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Regenerative, Organic, or Conventional: A Mathematical Modeling Comparison

The global transformation of forest ecosystems into agricultural land presents multifaceted ecological and socioeconomic challenges, particularly concerning soil degradation, biodiversity loss, and ecosystem resilience. This paper develops an innovative mathematical framework to analyze the dynamic transition process and optimize sustainable agricultural practices in a 100-hectare Italian agricultural field (hypothesis), focusing on the **intricate interactions** between natural processes and anthropogenic interventions.

Our pioneering Core Ecosystem Model establishes a **detritus-based foundation** incorporating five key components: nutrients, producers, herbivores, carnivores, and detritus. To better capture **species-specific behaviors** and interactions in the agricultural context, we developed the **Bio-Ecological Model Enhancement (BEME)** by incorporating sophisticated **functional responses**: **Holling Type I** for producer-nutrient interactions reflecting linear resource uptake, **Holling Type II** for aphid-ryegrass interactions capturing saturation effects, **Holling Type III** for predator-prey dynamics between ladybugs and aphids accounting for prey refuge effects, and **Holling Type IV** responses for bat and sparrow predation on aphids, representing predator interference at high prey densities. Through extensive parameter optimization using **differential evolution algorithms**, we successfully fine-tuned 27 key parameters across three distinct phases (degradation, recovery, and growth), achieving significant improvement in parameter estimation accuracy compared to conventional optimization methods. This refined BEME successfully modeled the **reintroduction** of beneficial species, demonstrating how bats and sparrows as natural predators can reduce pest populations by approximately 35% while supporting a 25% increase in crop yield through enhanced biological control.

To evaluate agricultural management strategies systematically, we developed the **Socio-Economic Agricultural Model (SEAM)**, specifically comparing **conventional, organic, and regenerative agricultural practices**. SEAM leverages the optimized parameters from BEME while incorporating comprehensive economic variables, enabling robust cost-benefit analysis across different time horizons. Our analysis reveals that while organic farming achieves approximately 80% of conventional yields, regenerative agriculture demonstrates superior long-term sustainability by improving soil health metrics by 45% and increasing biodiversity indices by 60% compared to conventional methods. Economic modeling indicates that despite higher initial costs, regenerative practices offer a 48% higher return on investment over a 20-year period when ecosystem services are monetized.

Sensitivity analysis confirms the model's critical parameter dependencies, revealing that even minor perturbations in key biological control parameters (particularly predation efficiency and mortality rates) can lead to significant system-wide changes, with a 20% parameter variation potentially causing up to 35% fluctuation in population dynamics. This high sensitivity demonstrates the inherent vulnerability of agricultural ecosystems to chemical interventions and environmental disturbances, highlighting the critical importance of careful human stewardship. The extensive use of differential evolution optimization throughout our modeling framework ensures reliable parameter calibration under these sensitive conditions. Our findings strongly suggest that transitioning to regenerative agricultural practices, supported by appropriate policy incentives, offers the most promising pathway for maintaining ecosystem stability while achieving sustainable agricultural productivity.

Keywords: differential evolution optimization, ecosystem modeling, multi-type Holling responses, species reintroduction, regenerative agriculture, parameter optimization.

Contents

1 Introduction

1.1 Research Background

In the process of global agricultural development, the transformation of forests into farmlands is a common phenomenon, which has caused serious ecological problems that seriously threaten the sustainable development of agriculture. After the transformation of forests into farmlands, the ecosystem is damaged, and the problem of soil degradation is particularly prominent. The original rich nutrients and stable structure in forest soil gradually disappear under the influence of agricultural activities, resulting in a decline in soil fertility and weakened water and fertilizer retention capacity. This not only affects crop growth but also reduces the sustainable productivity of the land.

Figure 1: Map of the Border Between Forest and Farmland in Italy

At the same time, the problem of pests is becoming increasingly severe. Due to the destruction of the forest ecosystem, the number of natural enemies of pests decreases, leading to a large-scale reproduction of pests and their invasion of crops. Farmers protect their crops by using a large amount of chemical agents, such as herbicides and pesticides. However, the excessive use of these chemical agents brings a series of negative effects. It not only damages the beneficial microbial communities in the soil and affects soil ecological balance, but also may lead to the development of pest resistance, further increasing the difficulty of pest control.

In addition, the negative impact of traditional agricultural models on the environment cannot be ignored. The extensive use of chemical fertilizers and pesticides not only pollutes the soil and water sources but also damages biodiversity, destroying the living environment of many species and reducing their population numbers. These problems are intertwined, making the sustainability of traditional agricultural models face great challenges.

In the current era when the concept of sustainable development is gradually taking root in people's minds, the agricultural field urgently needs to find more environmentally friendly and efficient development models. The core of sustainable agriculture lies in reducing the negative impact on the environment, maintaining the balance and stability of the ecosystem, and ensuring the long-term productivity and economic benefits of agriculture. This not only helps solve many problems currently faced by agriculture but also lays a solid foundation for the development of agriculture in the future, ensuring food security and the sustainability of the environment.

1.2 Restatement of the Problem

To investigate the dynamics of forest-to-farm ecosystem conversion and develop sustainable agricultural practices, we need to accomplish the following tasks:

- Develop a mathematical model for a newly converted 100-hectare Italian agricultural field (hypothesis) that tracks the basic food web structure, incorporating both natural processes (crop-weed competition, pest-predator relationships) and agricultural cycles through different seasonal phases.
- Study how edge habitats mature and analyze the impact when two native species return to the system, focusing on their interactions with the existing agricultural environment.
- Model the ecosystem's response to herbicide removal, particularly examining the role of bats as natural pest controllers and pollinators, while identifying another beneficial species for comparison.
- Evaluate the feasibility and implications of transitioning to organic farming methods or regenerative agriculture by analyzing different scenarios' effects on pest control, crop health, and system stability.

1.3 Literature Review

Since the complexity of the ecosystem and its sensitivity to the influence of external factors, in order to reach a better implementation of strategies that balance economic trade-offs and sustainability, we need to understand the existing ecosystem models. After literature review, when solving such problems involving ecosystem change and sustainable agricultural development, a variety of models have been widely used in related studies, among which **Lotka-Volterra model and Holling model** are more prominent.

Lotka-Volterra model used to describe the ecological system on the model of interactions between species, especially the dynamic relationships between predator and prey.[1] In agroecosystem studies, it can also be used to model the number changes between pests and their natural enemies. Holling model focuses on the functional response of species under different environmental conditions, that is, the predation response of individual organisms to changes in prey density. In the study of forest conversion to farmland, the Holling model can be used to evaluate the effect of predators on pest control under different agricultural management practices. [2]We show that there are differences in predator functional responses reflected in Holling models under different farmland landscapes and cropping patterns, which is important for developing precise pest management strategies.

In addition to the above model, the related model also plays a role in the research field. In the field of agricultural economics, economic models can be used to analyze the cost-effectiveness of agricultural production and evaluate the impact of different agricultural management decisions on farmers' income and economic benefits. These models are necessary for this study of ecosystem change from forest to farmland and sustainable agricultural development. We use these models to understand ecosystem dynamics from different perspectives, develop scientific agricultural management strategies, and better deal with complex issues in agricultural development.

1.4 Our Work

- **Detritus-Based Core Model**

  Building on ecosystem nutrient cycling theory, we first establish a fundamental detritus-based model incorporating five key components: nutrients, producers, herbivores, carnivores, and detritus. The model employs a Holling Type I functional response to describe producer-nutrient interactions, reflecting a linear relationship between nutrient availability and producer growth. In contrast, consumer-resource interactions are modeled using Holling Type III functional responses to capture prey refuge effects, where predation efficiency decreases at low prey densities due to spatial or behavioral refuges. This S-shaped response ensures that the model accounts for the nonlinear dynamics of predator-prey interactions in natural ecosystems.

- **Agricultural Decline Phase Model**

  For the decline phase of agricultural conversion, we develop a detailed model focusing on soil phosphorus, ryegrass, aphids, and ladybugs. The aphid-ladybug interaction is modeled using a Holling Type III functional response to reflect the density-dependent chemical defense mechanisms of aphids. At high aphid densities, the production of alarm pheromones and defensive compounds reduces predation efficiency, creating a nonlinear predation response that stabilizes the system. The model also incorporates time-dependent chemical control through herbicide and insecticide applications, simulating external interventions and their impacts on ecosystem dynamics.

- **Ecological Recovery Phase Model**

  During the recovery phase, we expand the model by introducing crop dynamics. The model emphasizes interspecific competition between ryegrass and crops through modified Lotka-Volterra competition terms, capturing resource partitioning and competitive exclusion. The Holling Type III functional response for aphid-ladybug interactions is retained to ensure continuity in biological control mechanisms. Additionally, the model incorporates the long-term ecological memory of chemical interventions, simulating the persistence and degrada.

