Problem Chosen	2025 MCM/ICM Summary Sheet	Team Control Number
E		2511940

Our Article

Summary

sumary sumary

Contents

1 Introduction

1.1 Background

In the past few decades, with the rapid population growth, food supply has become one of the most pressing global issues. Under the conditions where scientific and technological advancements have not been fully adopted, the existing arable land area is insufficient to meet the food demand. As a result, many regions have resorted to deforestation for land conversion, as shown in Figure 1. Figure 2 illustrates that when the forest ecosystem is artificially disrupted, its complex spatial structure is destroyed.

Figure 1: Deforestation for Farming

Figure 2: Deforested Forest

Therefore, the converted forest area must undergo a long process of ecological reconstruction. However, due to the influence of human activities during this process, the post-clearing forest ecosystem can no longer return to its original state, but instead continuously undergoes succession into a stable agricultural ecosystem. To achieve both economic and ecological benefits and fulfill sustainable development goals, it is necessary to examine the ecological succession from converted forest to agricultural ecosystems and explore how green agriculture can bring dual benefits in terms of economic and ecological indicators.

1.2 Problem Analysis

The basic requirements of the project are to establish a model that reflects the ecological succession process from a converted forest area to a mature agricultural ecosystem over time. The model should incorporate both natural processes and human agricultural activities. Specifically, the requirements are as follows:

- **Develop an ecological model** for the converted forest area, particularly:
  - **Food web construction**: The model should include at least producers (e.g., plants) and consumers (e.g., herbivores and predators) and their interactions.
  - **Consideration of agricultural cycles and seasonality**: The impact of seasonal and cyclical agricultural activities should be taken into account.
  - **Impact of chemicals**: The model should account for the effects of chemicals such as herbicides and pesticides on plants, insects, bats, birds, and the stability of the ecosystem.

- **Reemergence of species during ecosystem maturation**: As the ecosystem matures, the model should consider the reemergence of two species and their impact on the ecosystem.
- **Impact of removing chemicals**: After the ecosystem matures, humans will attempt to remove chemicals. The model should assess the stability of the ecosystem after herbicides are removed, with the effects reflected through producers and consumers.
- **Introduction of bats into the food web**: The model should examine how bats, as insectivores and pollinators, interact with plants, insects, and predators, and how their inclusion influences the stability of the ecosystem. Additionally, the model should identify another species that could benefit the ecosystem and compare the effects of different species.
- **Analysis of the impact of organic farming**: The model should assess the impact of adopting organic farming practices, considering various scenarios and components. The evaluation should include the effects on the overall ecosystem and individual elements, such as pest control, crop health, plant reproduction, biodiversity, long-term sustainability, and cost-effectiveness. The model should analyze the impact of organic practices on pest management, soil health, and biodiversity, while weighing the economic costs and benefits. A comprehensive ecological and economic trade-off analysis should be provided to assess the feasibility of organic farming.

1.3 Our Work

- 1
- 2
- 3

2 Assumptions and Notations

2.1 Assumptions and Explanations

- **Accurate Data Assumption**: The model assumes that the data used are accurate.
  Explanation: The data used in the model are sourced from official databases, and we believe the data to be accurate and reliable.
- **Geographic Applicability Assumption**: The model assumes that the applicable region is Southeast Asia, where two crops of rice are planted each year in the farmland.
  Explanation: The climate of Southeast Asia is rather simple, with only two seasons-rainy and dry. Additionally, as is shown in Figure 3, the temperature variation within a year is minimal, which has a trivial effect on the ecosystem. Consequently, temperature can be considered as a constant. Due to such weather pattern, it aligns with the planting patterns commonly observed in Southeast Asia

to plant three crops of rice each year(showed in Figure 4), and the simplicity of crop types makes the model easier to establish.

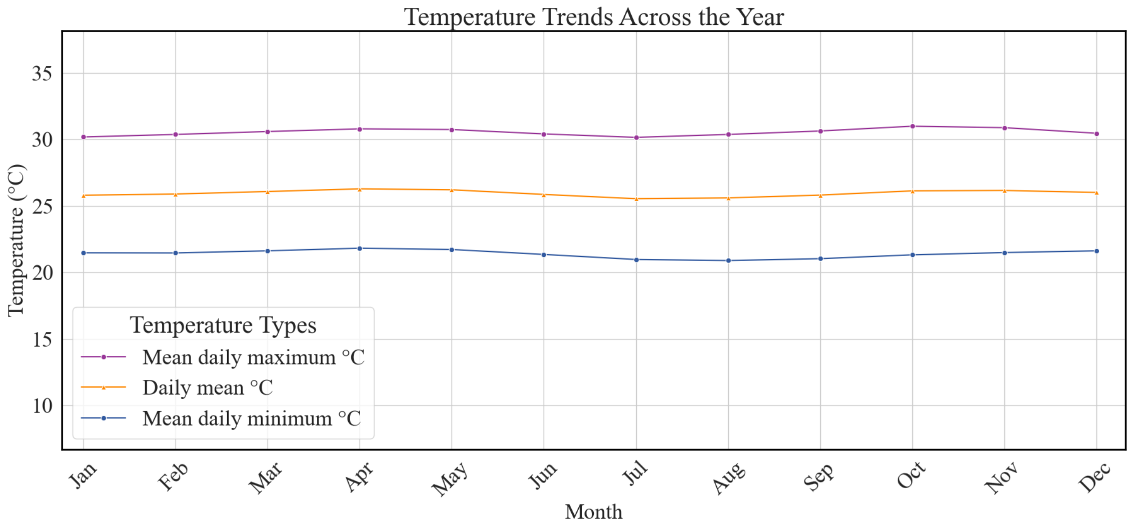

Figure 3: Temperature Data in Southeast Asia [1]

