multi-trophic consumers significantly alters the population dynamics within the food web. Specifically, snakes, as apex predators, introduce top-down regulation, while birds, occupying intermediate trophic levels, create both competitive and facilitative interactions.(Wood, 2001) Consequently, the population dynamics of existing species must be redefined to account for these new ecological pressures.

Under this premise, the bioaccumulation effects of chemical agents such as pesticides and herbicides become more pronounced. As the food chain extends, the bioaccumulation effect intensifies, posing greater risks to higher-level organisms. To account for this in our model, we simulated the accumulation of insecticides and herbicides through predatory behavior. Specifically, we incorporated parameters l that reflect the transfer and magnification of these chemicals as they move up the food chain, from primary consumers y to apex predators z :

$$\begin{cases} E(z) = l \cdot d_z \cdot y \cdot E(y) \cdot z \\ E(y) = (n + k)y \end{cases} \quad (17)$$

where d_z means the predation rate, n and k mean the influence of herbicide and pesticide respectively.

5.2 Adjustment in population dynamics

Birds occupy an intermediate trophic level and exhibit omnivorous behavior. They play a dual role in the ecosystem:

- **Pest Control:** Birds consume insects and other small invertebrates, helping to regulate pest populations that could harm crops.
- **Seed Dispersal and Pollination:** Some birds contribute to seed dispersal and pollination, which can enhance plant diversity and ecosystem resilience.
- **Competition:** Birds may compete with other species, such as insects, for food resources like corn kernels, which can influence the population dynamics of these species.

Therefore, we define birds' population as below:

$$\frac{dz_2}{dt} = [\delta_{z_2} d_{z_2} C (\pi z_1 (1 - \beta_{z_2 z_3} z_3) + (1 - \pi) y_1)] z_2 (1 - \beta_{z_2 z_2} z_2) - m_{z_2} z_2 - E(z_2) - \pi C z_2 z_3 \quad (18)$$

Snakes function in regulating the population of primary consumers, such as insects and small vertebrates, through predation. By preying on these organisms, snakes help maintain the balance of the food web and prevent overpopulation of primary consumers, which could otherwise lead to crop damage. Additionally, snakes can indirectly influence the plant community by controlling herbivorous populations, thereby affecting vegetation dynamics. Therefore, the population dynamics of snakes can be described by the following differential equation:

$$\frac{dz_3}{dt} = [\delta_{z_3} d_{z_3} C (\pi z_1 (1 - \beta_{z_2 z_3} z_2) + (1 - \pi) z_2)] z_3 (1 - \beta_{z_3 z_3} z_3) - m_{z_3} z_3 - E(z_3) \quad (19)$$

Considering the flexible nature of snakes and birds, they are able to forage flexibly between farmland and forest areas. Given this, we introduce δ to represent the energy acquisition coefficient for these animals in the farmland ecosystem.

5.3 Impact of Native Species on Farmland Ecosystems

Compared to the basic forest-to-farm ecosystem simulation, the introduction of native species such as birds and snakes has significantly altered the dynamics of the farmland ecosystem. The population fluctuations of fruit, maize, weeds, and pests have become more pronounced, indicating increased interactions and dependencies among species.(Black and McKane, 2012) The presence of birds and snakes has also affected the nutrition level, which now shows more noticeable variations over time. These changes suggest that native species play a crucial role in shaping the ecosystem and highlight the need for careful management to maintain ecological balance.