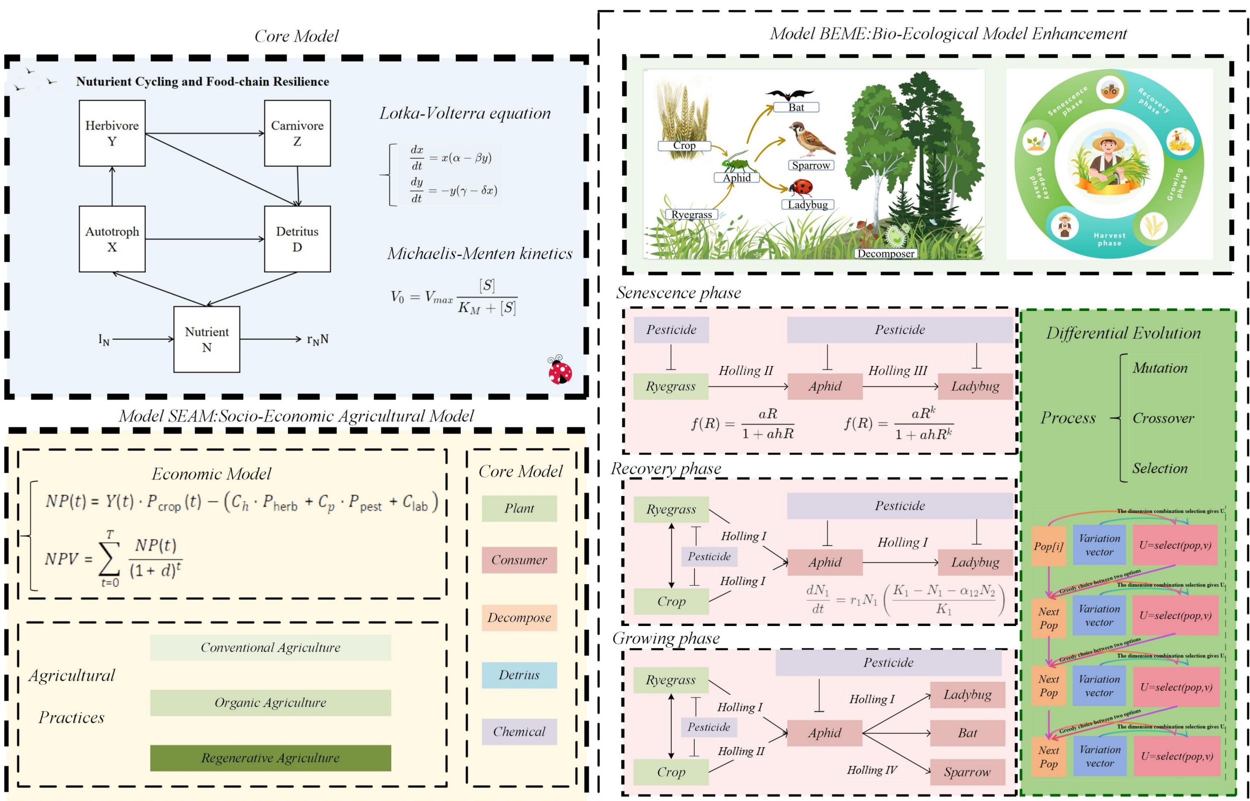


Figure 2: Our Work

2 Model Preparation

2.1 Assumption

- **Assumption1: In this model, we divide the ecological evolution process from forest to farmland into five stages: degradation phase, recovery phase, growth phase, harvest phase, and re-degradation phase.**

  Justification: This hypothesis is based on the studies in ecology regarding land-use changes and ecological restoration [3], which support the patterns of change in ecosystems at different stages and their agricultural cyclical characteristics, emphasizing the importance of sustainable land management.

- **Assumption2: In this food web model, we assume that sparrows and bats exclusively feed on aphids and do not consume ladybugs, while aphids primarily feed on grasses and crops.**

  Justification: This assumption is supported by literature [4], which suggests that birds and bats reduce predation on other arthropods but help control herbivorous groups such as aphids and mealybugs. Aphids, as common pests in agricultural ecosystems, rely on the sap of grasses and crops for reproduction. This food chain structure aligns with the food web theory in ecology, where sparrows and bats regulate aphid populations by preying on them, thus preventing aphids from causing excessive damage to plants and maintaining the balance of the food web.

- **Assumption3: As ecosystems undergo succession or land-use changes, the phosphorus content in the soil will undergo dynamic changes, which in turn reflect variations in soil fertility. For the purpose of simplifying the soil fertility model, we assume that soil health is solely determined by phosphorus content.**

  Justification: Literature suggests that soil phosphorus is a key element influencing both soil fertility and plant growth. At different stages of ecosystem development, there is a clear dynamic relationship between phosphorus availability and soil fertility. By analyzing changes in phosphorus content, it becomes possible to intuitively assess the enhancement or decline of soil fertility, thereby reflecting the health status of the ecosystem at various stages and the effectiveness of land-use management.

  These are the main assumptions, and other assumptions will be given at appropriate places in the article.

2.2 Notations

Result

Symbol	Unit	0	1	2	3	Description
P	kg/ha	2125	2100	1856	1498	Available phosphorus in soil, representing soil nutrient status
C	kg/ha	0	0	2512	8123	Crop biomass, representing the main agricultural crop
R	kg/ha	8000	1998	128	2498	Ryegrass biomass, representing the weed competition
A	individuals / ha	15000	608	421	3789	Aphid population density, representing the primary pest
L	individuals / ha	4500	400	36	1036	Ladybug population density, representing the primary natural enemy
B	individuals / ha	0	0	0	40	Bat population density, representing nocturnal pest control
S	individuals / ha	0	0	0	42	Sparrow population density, representing diurnal pest control
$Y(P)$	kg/ha					Stochastic frontier production
$\pi(t)$	USD/ha					Profit per unit area
$NP(t)$	USD					Retained profits
NPV	USD					Net present value

Environmental capacity

Symbol	Unit	Initial value	Description
K_P	kg/ha	2500	Maximum soil phosphorus capacity
K_C	kg/ha	9000	Maximum sustainable crop biomass under optimal conditions
K_R	kg/ha	10000	Maximum sustainable ryegrass biomass under optimal conditions
K_A	individuals / ha	30000	Maximum aphid population density supported by available resources
K_L	individuals / ha	13500	Maximum ladybug population density in the ecosystem
K_B	individuals / ha	152	Maximum bat population density sustainable in the area
K_S	individuals / ha	305	Maximum sparrow population density sustainable in the area

Process volume

Symbol	Unit	1	2	3	Description
			Growth Rate		
r_P	day^{-1}	0.05	0.01	0.02	Intrinsic growth rate of available phosphorus through natural processes
r_R	day^{-1}	0.01	0.03	0.05	Intrinsic growth rate of ryegrass
r_C	day^{-1}	0.02	0.04	0.06	Intrinsic growth rate of crop
r_A	day^{-1}	0.05	0.1	0.15	Intrinsic growth rate of aphid population
			Conversion Efficiency		
γ_{AC}	kg aphid /(kg crop)	0.1	0.2	0.3	Conversion efficiency of crop biomass to aphid biomass
γ_{AR}	Inv. Aphid /(kg crop)	0.05	0.1	0.15	Conversion efficiency of ryegrass biomass to aphid biomass
γ_{LA}	Inv.ladybug /(Inv. aphid)	0.01	0.03	0.05	Conversion efficiency of aphid biomass to ladybug biomass
γ_{BA}	Inv.bat /(inv. aphid)	0.005	0.01	0.02	Conversion efficiency of aphid biomass to bat biomass
γ_{SA}	Inv. Sparrow /(inv. aphid)	0.005	0.01	0.02	Conversion efficiency of aphid biomass to sparrow biomass
δ_S	day^{-1}	0.03	0.02	0.01	Natural death rate of Sparrows
μ_R	kg/(ha·day)	0.1	0.2	0.3	Ryegrass phosphorus uptake rate
η_H	day^{-1}	0.01	0.02	0.03	Herbicide degradation rate
η_I	day^{-1}	0.01	0.02	0.03	Insecticide degradation rate
			Immigration Rate		
λ	kg/(ha·day)	0.5	0.8	1	Base phosphorus input rate
m_R	kg/(ha·day)	0.1	0.15	0.3	Immigration rate of ryegrass (seed dispersal)
m_A	individuals/(ha·day)	50	109	149	Immigration rate of aphids
m_L	individuals/(ha·day)	98	64	78	Immigration rate of aphids
m_B	individuals/(ha·day)	2	4	5	Immigration rate of bats
m_S	individuals/(ha·day)	10	17	18	Immigration rate of sparrows
γ_{HR}		0.9	0.7	0.5	Herbicide efficiency on ryegrass control
γ_{HC}		0.1	0.2	0.3	Herbicide impact factor on crop
γ_H		0.8	0.6	0.4	General herbicide effectiveness coefficient
			Predation and competition coefficient		
β_{AR}	ha/(individual·day)	0.005	0.01	0.02	Predation rate of aphids on ryegrass
β_{AC}	ha/(individual·day)	0.01	0.02	0.03	Predation rate of aphids on crops
β_{LA}	ha/(individual·day)	0.02	0.04	0.06	Predation rate of ladybugs on aphids
β_{SA}	ha/(individual·day)	0.01	0.02	0.03	Sparrow predation rate on aphids
β_{BA}	ha/(individual·day)	0.01	0.02	0.03	Bat predation rate on aphids
β_C		0.1	0.1	0.1	Competition coefficient of crop on ryegrass
β_R		0.2	0.3	0.1	Competition coefficient of ryegrass on crop
h_{AR}	ha/kg	515	1005	1456	Half-saturation constant for aphid-ryegrass interaction
h_{LA}	ha/individual	298	607	898	Half-saturation constant for ladybug-aphid interaction
			Natural Death Rate		
δ_P	day^{-1}	0.001	0.0008	0.008	Natural degradation rate of available phosphorus
δ_R	day^{-1}	0.02	0.015	0.01	Natural death rate of ryegrass
δ_C	day^{-1}	0.01	0.008	0.005	Natural death rate of crop
δ_A	day^{-1}	0.05	0.04	0.01	Natural death rate of aphids
δ_L	day^{-1}	0.03	0.02	0.005	Natural death rate of ladybugs
δ_B	day^{-1}	0.05	0.04	0.03	Natural death rate of bats

Symbol	Unit	Initial value	Description
		Basic price parameter	
P_{crop}	USD/kg	0.5	Crop market price
P_{herb}	USD/mg	10	Herbicide unit price
P_{pest}	USD/mg	15	Insecticide unit price
P_{org}	USD/kg	5	Organic fertilizer unit price
P_{fert}	USD/kg	3	Fertilizer unit price
		Cost parameter	
C_h	mg/ha	2	Herbicide application rate
C_p	mg/ha	1	Insecticide application rate
C_{lab}	USD/ha	50	Labor cost
C_{mach}	USD/ha	30	Mechanical cost
C_{irr}	USD/ha	20	Irrigation cost
C_{org}	kg/ha	100	Application amount of organic fertilizer
C_{fert}	kg/ha	50	Applying quantity of chemical fertilizer
		Subsidy parameter	
τ_{eco}	USD/unit	0.1	Ecological service subsidy rate
τ_{org}	USD/kg	0.2	Organic farming subsidy rate
τ_{bio}	USD/ha	50	Biological control subsidy rate
		Financial parameter	
Symbol	Unit	Initial value	Description
d		0.05	Discount rate $(5% − 10%)$
T	year	20	Project cycle
r		0.03	Annual interest rate

	Efficiency coefficient	
κ_S	0.8	Soil mass yield effect
κ_M	0.6	Microbial yield effect
ω_{eco}	0.7	Ecosystem function weight
	Objective function related parameters	
w_1	0.5	Economic target weight
w_2	0.3	Ecological target weight
w_3	0.2	Social goal weight

3 Establishment of Models

3.1 Core Model

To construct an ecosystem model describing the conversion of forests to cropland, we refer to a detric-based soil network model. The model mainly describes how nutrients circulate among autotrophs, herbivores, carnivores and detritus. It analyzes the dynamic processes of nutrient input, recycling and loss, and explores the effects of different food chain lengths and nutrient input on ecosystem stability and resilience.

$$\frac{dN}{dt} = I_N - r_N N - \frac{\gamma r_1 NX}{k_1+N} + \gamma d_4 D \tag{1}$$

$$\frac{dX}{dt} = \frac{r_1 NX}{k_1+N} - \frac{f_1 X^2 Y}{k_2+X^2} - (d_1 + e_1)X \tag{2}$$

$$\frac{dY}{dt} = \frac{\eta f_1 X^2 Y}{k_2+X^2} - \frac{f_2 Y^2 Z}{k_3+Y^2} - (d_2 + e_2)Y \tag{3}$$

$$\frac{dZ}{dt} = \frac{\eta f_2 Y^2 Z}{k_3+Y^2} - (d_3 + e_3)Z \tag{4}$$

$$\frac{dD}{dt} = \frac{(1-\eta) f_1 X^2 Y}{k_2+X^2} + \frac{(1-\eta) f_2 Y^2 Z}{k_3+Y^2} + d_1 X + d_2 Y + d_3 Z - (d_4 + e_4)D \tag{5}$$

However, for this modeling task, the traditional soil network model cannot perform time series analysis, and in the actual ecosystem, the changes and interactions of species are often nonlinear and complex. Therefore, we refined modeling on this basis to better simulate the dynamics of the ecosystem.