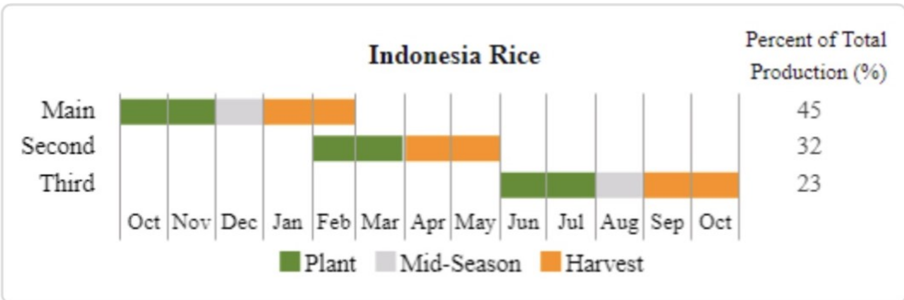

Figure 4: Agricultural Cycle in Southeast Asia [2]

- **Stable Trait Assumption**: The model assumes that the traits of all organisms remain stable.
  Explanation:Since the time span considered in the model is much shorter than the time required for evolutionary changes or mutations to occur, the traits of organisms are assumed to remain stable. This assumption also helps simplify the model.

- **Stable Lighting Conditions Assumption**: The model assumes that the region under study experiences stable lighting conditions throughout the four seasons.
  Explanation: Since the model focuses on tropical regions, the variation in daylight duration across different months within a year is minimal, thus the lighting conditions are treated as constant in the model.

- **Stable Growth Environment Assumption**: The model assumes that no natural disasters, which could significantly impact the agricultural ecosystem, will occur during the time frame considered.
  Explanation: Natural disasters are considered low-probability events in agricultural activities. To ensure the generalizability of the model, natural disasters should not be considered.

2.2 Notations

Table 1: Notations

Symbols	Description
$\mathbf{X}$	Vector $[N_{wd}, N_{crp}, N_{pst}, N_{ins}, ..., C_{hc}, C_{pc}]^T$ to describe the system,etc.
wd	Subscription for weeds
crp	Subscription for crops
stw	Subscription for straw
pst	Subscription for pest(who consumes crops)
ins	Subscription for other insects(who consume weeds)
bd	Subscription for small birds(herbivorous)
Bd	Subscription for huge birds(carnivorous)
bt	Subscription for bats
snk	Subscription for snake
frg	Subscription for frog
HC	Subscription for herbicide
PC	Subscription for pesticide
C_i	Concentration of certain chemical
N_i	Numbers of certain species
W_i	Density of biomass of certain species
w_i	Average mass density of individuals of certain individuals
r_i	Natural growth gate of certain population
$\mathscr{K}_i$	Carrying capacity of certain population
α	The effect of chemical concentration on growth rate
$\beta_{i\to j}$	Interspecific competition factor
γ	Activity of decomposer
A_i, B_i	Effect of the predator-prey relationship on population i (specified coefficient).
D_i, E_i	Effect of shortage of food on population i (specified coefficient)
N, P, K	Chemical elements

3 Models

3.1 Model Development Explanation and Sequence

3.1.1 Notes for Models

Before building all the models, here are some notes for all the models.

First, biomass is chosen over population density. This is because rice, as the primary producer in the agricultural ecosystem, has its population density artificially determined (i.e., it does not reproduce). Only the changes in its total biomass can reflect the developmental trend of the rice population.

Second, regarding interspecific competition, since the agricultural ecosystem is relatively simple compared to others, for the sake of model simplification, only interspecific competition between rice and weeds is considered.

Next, for the purpose of further simplifying the model, some parameters are combined. For example, the predation rate is incorporated into the predation coefficient of the prey species, denoted as A.

Finally, since consumers are in a natural reproductive state with a relatively fixed age structure, the average individual biomass can be assumed to be constant. Therefore, biomass is directly proportional to the number of individuals in the population.

It should be noted that at the start time, all the variations and coefficients mentioned above are positive real numbers.

3.1.2 Sequence

Based on the conditions outlined above, we will gradually develop the model. Given the numerous factors involved in the final model, we adopt a step-by-step approach, starting from the simplest and progressing to more complex structures.