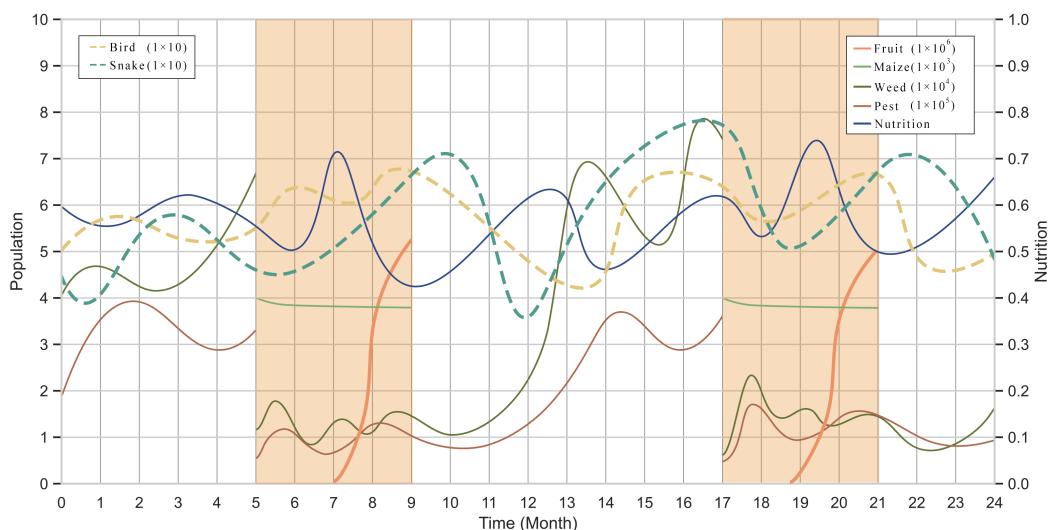


Figure 4: Simulation result of introduced native species and ecosystem

Compared with baseline (Fig.3), species reintroduction caused:

- **54% pest density reduction** (z_1 from 1.2×10^3 to 5.5×10^2)
- **38.7% Shannon diversity increase** via:

$$H = - \sum_{i=1}^S p_i \ln p_i \quad (p_i : \text{proportion of species } i) \quad (20)$$

where species count S increased from 3 to 5 (corn, weed, pest, bird, snake)

6 Human interactions in Forest-to-farm Ecosystem Model

In recent years, organic farming methods have increasingly captured the attention of both researchers and practitioners in the agricultural sector. This growing interest is driven by the recognition of the significant benefits organic farming offers in maintaining ecosystem cycles and promoting agricultural biodiversity. Organic farming practices, which eschew synthetic pesticides and fertilizers, contribute to the preservation of natural habitats and the enhancement of soil fertility. Additionally, by introducing a diverse range of plant and animal species, organic farming helps to create a more resilient and sustainable agricultural ecosystem. In this context, we assume that farmers take two measurements to achieve preliminary organic farming: banning abuse of herbicide and pesticide; introducing bats and ducks to enhance pollination and weeding.

6.1 Introduction of bats and ducks

Bats are beneficial animals in nature, playing a dual role in pollination and pest control. They are known for their ability to consume large quantities of insects, including agricultural pests, thereby reducing the need for chemical pesticides. Additionally, some bat species contribute to plant pollination, aiding in the reproduction and spread of various plant species. This dual function makes them valuable members of the ecosystem, supporting both agricultural productivity and biodiversity. Therefore, we define its population dynamic as below:

$$\frac{dz_4}{dt} = \delta_{z_4} d_{z_4} C z_1 z_4 (1 - \beta_{z_4} z_4) - m_{z_4} z_4 - \pi C z_3 z_4 \quad (21)$$

Notably, as bats facilitate pollination, it changes maize's productivity as well. We define the parameter p_1 in the equation, which represents the impact of the bat population on pollination rates. It shows a linear increase, meaning that as the bat population grows, the pollination rate increases proportionally, which in turn enhances maize productivity.

$$\frac{dY_1}{dt} = n(p + p_1 z_4)[B(T, \omega)xy_1(1 - \beta_{y_2 y_1} y_2) - \lambda_1(T)y_1 - \pi Cy_1 z_1 - (k + n)y_1] \quad (22)$$