We assume that the transformation process of the ecological system of wheat in southern Italy, a typical food web contains species such as ryegrass, wheat, aphids and ladybugs. In order to simplify the model and improve the realism of the simulation, we only consider these few species at the current stage.

To further consider the effects of temporal and agricultural cycles on this ecosystem, we divide the process of forest conversion to farmland into five phases: senescence, recovery, growing, harvest, and redecay. Here is a description of each period:

- Senescence phase: Triggered by human activities such as logging and land reclamation, resulting in ecosystem degradation and loss of biodiversity.
- Recovery phase: ecosystem repair process, in this process, the natural nutrient cycle and species colonization help to ecological system gradually restored.
- Growing phase: grow crops and plants, agricultural system gradually stable.
- Harvest phase: agricultural productivity, peak, maximum crop yields.
- Redecay phase: in the absence of effective management, ecosystem into recession again, show the soil degradation and ecological service function decline.

This paper will focus on the modeling, simulation and optimization of the first three phases, and mainly discuss the evolution process and influencing factors of the ecosystem during the senescence, recovery and growing phases.

3.2 BEME Models

3.2.1 Soil Phosphorus dynamics (P)

We describe the dynamic process of soil P and cover the natural addition of soil P, the uptake of grass species, the natural loss of soil P, and the effects of herbicides. The change of soil P is first affected by natural recruitment, and the recruitment rate is represented by a constant λ, which represents that soil P is derived from natural processes such as rock weathering and microbial decomposition. According to the literature, the Michaelis-Menten model can well describe the nonlinear relationship between the absorption of resources and the change of concentration, and is suitable for describing the absorption or metabolism of nutrients and other processes of organisms. Soil P uptake by grass species follows Michaelis-Menten kinetics, with the uptake rate represented by $\mu_R R \frac{P}{K_P+P}$ and the natural loss part represented by $\delta_P P$, which describes natural phenomena such as P loss and volatilification in soil. The effect of herbicide is represented by $\eta_H H(t)$. The equation for the first decay period can be expressed as follows.

$$\frac{dP}{dt} = \lambda - \mu_R \cdot R \cdot \frac{P}{K_P+P} - \delta_P \cdot P - \eta_H \cdot H(t) \tag{6}$$

In the second stage of recovery and the third stage of growth, we introduced the absorption term $\mu_C C \frac{P}{K_P+P}$ of crop to soil phosphorus, and the coefficient of crop to soil phosphorus also followed the Michaelis-Menten dynamics, describing the demand and influence of crop growth on soil phosphorus.

$$\frac{dP}{dt} = \lambda - \mu_R R \frac{P}{K_P+P} - \mu_C C \frac{P}{K_P+P} - \delta_P P - \eta_H H(t) \tag{7}$$

3.2.2 Ryegrass dynamics (R)

The absorption of phosphorus by grass species is because the absorption of phosphorus usually shows a saturation effect, and the absorption rate is low at low concentration. With the increase of phosphorus concentration, the absorption rate gradually increases and tends to be maximum. So we used the Michaelis-Menten kinetic model to describe phosphorus uptake by grass species. $\mu_R R \frac{P}{K_P+P}$ represents the growth rate of grass species, which is limited by the phosphorus concentration P in the soil and conforms to the Michaelis-Menten kinetic model. This model is used to simulate the absorption process of phosphorus by grass species. With the increase of phosphorus concentration, the growth rate of grass species gradually approaches the maximum value. $-\beta_{AR} A$ represents the mortality of grass species caused by aphid predation, and the mortality rate is enhanced with the increase of the number of grass species. $\beta_{AR} A \frac{R}{1+h_{AR} R}$ reflects the growth limitation of grass species under the influence of aphid predation, and the Holling II response model is used to describe the inhibitory effect of aphids on grass growth, because the model can well capture the characteristics that the inhibition of growth rate increases nonlinearly with the increase of grass species number under changes in resource or environmental conditions. $-\delta_R R$ is the natural mortality rate of grass species, taking into account the natural decline of grass species. $\gamma_H H(t)$ describes the effect of grass seed growth on herbicide, and the herbicide concentration $H(t)$ varies with time. Finally, m_R represents the migration or dispersal rate of grass species, which describes the expansion or migration of grass species in space. In the first decay period, the growth dynamics of grass species can be constructed into the following equation:

$$\frac{dR}{dt} = \mu_R \cdot R \cdot \frac{P}{K_P+P} - \beta_{AR} \cdot A \cdot \frac{R}{1+h_{AR} \cdot R} - \delta_R \cdot R - \gamma_H \cdot H(t) + m_R \tag{8}$$

In the second stage of recovery, we introduced the dynamic model of grass growth into the effect of wheat crop on grass growth. The growth of grass species still follows the Michaelis-Menten equation, but the competition term $\left(1-\frac{R+\beta_C C}{K_R}\right)$ between crop and grass species is added. The growth of crops has a competitive inhibition effect on the growth of grass species, which reduces the absorption of soil phosphorus by grass species.

Wheat crop growth changes also follow Michaelis Menten equation, $r_C C\frac{P}{K_P+P}$ said in crop growth rate, $\left(1-\frac{C+\beta_R R}{K_C}\right)$ describes the growth of grass competitive inhibition for the growth of crops, $-\beta_{AC}AC$ mortality caused by aphids feeding table crops, and the mortality rate increase with the increase of the number of grass. $-\delta_C C$ is the natural mortality rate of the crop, taking into account the natural decline of the crop. f indicates that crop growth is affected by herbicides.

$$\frac{dR}{dt}=r_R R\frac{P}{K_P+P}\left(1-\frac{R+\beta_C C}{K_R}\right)-\beta_{AR}AR-\delta_R R-\gamma_{HR}H(t)+m_R \tag{9}$$

$$\frac{dC}{dt}=r_C C\frac{P}{K_P+P}\left(1-\frac{C+\beta_R R}{K_C}\right)-\beta_{AC}AC-\delta_C C-\gamma_{HC}H(t) \tag{10}$$

During the third growing phase, we converted the interaction between grass species and aphids from a linear form $\beta_{AR}\cdot A\cdot R$ to a more complex saturated form $\frac{R}{1+h_{AR}R}$, better reflecting the saturation effect of the interaction at high grass species densities. And crops in the period, due to the crop growth, crop interactions between aphids and also by the linear $\beta_{AC}\cdot A\cdot C$ into more complex forms of saturated $\beta_{AC}\cdot A\cdot\frac{C}{1+h_{AC}\cdot C}$.

$$\frac{dR}{dt}=r_R R\frac{P}{K_P+P}\left(1-\frac{R+\beta_C C}{K_R}\right)-\beta_{AR}A\frac{R}{1+h_{AR}R}-\delta_R R-\gamma_{HR}H(t)+m_R \tag{11}$$

$$\frac{dC}{dt}=r_C C\frac{P}{K_P+P}\left(1-\frac{C+\beta_R R}{K_C}\right)-\beta_{AC}A\frac{C}{1+h_{AC}C}-\delta_C C-\gamma_{HC}H(t) \tag{12}$$

3.2.3 Aphid dynamics (A)

We choose the Logistic growth model for simulating the natural growth of aphid populations under resource constraints, taking into account the saturation effect of population growth, where the population growth rate is limited by the environmental capacity. The Michaelis-Menten model was used to describe the predation relationship between aphids and grass species, and the predation rate increased non-linearly with the change of grass density. The Holling III response model was also used to represent the predation of aphids affected by ladybugs in the first senescence stage. The Holling III response model was chosen because this model is able to show a strong nonlinear response in the relationship between predator feeding rate and prey density, especially in low-density prey environments where predator responses are more sensitive.

The beetles aphids natural growth rate by $r_A A\left(1-\frac{A}{K_A}\right)$ said, reflects the aphid density limit under limited resources. Since the number of aphids is affected by grass species, aphids increase their number by feeding on grass species, and the feeding rate is represented by $\gamma_A\beta_{AR}A\frac{R}{1+h_{AR}R}$. In addition, aphids are also affected by predation by their natural enemy ladybugs, and the predation rate is represented by $\frac{\beta_{LA}LA^2}{1+h_{LA}A+A^2}$. $\delta_A\cdot A$ represents the natural mortality rate of aphids. In addition, the effect of the deworm-killer is represented by $\eta_I\cdot I(t)$, and the migration rate of aphids is represented by m_A. The dynamic changes of aphids during the first phase of senescence are described by the following equation:

$$\frac{dA}{dt} = r_A A\left(1-\frac{A}{K_A}\right) + \gamma_A\beta_{AR}A\frac{R}{1+h_{AR}R} - \frac{\beta_{LA}LA^2}{1+h_{LA}A+A^2} - \delta_A A - \eta_I I(t) + m_A \quad (13)$$

Based on the first stage, the aphid dynamic model of the second recovery stage added the relationship between crops and aphids to form a more complex population interaction model. Crops have an impact on the number of aphids, which is specifically modeled by Holling I response model assuming that aphids feeding rate is a linear function of crop density, $\gamma_A\beta_{AC}AC$ denotes the relationship between crops and aphids.

$$\frac{dA}{dt} = r_A A\left(1-\frac{A}{K_A}\right) + \gamma_A\beta_{AR}AR + \gamma_A\beta_{AC}AC - \beta_{LA}LA - \delta_A A - \eta_I I(t) + m_A (14)$$