Initially, we will construct Model I: LVLG Model, based on the Lotka-Volterra model and the Leslie-Gower model, under the simplest food web conditions. This model will consider only producers, primary consumers, and secondary consumers.

Subsequently, as the ecosystem gradually develops, we will build Model II. In this model, we will incorporate agricultural cycle (three crops per year), seasonal rotation (rainy and dry seasons), Gussian noise, utilization of chemicals (herbicides and pesticides) and multiple digestion delays.

Next, we will consider the re-colonization of species and develop a more complex food web to form Model III. In this model, we will retain the features of Model II while considering the intricate interactions between multiple species and between species and the environment.

Finally, after the agricultural ecosystem matures, we will introduce human agricultural decisions, such as the removal of pesticides and the intentional introduction of new populations, to construct Model IV.

3.2 Model I: LVLG Model

LVLG Model represents the combination of Lotka-Volterra and Leslie-Gower Model. Before establishing the model, We will first discuss the initial conditions of the model from the perspective of biological populations. The vertical structure of tropical forests is typically divided into several layers, including the canopy layer, understory, shrub layer, and ground layer. Each layer not only supports different plant species but also provides habitat and food sources for various animals.

Deforestation will severely disrupt the vertical structure of the tropical rainforest food web. Therefore, our model assumes that at the initial time point following deforestation, the vertical structure of the ecosystem above the ground retains only a portion of the ground layer. All populations that previously depended on the canopy, understory, and shrub layers for habitat and food sources will have migrated out of the ecosystem.

Based on this assumption, the agricultural ecosystem in its initial food web retains only the following populations: plants, insects, and birds. First, to preserve interspecific competition and align with reality as closely as possible, we divide plants into two populations: rice and weeds. Second, although insects may exhibit food preferences, for simplicity, we assume that there is only one insect species that feeds on both crops and weeds. Finally, based on the feeding habits of birds in real life, we assume that birds feed on both insects and the two plant species. Figure 5 presents a schematic diagram of the ecosystem, and Figure 6 shows the initial food web of the ecosystem.

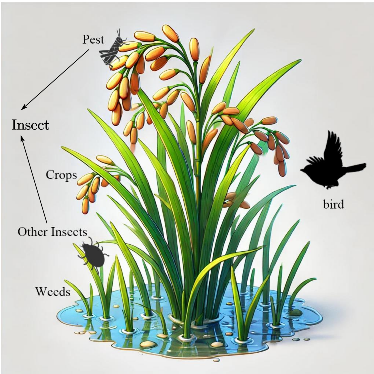

Figure 5: Schematic map for LGVG Model

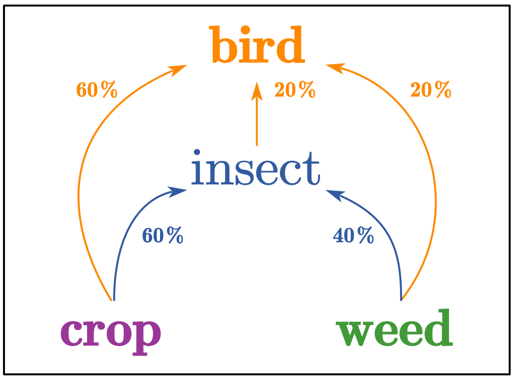

Figure 6: Food web in LGVG Model

Set February-when rice has just been planted-as the start time. Around the start time, in the simplest case, when climate, soil, and other conditions are favorable, only biological factors should be considered. If the population sizes of producers and primary consumers are used to describe the entire system, the Lotka-Volterra Model [3] and Leslie-Gower Model [4] can be applied as follows:

$$\begin{aligned}
\frac{\mathrm{d}W_{crp}}{\mathrm{d}t} &= r_{crp}W_{crp}\left(1-\frac{W_{crp}+\beta_{w\to c}W_{wd}}{\mathscr{K}_{crp}}\right)-\frac{A_{crp}W_{crp}W_{ins}}{1+B_{crp}W_{crp}}\\
\frac{\mathrm{d}W_{wd}}{\mathrm{d}t} &= r_{wd}W_{wd}\left(1-\frac{W_{wd}+\beta_{c\to w}W_{crp}}{\mathscr{K}_{wd}}\right)-\frac{A_{wd}W_{wd}W_{ins}}{1+B_{wd}W_{wd}}\\
\frac{\mathrm{d}W_{ins}}{\mathrm{d}t} &= r_{ins}W_{ins}\left[1-\frac{D_{ins}W_{ins}}{1+E_{ins}\left(0.6W_{crp}+0.4W_{wd}\right)}\right]-\frac{A_{ins}W_{ins}W_{bd}}{1+B_{ins}W_{ins}}\\
\frac{\mathrm{d}W_{bd}}{\mathrm{d}t} &= r_{bd}W_{bd}\left[1-\frac{D_{bd}W_{bd}}{1+E_{bd}(0.2W_{ins}+0.2W_{wd}+0.6W_{crp})}\right]
\end{aligned} \tag{1}$$

In general, these four equations introduce the natural growth term r_iW_i for population growth. The first two equations incorporate the interspecific competition term $\beta_{i\to j}W_i$, the larger this term, the more intense the interspecific competition, and the slower the biomass growth rate of population i.