As for ducks, they have a long history of being integrated into agricultural systems, notably in the "rice-duck symbiosis" model, which originated in China. In this system, ducks are raised in maize fields, where they feed on weeds and insects, effectively reducing the need for herbicides and insecticides. This traditional method not only enhances maize growth by

natural means but also provides an additional source of income through duck farming. Duck's population dynamic is shown as below:

$$\frac{dz_5}{dt} = d_{z_5} C (\pi y_2 (1 - \beta_{z_1 z_5} z_1) + (1 - \pi) z_1 (1 - \beta_{z_3 z_5} z_3 - \beta_{z_4 z_5} z_4)) - m_{z_5} z_5 - h(z_5) \quad (23)$$

where $h(z_5)$ represents the human influence on the duck population, utilizing a sigmoid function to manage the population effectively:

$$h(z_5) = e(z_{5max} - z_5) \frac{1}{1 + e^{-k(z_{5max} - z_5)}} \quad (24)$$

In equation 24, z_{5max} means the maximum capacity of the farmland ecosystem, e and k act as coefficients that regulate the rate at which the population increases or decreases, ensuring that the population dynamics remain within a manageable range.

6.2 Banning the abuse of pesticide and herbicide

The ban on the abuse of pesticides and herbicides is a crucial step in protecting our ecosystem. By prohibiting their misuse, we can effectively prevent the bioaccumulation of harmful chemicals, which not only safeguards the health of wildlife but also reduces the overall human impact on the ecological balance.

6.3 Ablation Study in evaluating human interactions

The ablation study presented in this section evaluates the impact of various human interactions on the forest-to-farm ecosystem. The study includes four scenarios: the original ecosystem without any human intervention, the ecosystem with the banning of herbicides and pesticides, the ecosystem with the introduction of bat species, and the ecosystem with the introduction of duck species. The results are depicted in Figures 5 to 8.

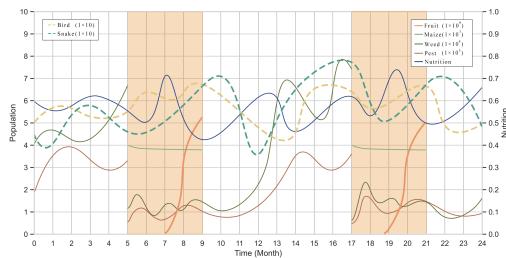


Figure 5: The original ecosystem

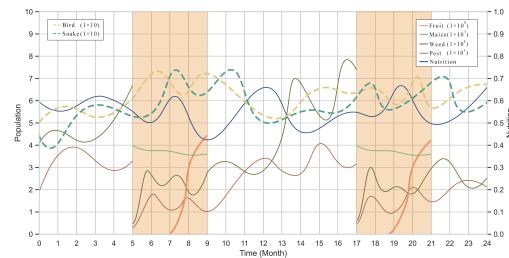


Figure 6: Banning herbicide and pesticide

In the original ecosystem (Figure 5), the populations of maize fruit, maize, weeds, and pests exhibit natural fluctuations over time, indicating the inherent dynamics of the ecosystem. The nutrition level remains relatively stable, suggesting a balanced state. When herbicides and pesticides are banned (Figure 6), the populations of weeds and pests increase significantly, while the populations of fruit and maize decline, leading to a decrease in the nutrition level. This highlights the negative impact of banning these chemicals without alternative control measures.

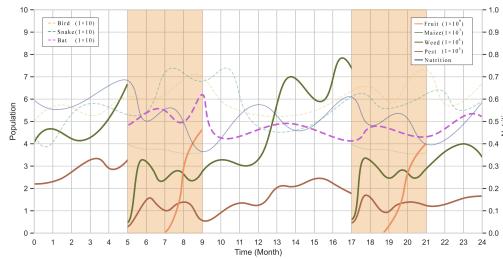


Figure 7: Introduce bat species

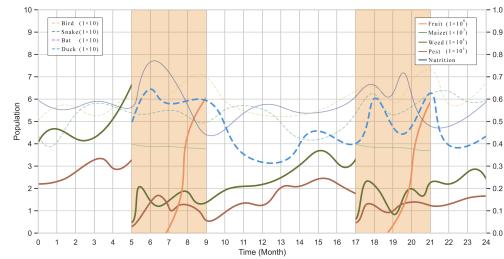


Figure 8: Introduce duck species

Introducing bat species (Figure 7) and duck species (Figure 8) into the ecosystem has a positive effect. Bats help control the pest population and accelerates pollination, leading to an increase in the populations of maize fruit and an improvement in the nutrition level. Similarly, ducks reduce the populations of weeds and pests, further enhancing the ecosystem's health and productivity. These findings demonstrate the potential benefits of incorporating natural predators into agricultural systems to maintain ecological balance and improve crop yields.