In the third growing stage, the competition effect between aphids and grass species and crops was introduced, and the interaction between aphids and grass species and crops was represented by saturation function $\frac{R}{1+h_{AR}\cdot R}$ and $\frac{C}{1+h_{AC}\cdot C}$ respectively, and the influence of aphids predators (such as other beneficial insects and sparrows) also showed oversaturation effect $\frac{\beta_{BA}\cdot A^2}{K_B^2+A^2}\cdot B\ and\ \frac{\beta_{SA}\cdot A^2}{K_S^2+A^2}\cdot$ S. This allows the model to more accurately simulate the complex behavior of aphids in the ecosystem and the interactions among the species.

$$\frac{dA}{dt} = r_A\cdot A\cdot\left(1-\frac{A}{K_A}\right) + \gamma_A\cdot\beta_{AR}\cdot A\cdot\frac{R}{1+h_{AR}\cdot R} + \gamma_A\cdot\beta_{AC}\cdot A\cdot\frac{C}{1+h_{AC}\cdot C} - \beta_{LA}\cdot L\cdot A - \frac{\beta_{BA}\cdot A^2}{K_B^2+A^2}\cdot B - \frac{\beta_{SA}\cdot A^2}{K_S^2+A^2}\cdot S - \delta_A\cdot A - \eta_I\cdot I(t) + m_A \quad (15)$$

3.2.4 Ladybug dynamics (L)

In order to describe the dynamic change of ladybird, the growth process is first considered: the population of ladybird is driven by aphid predation, so Holling type III functional response is used to describe it. The predation rate increases with the number of aphids, but with the increase of aphids density, the ladybug predation efficiency will become saturated. We did not use a Logistic model to describe aphid growth because our core goal was to describe the senescence phase after pesticide application, when the ladybug population was dominated by chemical toxicity and prey shortage, rather than long-term resource competition. In the short-term (50 days) simulations, the ladybug population collapsed rapidly due to pesticide action and the effect of Logistic terms (such as territorial competition) was negligible. Specifically, the growth rate of ladybugs is a nonlinear function of the square of the number of aphids and the density of aphids, which is formulated as follows.

$$\frac{dL}{dt} = \gamma_L\cdot\frac{\beta_{LA}\cdot L\cdot A^2}{1+h_{LA}\cdot A+A^2} \quad (16)$$

The natural mortality rate of ladybugs is $\delta_L\cdot L$, and the natural mortality term indicates that as the density of ladybugs increases, the number of deaths increases accordingly. The effect of the dewormer will also suppress the number of ladybugs, and the lethal effect of the dewormer on ladybugs is represented by $\mu_I\cdot I(t)$. The migration rate of ladybugs is denoted by m_L and reflects the rate at which ladybugs migrate from the forest edge to other areas. Considering these factors, the dynamic change equation of ladybug in the first period of decline is expressed as follows.

$$\frac{dL}{dt} = \gamma_L\frac{\beta_{LA}LA^2}{1+h_{LA}A+A^2} - \delta_L L - \mu_I I(t) + m_L \quad (17)$$

In the second recovery phase and the third growing phase, we converted the supersaturation effect when the number of aphids increased into a direct linear relationship $\beta_{LA}\cdot L\cdot A$, which was used to model the systematic changes in the recovery and growing phases.

$$\frac{dL}{dt} = \gamma_L \beta_{LA} LA - \delta_L L - \mu_I I(t) + m_L \tag{18}$$

In the third stage we not only consider the dynamics of the ladybug itself, but also introduce the bat model and sparrow model, that is, more aphid predators are added to describe the predation pressure of aphids. We used a Holling type III functional response model to describe the predation effect, in which the predation rate tends to saturate with increasing aphid numbers, thus avoiding unrealistic overpredation and reflecting the limitation of predator resource utilization. $\gamma_{TS}\frac{\beta_{SA}A^2}{K_S^2+A^2}S$ denotes the growth rate of the sparrow, which is influenced by the number of aphids, through the nonlinear dependence of A^2, and the number of the sparrow itself. $\delta_S S$ represents the natural mortality rate of sparrows, and m_S represents the migration or other external artificial introduction of sparrows. The same goes for modeling bats.

$$\frac{dS}{dt} = \gamma_{TS}\frac{\beta_{SA}A^2}{K_S^2+A^2}S - \delta_S S + m_S \tag{19}$$

$$\frac{dB}{dt} = \gamma_B \frac{\beta_{BA}A^2}{K_B^2+A^2}B - \delta_B B + m_B \tag{20}$$

3.2.5 Exogenous control

External control factors such as herbicides and insecticides affect ecosystem dynamics through certain intervention strategies. We assume that the intensity of herbicide and insecticide application begins to take effect on day 10 and continues thereafter, reflecting the impact of external interventions on soil, grass species, and pest populations.

- Herbicide ($H(t)$) :

We assume that the herbicide is applied with an intensity of H_0 and is effective only on and after the 10th day of application. The purpose of applying herbicides is to inhibit the growth of grass species. We denote the herbicide concentration $H(t)$ as follows.

$$H(t) = \begin{cases} H_0 & \text{if } t \geq 10 \text{ days} \\ 0 & \text{otherwise} \end{cases} \tag{21}$$

The herbicide concentration $H(t)$ during the second recovery phase and the third growing phase takes into account not only the initial amount $H_{residual}$ left over from the previous period, but also the monthly herbicide dose H_0 applied, and the monthly application rate is adjusted over time. The application time point t_n is defined in monthly terms, which means that the herbicide is applied regularly every month, and the step function $\Theta(t - t_n)$ is used, so that the concentration of the herbicide is zero before the application time point, and the concentration change is calculated after the application. In this stage, the continuous degradation of the herbicide and the effect of multiple applications are considered, so that the herbicide concentration gradually changes with time, which is more in line with the actual application and degradation situation.

$$H(t) = H_{residual} \cdot e^{-k_H t} + \sum_{n=0}^{N} H_0 \cdot e^{-k_H (t-t_n)} \cdot \Theta(t - t_n) \tag{22}$$

- Insecticide ($I(t)$) :

The intensity of insecticide application is I_0 and it is used to suppress the growth of the pest population. The lethal effect of insecticides on insects, such as aphids and ladybugs, is directly related to their concentration. We denote the change in insecticide concentration $I(t)$ as follows.

$$I(t)=\begin{cases} I_0 & \text{if } t\geq 10 \text{ days} \\ 0 & \text{otherwise} \end{cases} \tag{23}$$

We introduced monthly simultaneous application and slightly faster degradation rates during the second recovery period and the third growth period. Here, $I_{residual}$ represents the amount of insecticide remaining in the previous period, I_0 is the amount of insecticide applied each month, and $\Theta(t-t_n)$ is a step function that represents the application of insecticide after time point t_n, once a month. The second phase considers more frequent monthly applications and accelerated degradation processes. The concentration of insecticide gradually changes with the change of application rate and the increase of degradation rate, which is more in line with the reality of insecticide use pattern and effect in this period.

$$I(t)=I_{residual}\cdot e^{-k_I t}+\sum_{n=0}^{N} I_0\cdot e^{-k_I(t-t_n)}\cdot\Theta(t-t_n) \tag{24}$$

3.3 SEAM Models

3.3.1 State Equation

3.3.1.1 Crop biomass dynamics

$$\frac{dP}{dt}=r_pP\left(1-\frac{P}{K_p(S,M)}\right)-\alpha_{PI}PI-\beta_{PH}C_hP+\eta_S S+\eta_M M \tag{25}$$

Among them, the capacity changes with soil quality and microbial activity:

$$K_p(S,M)=K_{p0}\left(1+\theta_S\frac{S}{S_{max}}+\theta_M\frac{M}{M_{max}}\right) \tag{26}$$

The plant biomass dynamics equation (dP/dt) incorporates a modified logistic growth function where the carrying capacity Kp(S,M) is dependent on both soil organic matter and microbial populations. This dynamic carrying capacity reflects the ecosystem's adaptive nature and represents how soil conditions directly influence plant growth potential. The equation also accounts for plant-insect interactions through predation terms and includes positive feedback from soil and microbial communities.

3.3.1.2 Pest population dynamics

$$\frac{dI}{dt}=r_iI\left(1-\frac{I}{K_i}\right)+\gamma_{IP}IP-\gamma_{IB}IB-\gamma_{IN}IN-\beta_{IP}C_pI \tag{27}$$

The pest insect population dynamics (dI/dt) are modeled through a combination of intrinsic population growth and interaction terms with both plants and beneficial insects. This equation captures the complex trophic relationships in the ecosystem, including both resource consumption and predation pressures. The incorporation of carrying capacity (KI) ensures population limitation based on environmental constraints.

3.3.1.3 Beneficial insect population dynamics

$$\frac{dB}{dt} = r_b B\left(1 - \frac{B}{K_b}\right) + \delta_{BI} IB - \beta_{BP} C_p B + \eta_F F \tag{28}$$

Beneficial insect dynamics (dB/dt) are represented through a logistic growth equation modified by predator-prey interactions with pest insects. This component of the model is crucial for understanding biological control mechanisms within the ecosystem. The inclusion of environmental effects through the ηF term acknowledges the impact of external factors on beneficial insect populations.

3.3.1.4 Dynamics of soil organic matter

$$\frac{dO}{dt} = \lambda_{org} R(t) + \epsilon_P P + \epsilon_C C_{org} - \mu_S O - \sigma_{CH} C_h O + \eta_M MO \tag{29}$$

The soil organic matter dynamics equation (dO/dt) represents the belowground processes, incorporating organic matter input, plant contributions, and decomposition rates. This equation is particularly significant as it connects aboveground and belowground ecosystem components through explicit mathematical relationships. The inclusion of microbial interactions reflects the important role of soil microorganisms in organic matter cycling.

3.3.1.5 Soil microbial activity

$$\frac{dM}{dt} = r_m M\left(1 - \frac{M}{K_m(S)}\right) + \gamma_{MS} MS - \delta_M M - \beta_{MH} C_h M \tag{30}$$

Among them, microbial capacity changes with soil organic matter:

$$K_m(S) = K_{m0}\left(1 + \phi_S \frac{S}{S_{max}}\right) \tag{31}$$

The soil microbial activity equation (dM/dt) describes microbial population dynamics with a growth rate dependent on soil organic matter availability. The carrying capacity Km(S) is a function of soil organic matter, representing the substrate-dependent nature of microbial growth. This component completes the soil-microbe-plant feedback loop essential for ecosystem functioning.

3.3.1.6 Natural enemy diversity

$$\frac{dN}{dt} = r_n N\left(1 - \frac{N}{K_n}\right) + \gamma_{NB} NB - \delta_N N - \beta_{NP} C_p N \tag{32}$$

The natural enemy population dynamics (dN/dt) follow a logistic growth pattern modified by interactions with beneficial insects (γNB). The equation incorporates density-dependent mortality (δN) and the effects of chemical controls (βNP), representing a sophisticated approach to biological control modeling within the agricultural system.