The first three equations consider the effect of predation through the term(e.g. the first one) $\frac{A_{crp}W_{crp}W_{ins}}{1+B_{crp}W_{crp}}$.

The last two equations(e.g. the third one) include the term $\frac{D_{ins}W_{ins}}{1+E_{ins}(0.6W_{crp}+0.4W_{wd})}$, which represents biomass reduction due to food scarcity. In the denominator, one factor is weighted according to the predation ratio: the less food available, the more predators there are, resulting in a slower growth rate of the predator population.

3.3 Model II: CAGED Model

CAGED Model represents Conprehensive Agro-Ecosystem Dynamics Model, and it is the core model of the hole article. Model I is quite simple and aims to construct a basic short-term model. Considering the impact of long-term environmental factors, in order to better simulate the long-term evolutionary behavior of the ecosystem model, we will progressively introduce the effects of simplified agricultural cycles, seasonality, soil fertility, pollination, random factors and multiple digestion delays on the system dynamics model. Furthermore, we will consider the impact of chemical use, specifically the application of herbicides and pesticides, on the system, building upon this natural agricultural ecosystem model.

3.3.1 Agricultural Cycle

According to rice production in Indonesia(Figure 7), rice production in Southeast Asia follows a three-crop-per-year pattern. We assume that February, June, and October are the overlapping periods of two agricultural cycles (from the last post-harvest period to the new planting period).

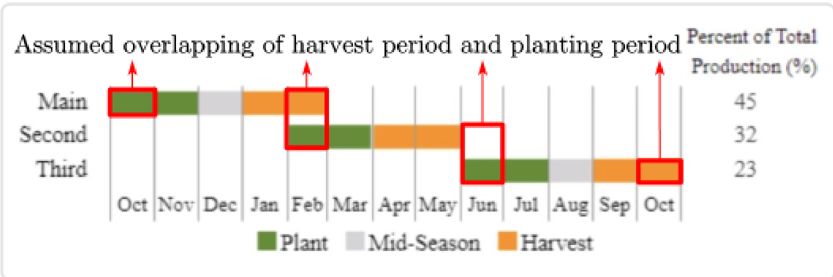

Figure 7: Overlapping Periods of Two Agricultural Cycles

During the overlapping period, the rice population re-enters the food web in the form of seeds after harvesting, starting a new agricultural cycle. The mature rice straw, as an agricultural byproduct, remains in the ecosystem after harvesting, and after being treated by methods such as burning or returning to the field, the rice biomass is decomposed and ingested by decomposers and insects, ultimately decreasing to zero.

Based on literature review [5, 6], the biomass fate of mature rice during each overlapping period can be uniformly described by Figure 8.

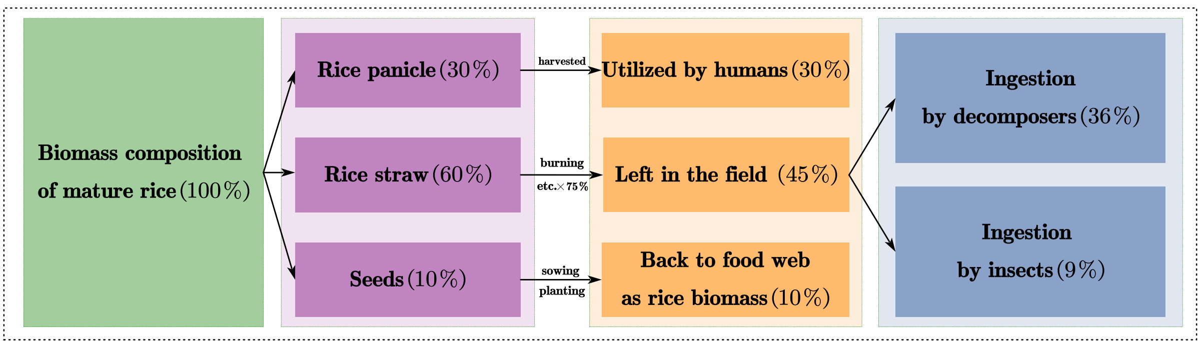

Figure 8: Biomass Fate of Mature Rice during Each Overlapping Period

Since decomposers' biomass is not considered in our food web model, we only analyze the impact of decomposed rice straw residue(the 36% part) on the producers—namely rice and weeds—in the new cycle. For further details, refer to the soil fertility section later in the paper.