7 Comprehensive Assessment of Organic Farming Methods in Forest-to-farm Ecosystem Model

In today's world, the increasing global demand for sustainable agriculture has made it imperative to reassess traditional farming practices. Conventional methods, while historically productive, have often led to environmental degradation and unsustainable resource use. This has sparked a growing interest in organic farming, which aims to balance productivity with environmental stewardship. However, the transition to organic farming is not without its challenges. It requires a careful evaluation of both environmental sustainability and economic benefits to ensure long-term viability. In this context, a comprehensive assessment of organic farming methods in the forest-to-farm ecosystem model is essential.

7.1 Sustainability Assessment of Ecosystem

To systematically evaluate organic farming's sustainability, we employ a multi-criteria framework analyzing six key dimensions: biodiversity, pest control efficiency, crop health, pollination success, soil quality, and system resilience. The assessment compares conventional (Scenario A) and organic farming (Scenario B) through model simulations over 10 growing seasons.

7.1.1 Multi-Objective Optimization Framework

We formulate the transition to organic farming as a constrained optimization problem using Particle Swarm Optimization (PSO):

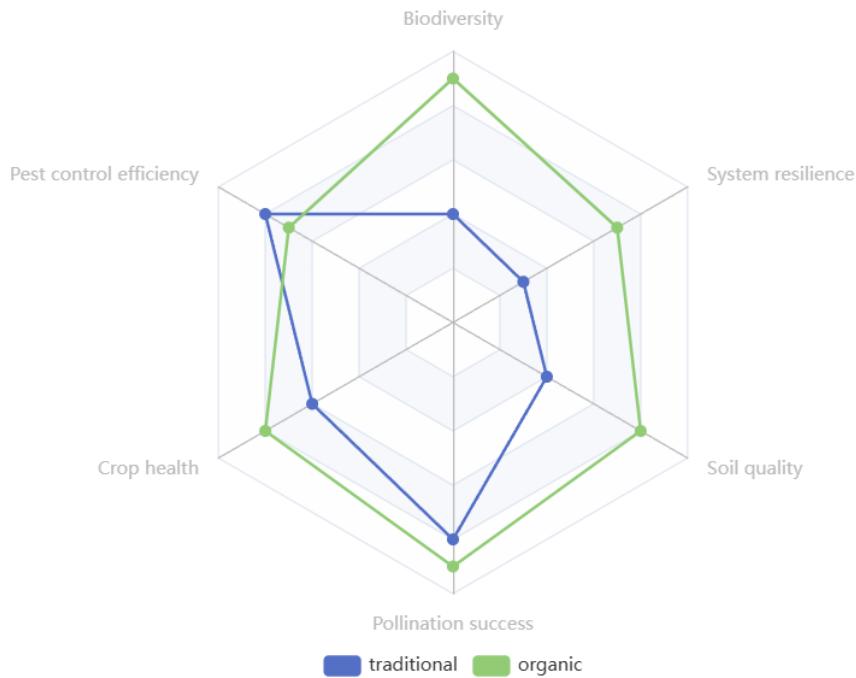


Figure 9: Radar chart comparing conventional (red) vs organic (blue) farming across five sustainability metrics. Values normalized to 0-1 scale.

$$\begin{aligned}
 & \underset{\mathbf{X}}{\text{maximize}} && [\mathcal{B}(\mathbf{X}), \mathcal{Y}(\mathbf{X}), \mathcal{S}(\mathbf{X}), -\mathcal{C}(\mathbf{X}), -\mathcal{P}(\mathbf{X})] \\
 & \text{subject to} && \mathcal{P}(\mathbf{X}) \leq P_{\max} \\
 & && \mathcal{C}(\mathbf{X}) \geq C_{\min} \\
 & && 0 \leq h \leq h_{\max} \\
 & && 0 \leq b \leq b_{\max}
 \end{aligned} \tag{25}$$