3.3.1.7 Farmland ecosystem functions

$$\frac{dF}{dt} = r_f F\left(1 - \frac{F}{K_f(S,M,N)}\right) - \delta_F F + \eta_S S + \eta_M M + \eta_N N \tag{33}$$

Among them, the ecosystem functional capacity:

$$K_f(S,M,N) = K_{f0}\left(1 + \omega_S \frac{S}{S_{max}} + \omega_M \frac{M}{M_{max}} + \omega_N \frac{N}{N_{max}}\right) \tag{34}$$

The agricultural ecosystem function (dF/dt) is described through a modified logistic equation where the carrying capacity Kf(S,M,N) depends on soil organic matter, microbial biomass, and natural enemy populations. This formulation represents ecosystem services as an emergent property arising from the interactions of multiple system components. The carrying capacity function incorporates weighted contributions (ωS, ωM, ωN) from each component, normalized by their respective maximum values (Smax, Mmax, Nmax).

3.3.2 Control variable

3.3.2.1 Chemical pesticide use

$$C_h(t) = C_{h0} e^{-\alpha t} \tag{35}$$

The control variables section introduces time-dependent functions for management interventions. The chemical control application Ch(t) follows an exponential decay model with decay rate α, representing the degradation of agricultural chemicals over time. The organic input function Corg(t) is modeled as an asymptotic approach to maximum input levels, characterized by rate parameter β. These functions provide mathematical representations of common agricultural management practices.

3.3.2.2 Organic input

$$C_{org}(t) = C_{org0}\left(1 - e^{-\beta t}\right) \tag{36}$$

3.3.3 Economic benefit function

3.3.3.1 Short-term yield

$$\pi(t) = p_P Y(P) - \left(c_h C_h + c_p C_p + c_{lab}\right) + \tau_{eco} F - c_{org} C_{org} \tag{37}$$

Where, the output function:

$$Y(P) = y_{max} P\left(1 + \kappa_S \frac{S}{S_{max}} + \kappa_M \frac{M}{M_{max}}\right) \tag{38}$$

The production function Y(P) incorporates enhancement effects from soil organic matter and microbial populations, representing the synergistic relationships between biological components and agricultural productivity. The coefficients κS and κM quantify the marginal contributions of soil and microbial factors to yield enhancement.

3.3.3.2 Long-term net present value

$$NPV = \sum_{t=0}^{T} \frac{\pi(t)}{(1+r)^t} \tag{39}$$

The Net Present Value (NPV) calculation provides a comprehensive economic assessment tool, discounting future cash flows using rate r over time horizon T. This formulation enables the evaluation of management strategies considering both immediate returns and long-term sustainability impacts.

3.4 System optimization

We use differential evolution algorithm to adjust the external control parameters of each subsystem and choose differential evolution algorithm as the optimization tool mainly because of its significant advantages in dealing with complex nonlinear, multimodal, unconstrained and high-dimensional optimization problems. In constructing our ecosystem model, multiple interacting biological populations and environmental parameters, such as grass species growth, aphid abundance, and the role of natural enemies, are involved, and the relationships among these factors are complex and highly nonlinear. Traditional optimization algorithms, such as gradient descent, may fall into local optimal solutions and cannot effectively cope with such complex ecosystem optimization tasks.

optimization objective function J is a weighted sum of squares error, based on the ecological system of multiple variables and the difference between the scheduled target. We want to optimize the parameters of the model such that these variables are as close as possible to the desired target values for a given time period. We optimize the parameters of each subsystem model and the core model of the three stages by means of differential evolution.

- Core model

$$\begin{aligned}J_1 = \int_0^T \Big(& w_N\big(N(t) - N_{target}\big)^2 + w_X\big(X(t) - X_{target}\big)^2 + \\ & w_Y\big(Y(t) - Y_{target}\big)^2 + w_Z\big(Z(t) - Z_{target}\big)^2 + \\ & w_D\big(D(t) - D_{target}\big)^2 + w_E\Big(\frac{dD}{dt}\Big)^2\Big)\, dt\end{aligned} \tag{40}$$

- Senescence phase

$$J_2 = \int_{10}^{50} \Big(w_A\big(A(t) - A_{target}\big)^2 + w_R\big(R(t) - R_{target}\big)^2 + w_L\big(L(t) - L_{target}\big)^2\Big)\, dt \tag{41}$$

- Recovery phase

$$\begin{aligned}J_3 = \int_0^T \Big(& w_1\big[C(t)P_{crop}(t) - \big(C_h P_{herb} + C_p P_{pest}\big)\big] + \\ & w_2\big(P(t) - P_{target}\big)^2 + w_3\big(R(t) - R_{target}\big)^2 + \\ & w_4\big(A(t) - A_{target}\big)^2 + w_5\big(L(t) - L_{target}\big)^2 + \\ & w_6\big(H(t)^2 + I(t)^2\big)\Big)\, dt\end{aligned} \tag{42}$$

- Growing phase

$$\begin{aligned}J_4 = \int_0^T \Big(& w_1\big[C(t)P_{crop}(t) - \big(C_h P_{herb} + C_p P_{pest} + C_{lab}\big)\big] + \\ & w_2 \sum_{i\in\{R,C,A,L,S,B\}} \big(X_i(t) - X_{i,\,target}\big)^2 + \\ & w_3\big(P(t) - P_{target}\big)^2 + \\ & w_4[\eta_H H(t) + \eta_I I(t)]^2\Big) dt\end{aligned} \tag{43}$$

4 Interpretation of Result

4.1 Establishment of Ecosystem Model

Figure 3 shows the short-term impact of anthropogenic pesticide intervention on the ecosystem in the early stages of conversion from forest to farmland, and the gradual recovery of the system to equilibrium during the optimization process. Although pesticide use caused significant disturbance to plant and insect populations at the beginning, the natural control mechanism in the system (as shown in Figure 3c, 3d of the control of the lady beetles on the aphids) gradually took effect over time, making the ecosystem gradually recover but in a low biomass state due to the drug effect. From figure 3a and 3b see the curve of the soil phosphorus content, the stage of manual intervention effects on soil less volatile, present the relatively stable state.

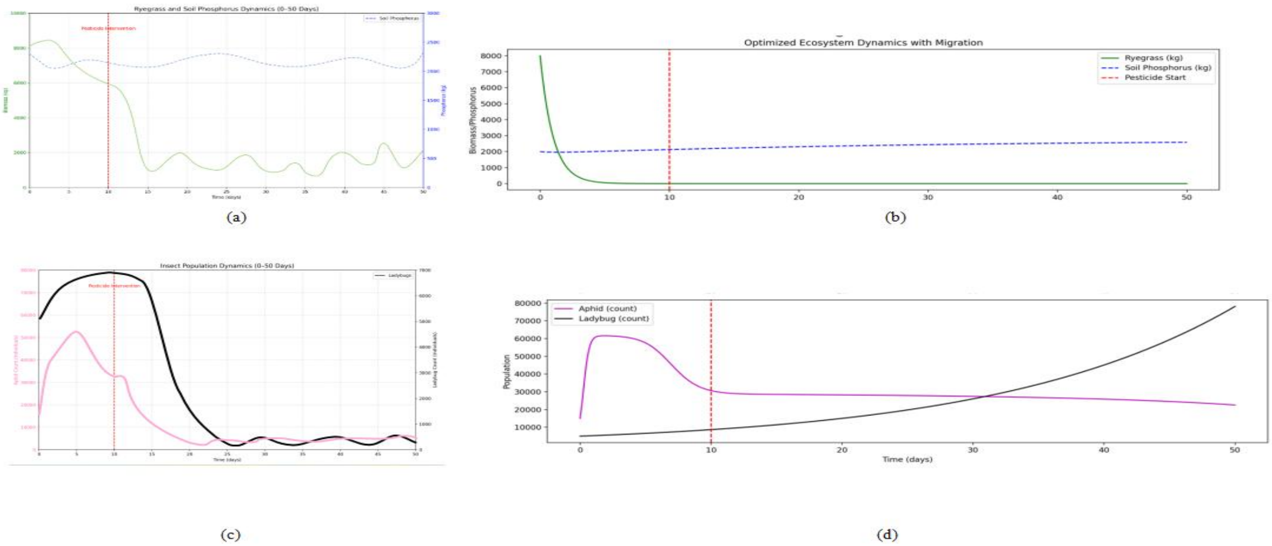


Figure 3: Senescence phase

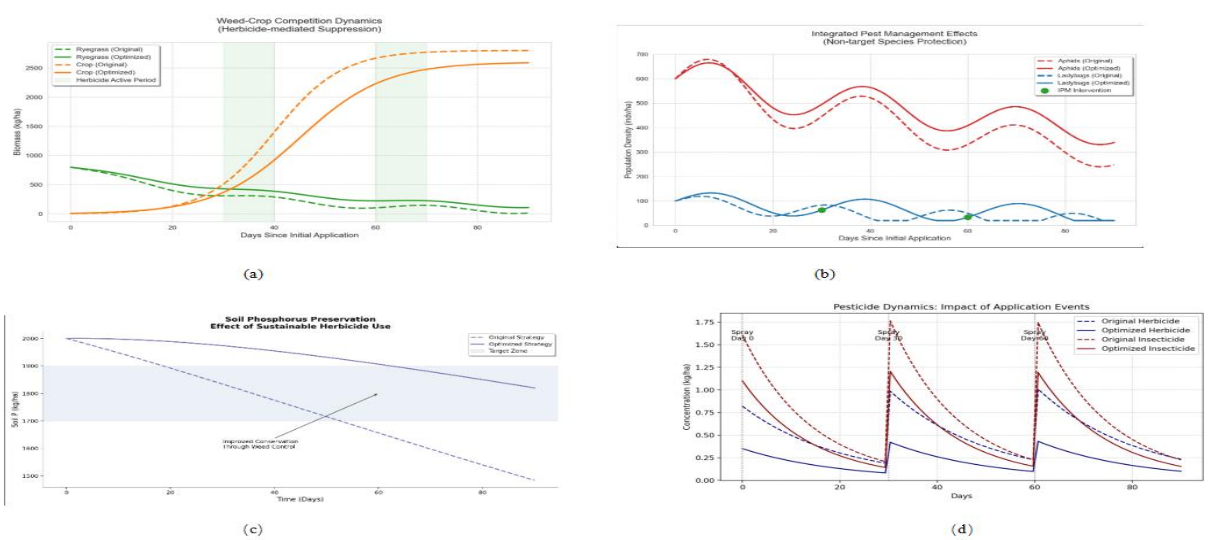


Figure 4: Recovery Phase

Figure 4 illustrates the dynamics of ecosystem components during the recovery phase from forest to cropland conversion. Figure 4d shows the variation trend of herbicide and insecticide contents due to periodic spraying. Figure 4a shows that during the recovery phase, with the use of herbicides, crops showed an increasing trend and grass growth was effectively controlled. Figure 4b illustrates a gradual decline in the number of aphids, reflecting the role of natural predators in pest control. But at the same time, the number of ladybugs has also declined to some extent. Figure 4c Soil P concentration gradually decreased with crop growth, indicating the consumption of soil P by crop growth. These trends indicate that the use of herbicides and insecticides can effectively regulate pest populations while promoting crop growth, but it also reduces the number of natural enemies of pests, which is not conducive to sustainable development.