For simplification of the model, the biomass change of the rice population during each overlapping period is represented by a biomass step function at specific time points in the mathematical model (i.e., the system of difference equations). Since $t = 0$ corresponds to the start of the first planting season, with one year assumed to have 52 weeks, and each week being a time step, based on the rice production pattern Figure 7, we define the step moments at week 0, week 17, and week 34 of each year. The biomass of rice at these times follows:

$$W_{crp}|_{t=n} = 0.1W_{crp}|_{t=n-1}, \quad n = 52k, 52k+17, 52k+34, \quad (year\, k \geqslant 0,\, week\, n \geqslant 1) \tag{2}$$

When considering the impact of rice straw on insect biomass, we treat rice straw as the 'prey' of insects and use the modified Lotka-Volterra (LG) predator-prey model to characterize this effect. At each step moment, rice straw enters the food web model with an initial biomass of $0.09W_{crp}$, and $r_{stw} = 0$. Thus, the rice straw-insect model is established as:

$$\frac{\mathrm{d}W_{stw}}{\mathrm{d}t} = \frac{A_{stw}W_{stw}W_{ins}}{1 + B_{stw}W_{stw}} \quad (t \neq n) \tag{3}$$

$$W_{stw}|_{t=n} = W_{stw}|_{t=n-1} + 0.09W_{crp}|_{t=n-1}, n = 52k, 52k+17, 52k+34, \quad (k \geqslant 0,\, n \geqslant 1) \tag{4}$$

The difference equation for insect biomass is modified as follows:

$$\frac{\mathrm{d}W_{ins}}{\mathrm{d}t} = r_{ins}W_{ins}\left[1 - \frac{D_{ins}W_{ins}}{1 + E_{ins}\left(0.6W_{crp} + 0.4W_{wd} + W_{stw}\right)}\right] - \frac{A_{ins}W_{ins}W_{bd}}{1 + B_{ins}W_{ins}} \tag{5}$$

3.3.2 Seasonality

The seasonal influences primarily include factors such as light, climate (temperature, precipitation), and biological habits, all of which have significant direct effects on both r and $\mathscr{K}$ within populations. Considering that many of these factors are difficult to quantify precisely, we set sinusoidal perturbations in the periodic parameter $p(T)$ as follows [7]:

$$p(t) = \bar{p}\left[1 + \epsilon \sin(\Omega t + \phi)\right] \tag{6}$$

Specifically, in the LV-LG model mentioned above, for population i, the values of r_i and K_i are defined as follows:

$$r_i = \bar{r}_i\left[1 + \epsilon_i \sin\left(\Omega_i t + \phi_i\right)\right] \tag{7}$$

$$\mathscr{K}_i = \bar{\mathscr{K}_i}\left[1 + \epsilon_i \sin\left(\Omega_i t + \phi_i'\right)\right], \quad (i = \text{crp or wd}) \tag{8}$$

$$D_i = \frac{\bar{D}_i'}{1 + \epsilon_i \sin\left(\Omega_i t + \phi_i'\right)}, \quad (i \neq \text{crp or wd}) \tag{9}$$

Where $\bar{r}_i$ and $\bar{\mathscr{K}_i}$ are the corresponding periodic means, which can be treated as constants; Ω_i is the seasonal fluctuation angular frequency, and $T = \frac{2\pi}{\Omega}$ is the seasonal fluctuation period; ϵ_i is the seasonal impact parameter. Since $r_i, \mathscr{K}_i \geqslant 0$, it follows that $-1 \leqslant \epsilon_i \leqslant 1$; ϕ_i and ϕ_i' are the phases, with $0 \leqslant \phi_i < 2\pi$, which characterize the asynchronous fluctuations of biomass in different species.

It can be mathematically proven that, after incorporating these variations, the LV-LG model system theoretically possesses non-trivial stable points when the parameters are within a certain range. When the system is near these points, the ecosystem can recover from small perturbations, reaching a dynamic ecological equilibrium.

3.3.3 Soil Fertility

Now, we introduce the effect of soil fertility on plant growth. i in the following statements represents rice or weed, j the other. For the sake of simplicity in the model, the influence of soil fertility on plant growth is divided into two main factors: the effect of carbon dioxide (CO_2) concentration and the concentration of inorganic salts absorbed by the plants.

Regarding the CO_2 concentration term, since the agricultural ecosystem is an open system and, in our context, can be considered to be surrounded by a vast and complex forest ecosystem, the impact of respiration from the components of the agricultural ecosystem on the atmospheric CO_2 concentration can be neglected. Thus, the CO_2 concentration is approximated as a constant, C_{CO_2}. Based on this, we introduce the soil fertility factor $\mu_{fri} = f(C_{isi})$. Soil fertility has a complex and profound effect on parameters such as the growth rate of population biomass, competition coefficients, and the maximum carrying capacity of the environment. An important consideration here is the effect of μ on the environmental maximum biomass carrying capacity, as shown below:

$$\frac{\mathrm{d}W_i}{\mathrm{d}t} = r_i W_i \left(1 - \frac{W_i + \beta_{j\to i} W_j}{\mathscr{K}_i \cdot \mu_{fri}}\right) - \frac{A_i W_i W_{ins}}{1 + B_i W_i}$$

For the inorganic salt concentration term, it is closely related to fertilizer concentration (which is influenced by straw and chemical fertilizers), decomposer activity, and the growth stage of the plant. Taking rice as an example: when rice reaches the seedling stage, its internal inorganic salt concentration is low, and the growth acceleration of the concentration is positive; during the tillering to jointing stage, the demand for inorganic salts increases rapidly, and the concentration reaches a turning point; during the booting to flowering stage, the rate of increase in inorganic salt concentration slows down until it reaches its maximum; during the milk-ripe and yellow-ripe stages, the absorption of inorganic salts decreases gradually, and the concentration drops. [?]