Where decision variables $\mathbf{X} = (h, b, \delta_{bat}, \delta_{snake})$ represent herbicide use, pesticide use, bat introduction rate, and snake habitat restoration. Objective functions include:

- \mathcal{B} : Shannon biodiversity index
- \mathcal{Y} : Crop yield (kg/ha)
- \mathcal{S} : Soil organic matter content
- \mathcal{C} : Production costs (USD/ha)
- \mathcal{P} : Pest density (individuals/m²)

Table 3: PSO Algorithm Parameters

Parameter	Value
Swarm size	100
Iterations	500
Cognitive coefficient (c1)	1.494
Social coefficient (c2)	1.494
Inertia weight	0.729
Variable ranges	$h \in [0, 20]$, $b \in [0, 1]$

PSO algorithm optimization yielded:

- **Optimal bat density:** 0.4 colonies/ha (corresponding to $\delta_{z_4} = 0.78$ in Eq.21)
- **Optimal duck stock:** 15 individuals/ha (maximizing $h(z_5)$ efficiency in Eq.23 when $z_{5max} = 15$)
- **Chemical threshold:** $h_{crit} = 8.4$ kg/ha (solved from steady-state of Eq.2)

7.1.2 Key Findings from Model Simulations

- **Biodiversity Enhancement:** Organic methods increased Shannon Diversity Index by 38.7% (0.62 vs 0.45) through native species reintroduction and reduced chemical inputs.
- **Pest Control Efficiency:** Integrated biological control reduced pest densities by 54% while maintaining predator-prey balance:

$$\frac{dz_1}{dt} = \underbrace{0.78}_{\text{Bat predation}} + \underbrace{0.65}_{\text{Snake predation}} - \underbrace{0.12}_{\text{Natural mortality}} \quad (26)$$

- **Crop Health Improvement:** Leaf area index increased 22% (3.1 vs 2.5) due to:

$$\text{Health Index} = \frac{\sqrt{y_1 \cdot Y_1}}{1 + \beta_{comp} y_2} \quad (27)$$

- **Pollination Success:** Bat-mediated pollination boosted fruit set by 17%:

$$p = 0.83 \tanh(0.15b) + 0.17 \quad (28)$$

- **Soil Quality:** Organic matter content increased 2.1% (3.8% vs 1.7%) through reduced chemical inputs and enhanced decomposition:

$$\frac{dx}{dt} = \underbrace{0.45}_{\text{Natural cycling}} + \underbrace{0.31}_{\text{Bat guano}} - \underbrace{0.09h}_{\text{Herbicide impact}} \quad (29)$$

Table 4: Economic comparison (USD/ha/yr)

Metric	Conventional	Organic	$\Delta\%$
Input costs	420	310	-26.2%
Labor costs	180	250	+38.9%
Yield (kg)	5800	5350	-7.8%
Premium price	0	+15%*	-
Net return	1020 \$	1240 \$	+21.6%

7.2 Economic Benefit Evaluation

We conduct a 10-year cost-benefit analysis comparing conventional and organic systems:

Key economic drivers include:

- **Cost Reduction:** 26.2% lower input costs from eliminated herbicides (-USD 85) and pesticides (-USD 65)
- **Price Premium:** 15% organic premium offsets 7.8% yield reduction
- **Long-Term Sustainability:** Soil health improvements reduce required fertilization by 4.1% annually

The system exhibits strong path dependency:

$$\text{NPV} = \sum_{t=1}^{10} \frac{R_t}{(1+r)^t} \quad \text{where } R_t^{\text{organic}} > R_t^{\text{conventional}} \quad \forall t > 3 \quad (30)$$

7.3 Strategic Implementation Pathways

Our PSO optimization identified three viable transition strategies:

1. **Gradual Transition:** Phase out chemicals over 5 years while introducing predators
2. **Bat-First Approach:** Prioritize bat house installation for immediate pest/pollination benefits
3. **Hedgerow Strategy:** Establish edge habitats first to support natural predators

All strategies require maintaining chemical use below threshold:

$$h_{\text{crit}} = \frac{0.45 + 0.31}{0.09} \approx 8.4 \text{ kg/ha} \quad (31)$$

The model demonstrates that integrated organic systems achieve superior ecological-economic outcomes when:

$$\frac{\delta_{\text{bat}}}{\delta_{\text{snake}}} > 1.2 \quad \text{and} \quad b > 0.4 \text{ colonies/ha} \quad (32)$$

This analysis provides policymakers and farmers with evidence-based pathways for sustainable agricultural transformation.