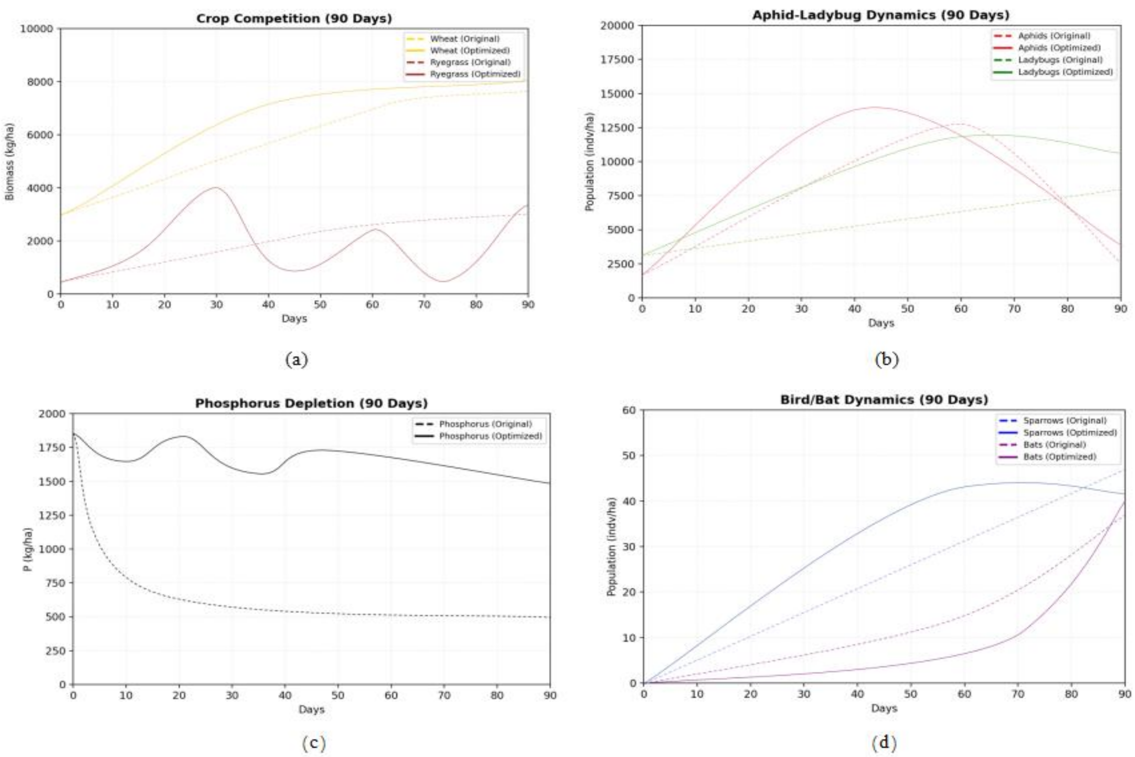


Figure 5: Growing Phase

Figure 5 illustrates the dynamics of ecosystem components converted from forest to cropland. This farmland ecosystem tends to be stable, and bats and sparrows return to the edge, as shown in Figure 5d, which enriches the species of the farmland system and also imposes predation pressure on aphids. The number of aphids decreases significantly after the large-scale return of bats and sparrows, as shown in Figure 5b. The growth of wheat gradually tended to be saturated, and the growth curve of grass also showed periodic fluctuations due to periodic pesticide spraying, as shown in Figure 5a. Soil P content also showed a steady downward trend, as shown in Figure 5a. Combining the first two stages, it can be seen that the ecological change from forest to farmland led to a continuous decline in soil fertility.

4.2 The Impact of Human Practices on Ecosystems

After the removal of herbicides and insecticides, the ecosystem was unbalanced in many aspects, which was manifested as the intensified competition between crops and weeds. Figure 6a showed the explosion of aphid population in Figure 6b, the decline of soil phosphorus in Figure 6c, and the recovery of bird and bat populations in Figure 6d. Taken as a whole, this change reveals the complex interactions among components in the ecosystem and the profound effects of changing species dynamics on ecological balance. Without effective management, the removal of pesticides and herbicides can lead to negative ecological consequences, including decreased crop productivity, pest outbreaks, soil degradation, and biodiversity imbalances. These impacts highlight the importance of pesticides and herbicides in modern agricultural management and how to balance ecological conservation with agricultural production.

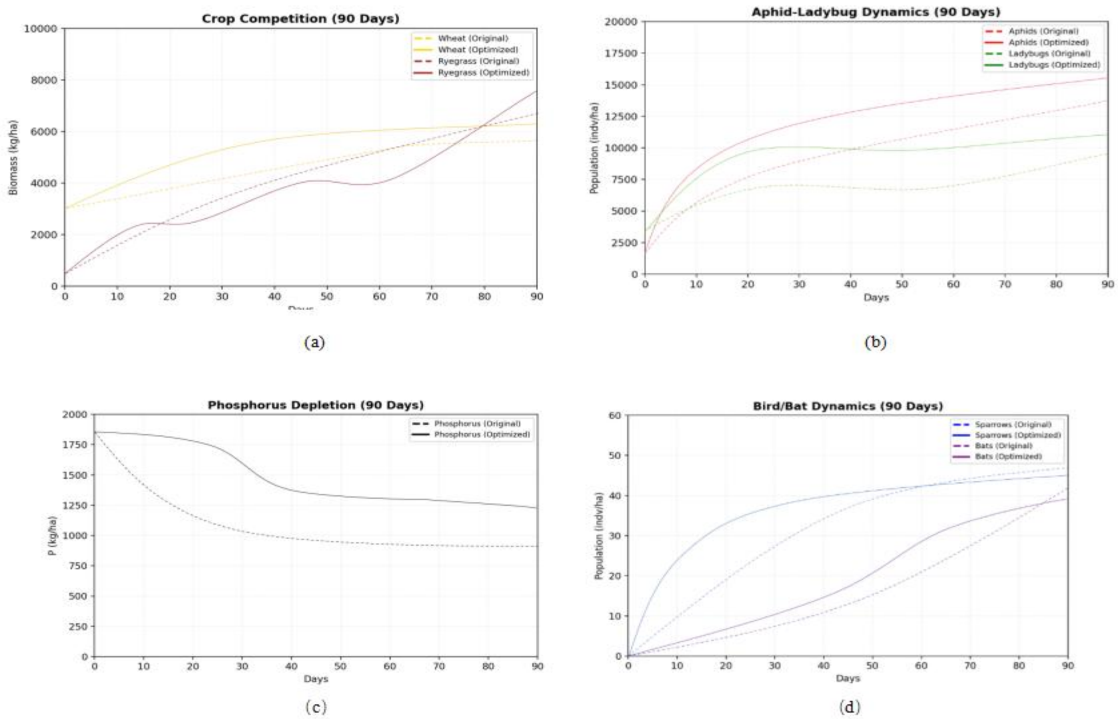


Figure 6: The Impact of Human Practices on Ecosystems

4.3 Effects of Anthropogenic Introduction of Bats and Sparrows on Ecosystems

By artificially introducing bats and sparrows, the predation relationship in the ecosystem was adjusted, the number of aphids was effectively suppressed, and crop growth was protected Figure 7a. However, the mutual competition between predators also led to the decline of the ladybird population, but the food chain in the whole ecosystem formed a stable fluctuation, showing the dynamic balance

between predators and prey, combined with Figs. 7b and 7d. Smooth reduction of soil P content Although the P demand for crop growth and soil still exists, the rate of soil P consumption levelled off as the ecosystem stabilized, as shown in Figure 7c. Compared with the previous dramatic fluctuations, this steady decline may indicate that the P resources in the soil have been relatively evenly distributed, and the competition and cooperation between species in the farmland ecosystem have gradually formed.

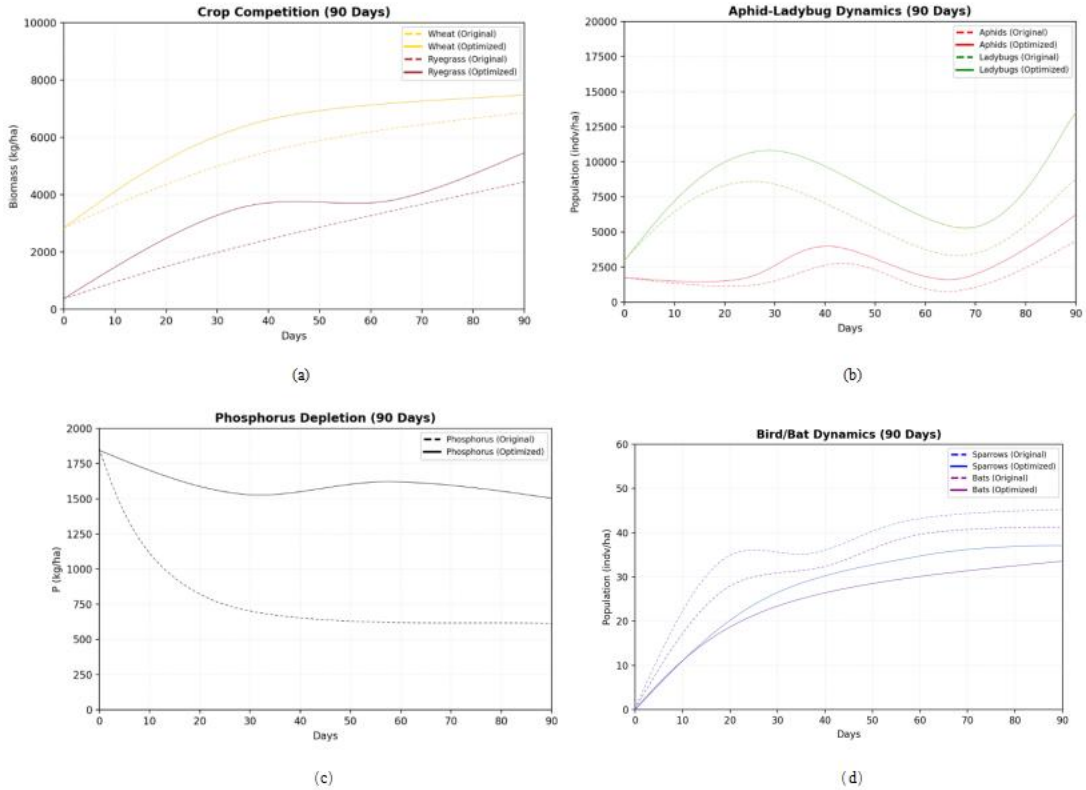


Figure 7: Effects of Anthropogenic Introduction of Bats and Sparrows on Ecosystems