We use a Gaussian-like probability density function to fit the trend of the inorganic salt concentration in the plant over each agricultural cycle, given by:

$$C_{isi}(t) = \alpha_{isi} e^{-\frac{(t-T_{mc})^2}{\sigma_{isi}}}$$

where T represents the time at which the concentration of inorganic salts in rice or weeds is at its maximum during a cycle; the remaining two parameters correspond to the model constants for rice or weeds, and are determined by fertilizer concentration (from both chemical fertilizers and straw), decomposer activity, and the plant's growth stage.

Again, for the sake of model simplification, we assume $\mu_{fri} = \xi_i C_{isi}$.

3.3.4 Random Factors

Considering the influence of random factors in nature, we introduce Gaussian white noise σ_i for each population.

The probability density function of the Gaussian white noise $\sigma_i(t) = x$ is given by:

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{x^2}{2\sigma^2}} \tag{10}$$

which means that σ_i follows a normal distribution with a mean of 0.

Our generation method is as follows:

- Generate two distinct random functions $U_1(t)$ and $U_2(t)$ within the interval $[0, 1]$;
- Take $\eta(t) = -\sqrt{-2\ln U_1(t)} \cdot \cos(2\pi U_2(t))$, which gives $\eta(t)$ as the Gaussian white noise function.

The noise corresponding to different species in the equations is shown in Figure 9.

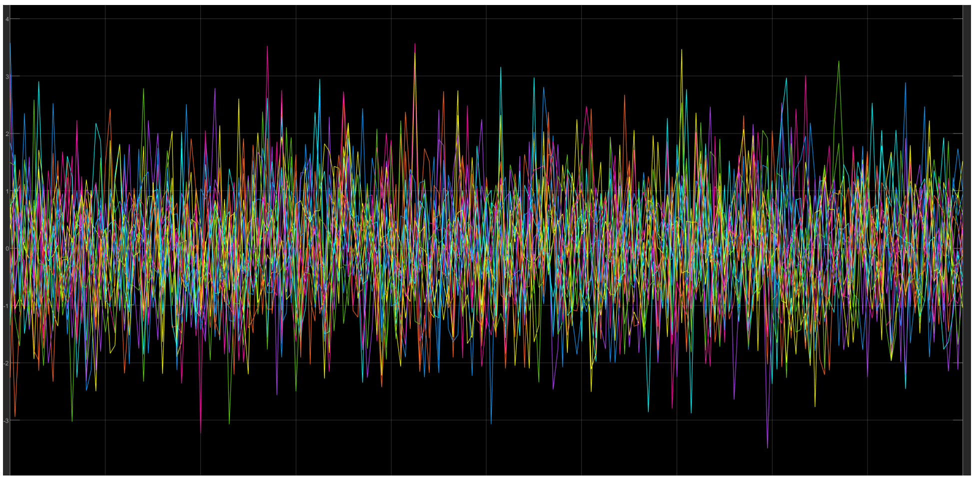

Figure 9: Gussian Noises of Each Population

3.3.5 Chemical Use

For herbicides, considering that the application times of herbicides during rice cultivation are primarily before sowing, at the seedling stage, and at the tillering stage, we assume that herbicides are applied three times during an agricultural cycle, with the application occurring at weeks 0, 3, and 8. The herbicide concentration is proportional to the current weed biomass. Since the application frequency is relatively low, we can ignore the specific negative effects of herbicides on rice (any minor negative effects can be covered by the random process described in random factors).

We consider weeds as the "prey" of the herbicides. Similarly to the straw-insect model mentioned earlier, we can use the modified Lotka-Volterra predator-prey model, where $r_n \equiv 0$.

For the degradation of the herbicide, we can use an exponential decay model. Thus, we establish the weed-herbicide model as follows:

$$C_{hc}|_{t=m} = C_{hc}|_{t=m-1} + \alpha_{uh} W_{wd}|_{t=m}, \tag{11}$$

$$\frac{dW_{wd}}{dt} = r_{wd} W_{wd} \left(1 - \frac{W_{wd} + \beta_{c\to w} W_{crp}}{\mathscr{K}_{wd}}\right) - \frac{A_{wd} W_{wd} W_{ins}}{1 + \beta_{wd} W_{wd}} - \frac{A_{hc} W_{wd} C_{hc}}{1 + B_{hc} W_{wd}}, \tag{12}$$

$$\frac{dC_{hc}}{dt} = -\alpha_{dh} C_{hc}. \tag{13}$$

For insecticides, we can establish an insect-insecticide model that follows a similar mechanism to the weed-herbicide model. We set the insecticide application times during an agricultural cycle to be at week 4, week 8, and week 12. Unlike the weed-herbicide model, since there are pests that primarily feed on rice and other insects that primarily feed on weeds, and the insecticide has a much more significant effect on eliminating pests than on eliminating other insects, the food composition of insects as a whole changes after insecticide application. Specifically, the proportion of rice in their diet decreases significantly, while the proportion of weeds increases significantly. Based on this, we introduce the parameter λ_{pc}, which is dominated by the insecticide concentration, to describe the impact of the insecticide on the insect food composition as follows:

$$C_{pc}|_{t=m} = C_{pc}|_{t=m-1} + \alpha_{up} W_{ins}|_{t=m}, \tag{14}$$

$$\begin{aligned}\frac{dW_{ins}}{dt} = r_{ins} W_{ins} &\left(1 - \frac{D_{ins} W_{ins}}{1 + E_{ins}\left[(0.6 - \lambda_{pc}) W_{crp} + (0.4 + \lambda_{prc}) W_{wd}\right]}\right) \\ &- \frac{A_{ins} W_{ins} W_{bd}}{1 + \beta_{ins} W_{ins}} - \frac{A_{pc} W_{ins} C_{pc}}{1 + B_{pc} W_{ins}},\end{aligned} \tag{15}$$

$$\frac{dC_{hc}}{dt} = -\alpha_{dp} C_{hc}. \tag{16}$$

3.3.6 Multiple Digestion Delay

Due to the time required for energy flow, the impacts of different predation relationships in the food web on system dynamics are actually asynchronous [4]. Considering this asynchrony, we introduce multiple digestion delays corresponding to the digestion periods of the consumer-eat-producer and predator-eat-consumer interactions, referred to as the producer digestion delay (PDD) and consumer digestion delay (CDD), respectively.

Mathematically, the PDD and CDD influence the food scarcity term L_i in the differential equation corresponding to the consumer population i:

$$L_i = -r_i \frac{D_i W_i^2}{1 + E_i \cdot \Sigma_{\text{food}} \gamma_i W_{i_j}} \tag{17}$$

where $\Sigma_{\text{food}}\gamma_i W_{i_j}$ is the weighted sum of the biomass of the populations preyed upon by i, weighted by the predation ratio. After considering the delay, this term is modified as follows and incorporated into the original differential equation:

$$L_i' = -\frac{r_i}{t-\tau_i} \cdot \frac{D_i W_i^2}{1 + E_i \cdot \Sigma_{\text{food}}\gamma_i W_{i_j}} \tag{18}$$

where τ_i is the digestion delay factor of population i, and D_i, E_i are the corresponding environmental parameters for population i.

3.4 CAGED Model Considering Restatement

As the ecosystem gradually matures, previously existing populations will re-enter the system. We assume that when the biomass of the prey species reaches a certain threshold (a tunable parameter), the species will migrate into the ecosystem, forming a more complex food web. In our model, we only consider the migration of frogs and snakes. After their migration, the previously constructed equations are applicable to describe their biomass dynamics (assuming they are not affected by chemicals).

3.5 Model III: SAGED Model

SAGED Model represents sustainable Agro-Ecosystem Dynamics Model. When the food web becomes sufficiently complex, humans can begin making agricultural decisions. The agricultural decision considered in our model involves removing herbicides and insecticides, while introducing bats and ducks.

Bats play a role in promoting pollination; thus, the pollination factor becomes:

$$f_{pd} = \begin{cases} 1, & \text{non-pollinating period,} \\ f_0 + c_1 W_{ins} + c_2 W_{bt}, & \text{pollinating period.} \end{cases}$$

Besides this, the modified model only requires the removal of chemicals from the CAGED model, and the introduction of two new populations to form the ultimate food web.

4 Appication of the Models

The process of model establishment has been thoroughly presented in the previous subsection. In this subsection, we will discuss the application of the model.

4.1 Selection of Parameters

After reviewing the literature and aligning the parameters with their real-world significance, we have determined a series of parameters. Due to the large number of parameters, we will only present the table for the main ones:

Table 2: Parameters

Symbols	Description
123	123

All of the following models will apply these parameters.

4.2 Situation 1: No Agricultural Activities

This scenario will serve as a control group for familiarizing with the model. We consider a situation without chemicals, sowing, or harvesting, but with the migration of other species (since the migration of other species is an inevitable result of ecosystem maturation). In this situation, we obtained the following population dynamics curve.

From the figure, we can observe that under Scenario 1, the ecosystem develops normally, but rice cannot survive in the long term, meaning the system cannot evolve into an agricultural ecosystem. This indicates that the competitive ability of rice against weeds and its resistance to pests are relatively weak, preventing it from sustainably existing in the ecosystem without human intervention. This result is consistent with real-world observations and serves as the first validation of the model's accuracy.