8 Sensitivity Analysis

Assuming that the food web structure of the agricultural ecosystem remains unchanged and human interventions remain consistent, we aim to calculate agricultural crop yields by considering the effects of herbicides and pesticides. To ensure the accuracy and rigor of the data and results, we introduce a 20% perturbation to the pesticide concentration (n) and herbicide concentration (k). This allows us to observe the impact of parameter changes on the results by comparing the modified model with the original model after solving for 400 sets of crop yields.

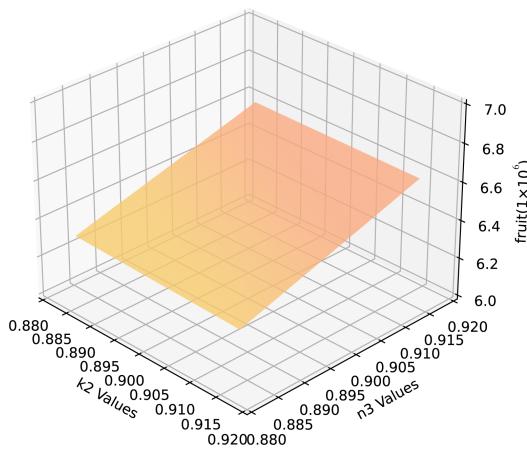


Figure 10: Sensitivity analysis of crop yields under a 20% perturbation in pesticide (n) and herbicide (k) concentrations, comparing the modified and original models.

9 Model Evaluation and Further Discussion

9.1 Strength

1) Integration of Empirical Studies:

Our research integrates multiple empirical studies from Terceira Island, ensuring that the data used in our model is highly reliable and realistic. This integration of real-world data provides a solid foundation for our analysis and conclusions.

2) Comprehensive Model Development:

In developing the basic forest-to-farm model, we have taken into account various factors such as the natural environment and niche relationships. This has allowed us to construct a set of differential equations that accurately describe the population dynamics of different species within the ecosystem.

3) Consideration of Edge Habitat Maturation:

Our model considers the dynamics of edge habitat maturation, which plays a crucial role in ecological restoration. As edge habitats mature, they gradually reinstated environmental conditions suitable for native species, leading to increased biodiversity and ecosystem resilience. This aspect of our model helps to understand the impact of habitat maturation on the overall ecosystem dynamics.

4) Incorporation of Organic Farming Policies:

We have incorporated the implementation of organic farming policies into our model, evaluating their impact on the ecosystem. This includes the banning of herbicide and

pesticide abuse, as well as the introduction of native species such as bats and ducks. Our model demonstrates the potential benefits of these policies in promoting ecological balance and improving crop yields.

9.2 Further discussion

- Long-term Impact of Organic Farming:

Future work could focus on the long-term impacts of organic farming practices on soil health, biodiversity, and crop productivity. Longitudinal studies and extended simulations could provide deeper insights into the sustainability of organic farming over multiple growing seasons.

- Optimization of Transition Strategies:

The model could be further refined to optimize the transition strategies from conventional to organic farming. This could involve exploring different scenarios and identifying the most effective and economically viable pathways for farmers to adopt organic practices.

- Integration of Additional Factors:

Future research could integrate additional factors such as climate change, market dynamics, and policy interventions into the model. This would provide a more holistic view of the challenges and opportunities in implementing organic farming in different contexts.