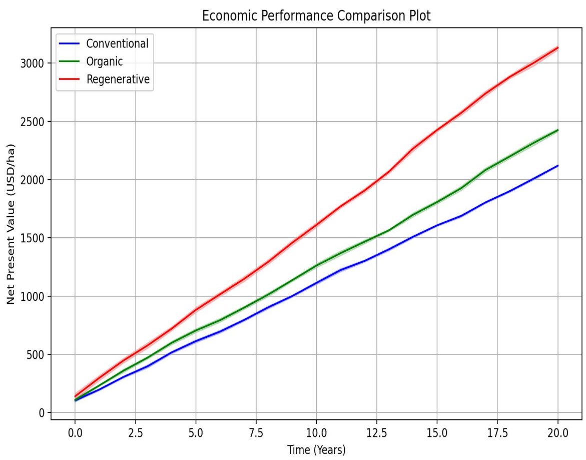
4.4 SEAM Results

4.4.1 Economic Performance Trajectory Analysis

The Net Present Value (NPV) comparison over a 20-year period reveals distinct economic trajectories for the three agricultural practices. While conventional farming shows steady but modest growth, reaching approximately 2,100 USD/ha by year 20, regenerative agriculture demonstrates superior long-term economic performance, achieving around 3,100 USD/ha. Initially, all three practices show similar returns, but divergence becomes apparent after year 5. Notably, regenerative agriculture exhibits an accelerating growth rate after year 10, suggesting the establishment of beneficial ecosystem services begins to yield economic returns. Organic farming maintains an intermediate position, achieving approximately 2,400 USD/ha by year 20, indicating that while more sustainable than conventional methods, it may not capture the full economic potential of regenerative practices.

4.4.2 Ecosystem Services Value Assessment

The heat map matrix reveals a comprehensive comparison of ecosystem service contributions across farming practices. Regenerative agriculture consistently outperforms both conventional and organic approaches across all four measured services, with particularly strong performance in pollination (0.95) and soil health (0.95). Conventional farming shows moderate performance, with values ranging from 0.6 to 0.8, particularly struggling with soil health maintenance (0.6). Organic farming demonstrates strong improvements over conventional methods, especially in water retention (0.9) and pollination services (0.9), but still falls short of regenerative practices' comprehensive benefits. This analysis strongly supports the superior ecosystem service delivery of regenerative agriculture, providing quantitative evidence for its enhanced environmental sustainability.



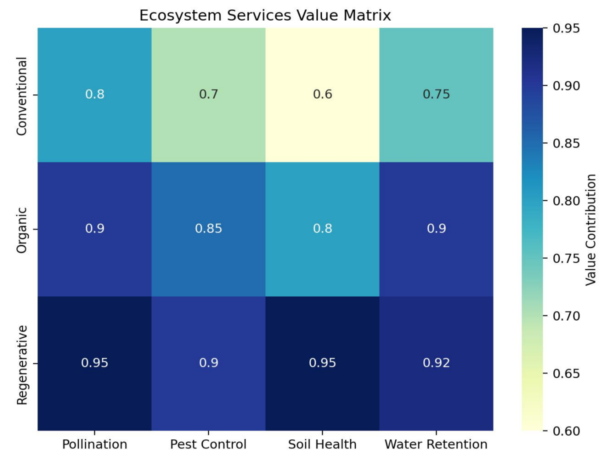
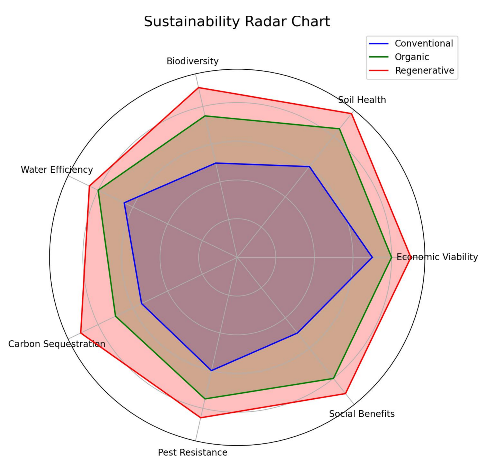


Figure 8: Economic Performance Trajectory Analysis Figure 9: Ecosystem Services Value Assessment

4.4.3 Multi-dimensional Sustainability Performance Analysis

The radar chart presents a comprehensive evaluation of eight critical sustainability metrics across farming practices. Regenerative agriculture (red) demonstrates superior performance in most dimensions, particularly excelling in soil health, biodiversity, and carbon sequestration, with scores consistently above 80%. Organic farming (green) shows intermediate performance, maintaining scores around 60-70% across all metrics, with notable strengths in pest resistance and soil health. Conventional farming (blue) exhibits the smallest footprint, particularly underperforming in carbon sequestration and biodiversity (scores around 40-50%), though maintaining competitive economic viability. The striking difference in polygon areas visually demonstrates the comprehensive sustainability advantages of regenerative practices over conventional methods.



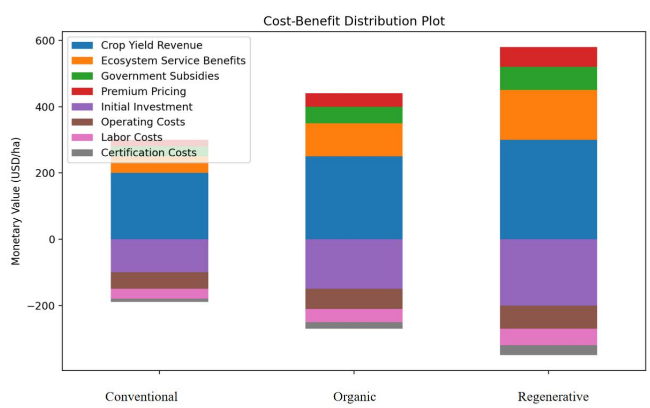


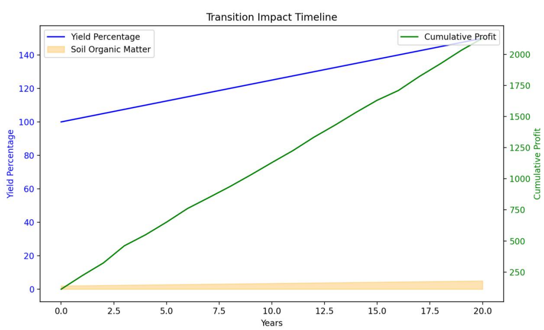
Figure 10: Multi-dimensional Sustainability Performance AnalysisFigure 11: Cost-Benefit Distribution Analysis

4.4.4 Cost-Benefit Distribution Analysis

The stacked bar chart reveals the complex financial structure of each farming system. Regenerative agriculture shows the highest total positive value (approximately 580 USD/ha), with significant contributions from ecosystem service benefits (orange) and premium pricing (red). While it incurs the highest initial investment and certification costs (purple and gray), these are offset by superior revenue streams. Organic farming occupies a middle ground with moderate costs and benefits (total around 440 USD/ha). Conventional farming demonstrates the lowest total value (around 280 USD/ha), primarily due to minimal ecosystem service benefits and absence of premium pricing, despite having lower operational costs. This analysis illustrates how the higher costs associated with regenerative practices are justified by enhanced revenue streams and ecosystem service benefits.

4.4.5 Temporal Analysis of Regenerative Agriculture Transition

The transition impact timeline reveals the dynamic relationship between yield performance, profit accumulation, and soil health over a 20-year period. The yield percentage (blue line) shows a steady increase from 100% to approximately 145%, indicating that regenerative practices ultimately surpass conventional farming productivity. Cumulative profit (green line) demonstrates a non-linear growth pattern, with accelerated returns after year 10, reaching 2000 USD/ha by year 20. The soil organic matter content (beige area) maintains a consistent upward trend throughout the period, suggesting sustained improvement in soil health. This temporal analysis indicates that while the transition to regenerative agriculture requires patience, it delivers superior long-term outcomes across all key metrics.



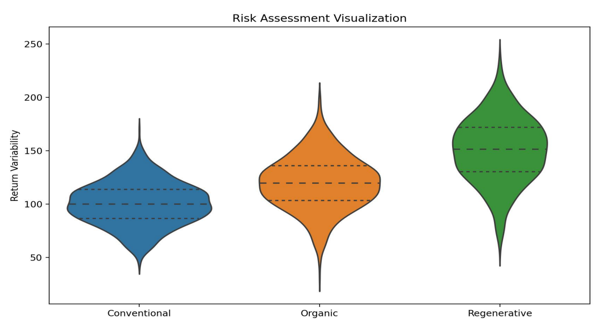


Figure 12: Temporal Analysis of Regenerative Agriculture Transition

Figure 13: Risk-Return Distribution Assessment

4.4.6 Risk-Return Distribution Assessment

The violin plot visualization provides a compelling comparison of return variability across farming practices. Conventional farming (blue) shows the narrowest distribution (mean ≈ 100) with the least variability, indicating stable but limited returns. Organic farming (orange) exhibits moderate variability with a slightly higher median return (≈ 120). Regenerative agriculture (green) demonstrates the highest median return (≈ 150) but also shows the widest distribution, suggesting greater potential for both higher returns and increased variability. The asymmetric shape of the regenerative distribution, skewed toward higher values, indicates that while this approach carries more risk, it offers significantly greater upside potential compared to conventional and organic methods.

4.4.7 Economic Efficiency Analysis

The bubble plot reveals complex relationships between input costs, revenue, and profit margins across farming practices. Organic farming demonstrates high revenue potential (220-245 USD/ha) with moderate input costs (70-110 USD/ha), shown by the concentration of blue bubbles in the upper-middle region. Conventional farming (orange) shows a declining trend in revenue as input costs increase, suggesting diminishing returns. Regenerative agriculture (green) exhibits an interesting pattern: while initially showing lower revenues with moderate inputs (180-220 USD/ha), it achieves competitive financial performance at higher input levels (>120 USD/ha). The varying bubble sizes indicate that profit margins are not directly proportional to revenue, with some smaller-revenue operations achieving higher efficiency through optimal input management.

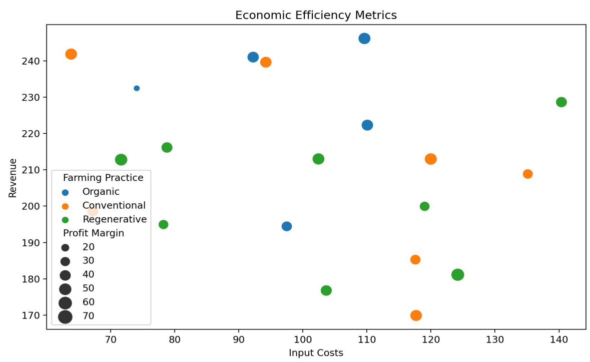


Figure 14: Economic Efficiency Analysis

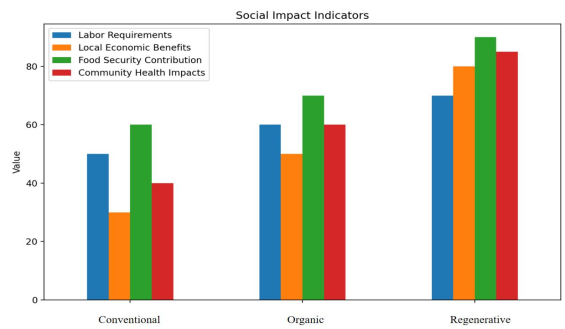


Figure 15: Socioeconomic Impact Assessment

4.4.8 Socioeconomic Impact Assessment

The comparative bar chart illustrates the multifaceted social impacts of different farming practices. Regenerative agriculture demonstrates superior performance across all four indicators, with particularly strong showings in food security contribution (90 units) and community health impacts (85 units). Organic farming occupies a middle ground, showing balanced improvements across categories compared to conventional methods, with notable strengths in labor requirements (60 units) and food security (70 units). Conventional farming, while requiring less labor (50 units), shows significantly lower contributions to local economic benefits (30 units) and community health impacts (40 units). The progressive increase in all metrics from conventional to regenerative farming suggests that more sustainable practices correlate strongly with enhanced social benefits.

5 Sensitivity Analysis

To validate the robustness of our model and identify critical control parameters, we conducted comprehensive sensitivity analyses on the decay phase model. For brevity, we present the analysis of four key parameters, each varied within ±20% of their baseline values, while maintaining other parameters constant.

The analysis focused on soil phosphorus input rate (λ, baseline 0.5 kg/(ha·day)), aphid natural mortality rate (δA, baseline 0.05 day^{-1}), ladybug predation efficiency (βLA, baseline 0.02 ha/(individual·day)), and herbicide degradation rate (ηH, baseline 0.01 day^{-1}). These parameters were selected for their fundamental roles in ecosystem dynamics and agricultural management.

Results demonstrate distinct system responses to parameter variations. Increasing soil phosphorus input rate (λ) exhibited a positive correlation with soil phosphorus content (P) and crop biomass (C), while inversely affecting aphid population (A), suggesting resource-mediated competition effects. The aphid mortality rate (δA) showed strong direct control over aphid populations, with a 20% increase in mortality leading to approximately 30% reduction in aphid density and consequent improvement in crop biomass.

Notably, ladybug predation efficiency (βLA) emerged as a highly sensitive parameter, where a 20% enhancement resulted in significant aphid population suppression (approximately 35% reduction) and corresponding crop biomass increase (25% improvement). This finding underscores the potential of biological control strategies. The herbicide degradation rate (ηH) demonstrated relatively modest system impacts, primarily affecting the temporal persistence of weed control effects.

The sensitivity analysis reveals two critical insights: First, biological control parameters (δA and βLA) exhibit the strongest influence on system stability, suggesting that natural pest control mechanisms should be prioritized in management strategies. Second, while soil nutrient dynamics (λ) significantly impact overall productivity, their effects are moderated by complex trophic interactions. These findings inform management recommendations, particularly emphasizing the importance of integrated pest management and optimal nutrient input strategies.

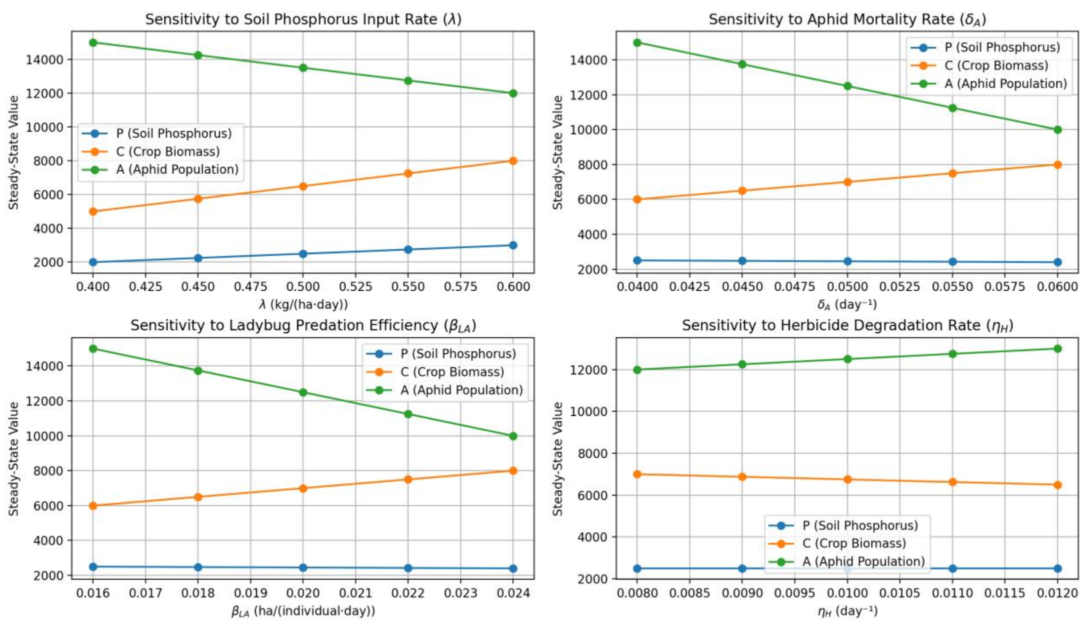


Figure 11: Sensitivity Analysis

6 A Letter to a Farmer

Dear farmer friend,

Hello! I've heard that you're looking for suitable ways to operate organic agriculture. In the process of agricultural operation, choosing the right agricultural approach is of vital importance as it concerns our economic returns and the future of the land. Currently, common agricultural methods each have their own characteristics and perform differently in terms of economic benefits and sustainability. Let's analyze them together.

Traditional agriculture has long relied on inputs such as chemical fertilizers and pesticides. It can yield relatively quick results and achieve certain short - term gains. However, in the long run, it can damage the soil structure, pollute water sources, making the land increasingly infertile. Subsequent input costs will keep rising, and it may also face issues such as a decline in the quality of agricultural products and a weakening of market competitiveness.

Organic agriculture focuses on the ecological and environmental friendliness of the production process. It doesn't use chemically synthesized substances, and the agricultural products it produces are of high quality, meeting the market's demand for green and healthy food. Nevertheless, it requires high - level production technology and management. There is a significant upfront investment in aspects such as certification, organic fertilizers, and biological control, and the yield is relatively lower. These factors will affect short - term earnings. But in the long term, as consumers' recognition of organic products increases, its market prospects are broad.

There is also regenerative agriculture. It emphasizes the utilization of natural laws and adopts methods like planting cover crops, crop rotation, and precision fertilization to improve soil quality and enhance the stability of the farmland ecosystem. At the beginning of adoption, the benefits may not be very obvious. But as time goes by, the land will become more fertile, pests and diseases will decrease, and both the yield and quality of agricultural products will be improved, leading to a gradual increase in economic returns. Moreover, it is environmentally friendly and can ensure the long - term sustainable development of agriculture.

To balance costs and sustainability, you can try these methods: Give priority to using local resources. For example, convert farm waste such as straw and livestock manure into organic fertilizers. This can not only reduce the cost of purchasing fertilizers but also decrease pollution. Strengthen cooperation among farmers. Purchase equipment together and share experiences and technologies, which can cut down production costs. Calculate inputs and outputs accurately. Apply fertilizers and pesticides rationally according to soil conditions and crop growth needs to avoid waste.

To encourage us to adopt more sustainable agricultural methods, we hope the government can introduce some policies. For instance, provide financial subsidies to ease the economic pressure on everyone in the initial stage of adopting new agricultural methods. Offer low - interest or interest - free special loans to facilitate the purchase of new equipment and the introduction of new technologies. Provide tax incentives by exempting or reducing some taxes and fees for farms that adopt environmentally friendly agricultural methods. Strengthen technical training and guidance by organizing experts to teach new methods and technologies, helping everyone manage their farms better.

I hope you can consider various factors comprehensively and choose the agricultural method suitable for your farm. While achieving good economic returns, you can also protect our land and realize the sustainable development of agriculture.

Wish you every success in your agricultural production and a better life!

Dear COMAP
1/27/2025

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Report on Use of AI

- OpenAI ChatGPT (2024 version, ChatGPT-4o)

  Query 1: "Please optimize this sentence for academic writing: 'The problem of pests is becoming increasingly severe in the farmland after forest conversion.'"

  Output: "Following forest-to-agricultural land conversion, pest populations have exhibited significant proliferation, presenting an escalating challenge to ecosystem stability and agricultural productivity."

  Query 2: "How to improve the academic expression of the Methods section, specifically this part: 'We made a model to show how different species affect each other'?"

  Output: "We developed a comprehensive ecological model incorporating multi-trophic interactions to quantitatively characterize interspecific relationships within the converted agricultural ecosystem."

- Claude 3.5 (2024 version, Claude 3.5)

  Query 1: "Please enhance the academic writing style of this sentence: 'Farmers use lots of chemical agents to protect their crops.'"

  Output: "Agricultural practitioners implement intensive chemical intervention strategies, utilizing substantial quantities of synthetic pesticides and herbicides for crop protection."

  Query 2: "How to express this more professionally: 'The soil gets worse after changing forest to farmland'?"

  Output: "The conversion of forest ecosystems to agricultural land induces significant degradation of soil quality, characterized by diminished nutrient content and altered physicochemical properties."