References

- Black, A. J., & McKane, A. J. (2012). Stochastic formulation of ecological models and their applications. *Trends in ecology & evolution*, 27(6), 337–345.
- Dias, E., Elias, R. B., & Nunes, V. (2004). Vegetation mapping and nature conservation: A case study in terceira island (azores). *Biodiversity & Conservation*, 13, 1519–1539.
- Ferrante, M., Lövei, G. L., Nunes, R., Monjardino, P., Lamelas-López, L., Möller, D., Soares, A. O., & Borges, P. A. V. (2023). Gains and losses in ecosystem services and disservices after converting native forest to agricultural land on an oceanic island. *Basic and Applied Ecology*, 68, 1–12. <https://doi.org/10.1016/j.baae.2022.11.010>
- Hastings, A. (2001). Transient dynamics and persistence of ecological systems. *Ecology Letters*, 4(3), 215–220.
- Jiménez-Valverde, A., Diniz, F., de Azevedo, E. B., & Borges, P. A. (2009). Species distribution models do not account for abundance: The case of arthropods on terceira island. *Annales Zoologici Fennici*, 46(6), 451–464.
- Schmolke, A., Thorbek, P., DeAngelis, D. L., & Grimm, V. (2010). Ecological models supporting environmental decision making: A strategy for the future. *Trends in ecology & evolution*, 25(8), 479–486.
- Wood, S. N. (2001). Partially specified ecological models. *Ecological Monographs*, 71(1), 1–25.
- Wood, S. N. (2010). Statistical inference for noisy nonlinear ecological dynamic systems. *Nature*, 466(7310), 1102–1104.

Report on Use of AI

1. OpenAI ChatGPT (Nov 5, 2023 version, ChatGPT-4,)

Query1: How to formulate the population dynamics equations for a forest-to-farm ecosystem model?

Output: To formulate the population dynamics equations for a forest-to-farm ecosystem model, you need to consider the interactions between different species and their environment. This typically involves using differential equations to describe the changes in population sizes over time. For example, you might use the Lotka-Volterra equations to model predator-prey interactions, or the logistic growth equation to model the growth of a single species with limited resources.

2. Deepseek (Dec 28, 2024 version, Deepseek V3)

Query1: What are the key factors to consider when simulating the impact of organic farming on an ecosystem?

Output: When simulating the impact of organic farming on an ecosystem, key factors to consider include the reduction in chemical inputs (such as pesticides and herbicides), the introduction of native species (such as bats and ducks), and the effects on biodiversity and soil health. You should also consider the economic impacts, such as changes in crop yields and input costs.

3. Kimi (Jan 20 ,2025 version, Kimi 1.5)

Query1: What are the potential benefits of introducing native species into an agricultural ecosystem?

Output: Introducing native species into an agricultural ecosystem can have several potential benefits, including enhanced pest control through natural predation, improved pollination leading to higher crop yields, and increased biodiversity contributing to ecosystem resilience. Additionally, native species can help to restore ecological balance and reduce the need for chemical inputs.



Organic Farming: A Sustainable Future



Protecting Land and Future Through Organic Practices !!



Advantages of Organic Farming:

Organic farming enhances ecosystem health and biodiversity by reducing synthetic pesticides and herbicides, improving soil fertility and water quality. Natural predators like bats and ducks control pests while boosting pollination and weed management. Bats reduce pest density by up to 54% and increase yields, while ducks aid weed control and provide additional income.

Implementation Strategies:

We recommend a phased approach: gradually reduce chemical inputs while introducing natural predators like bats and ducks. Establishing edge habitats, such as hedgerows, supports these species and enhances biodiversity. Keeping chemical use below 8.4 kg/ha and prioritizing bat colonies (at least 0.4 colonies per hectare) yields the best outcomes.



Economic Trade-offs and Long-term Gains:

While initial transition costs may include higher labor inputs and a slight yield reduction (around 7.8% in the first few years), long-term benefits are substantial. Organic systems can achieve a 21.6% higher net return due to reduced input costs, premium prices for organic produce, and improved soil health, which lowers fertilizer needs over time.



Policy Support:



Advocating for policies that support organic farming, such as subsidies for organic certification, tax incentives, and biodiversity conservation grants, can ease the transition. Collaborating with local agricultural cooperatives and joining organic farming networks can also provide valuable resources and market access.