4.3 Sutuation 2: Chemicals or Green Agriculture Solutions Used

In the discussion of Scenario 2, we consider a realistic situation. A farmer has just cleared a forest to plant rice. Initially, he uses chemicals such as herbicides and pesticides to suppress weeds and pests as the ecosystem gradually develops. When the ecosystem matures to a certain extent, some species that had migrated from the forest ecosystem return, enriching the food web of the farmland ecosystem. After further development, the ecosystem becomes relatively stable, and the farmer stops using herbicides and pesticides, instead turning to a green agriculture solution by introducing ducks and bats into the system. Specifically:

- The physiology of ducks prevents them from eating rice, but they can consume weeds and pests.
- Ducks are introduced two weeks after each sowing season and are harvested simultaneously with rice at the end of the season.
- Bats are introduced all at once and serve as both pollinators and insect predators.

When the system evolved mature, the final food web of traditional farming mode and green farming mode are shown in Figure 10 and Figure 11 respectively.

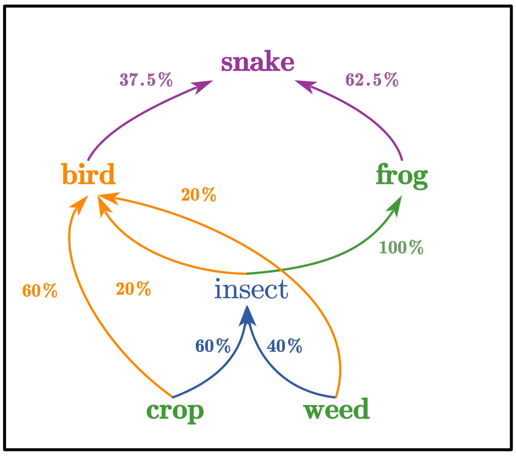

Figure 10: Traditional Mode

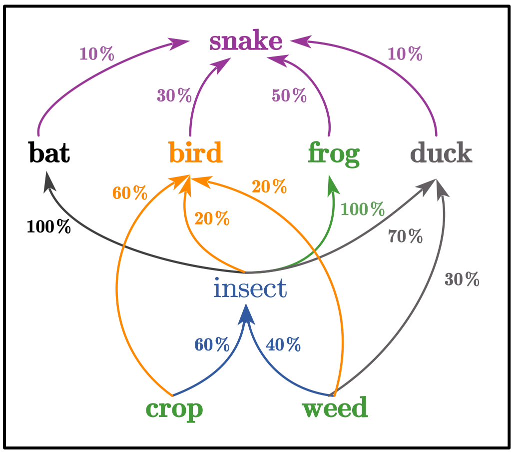

Figure 11: Green Mode

We will focus on comparing the succession of the ecosystem in the scenarios where humans use chemicals (conventional scenario) and where humans use green agriculture solutions (target scenario). In both cases, the ecosystem is unstable during the initial phase, so we only show the dynamic behavior of the ecosystem after it reaches a stable state.

When chemicals are used, The ecosystem dynamics are as shown in the figure below:

We find that compared to Scenario 1, human activity can effectively control weed growth and suppress pests, allowing for continuous rice harvests and forming a viable agricultural system.

When green agriculture solutions are used, the ecosystem dynamics are as shown in the figure below:

We find that, similar to Scenario 1, green agriculture solutions can also effectively control weed growth and suppress pests, allowing for continuous rice harvests and forming a viable agricultural system.

To compare the differences between chemical use and green agriculture, we attempt to stop using chemicals after achieving stability (without introducing biological control), and obtain the following ecosystem dynamics:

We immediately observe that, in the absence of green agriculture solutions, once chemicals are discontinued, weeds and pests rapidly proliferate and compete with rice. The system's biomass fluctuates significantly, with low stability. However, if green agriculture solutions are applied, even without chemicals, weeds and pests are effectively controlled, the system's biomass fluctuations are minimal, and the system is highly stable. This is because more components have been introduced, making the food web more complex and the biodiversity stronger. When one species is at a disadvantage, other species can temporarily take over its ecological niche, thereby enhancing the system's stability. This aligns well with modern ecological theory.

In summary, when the model is applied to this scenario, it closely matches real-world conditions, proving the model's versatility and accuracy.

5 Sensitivity Analysis

6 Evaluation of the Model

6.1 Strengths

6.2 Weaknesses

7 Suggestions

References

[1] World Bank Group. Indonesia temperature. Accessed: 2025-1-25, at `https://climateknowledgeportal.worldbank.org/country/indonesia/climate-data-historica`.

[2] U.S. Department of Agriculture. Indonesia rice. Accessed: 2025-1-26, at `https://ipad.fas.usda.gov/countrysummary/Default.aspx?id=ID&crop=Rice`.

[3] Peter J Wangersky. Lotka-volterra population models. *Annual Review of Ecology and Systematics*, 9:189–218, 1978.

[4] Lei Guo, Zi-Gen Song, and Jian Xu. Complex dynamics in the leslie–gower type of the food chain system with multiple delays. *Communications in Nonlinear Science and Numerical Simulation*, 19(8):2850–2865, 2014.

[5] Viktoria Oliver, Nicole Cochrane, Julia Magnusson, Erika Brachi, Stefano Monaco, Andrea Volante, Brigitte Courtois, Giampiero Vale, Adam Price, and Yit Arn Teh. Effects of water management and cultivar on carbon dynamics, plant productivity and biomass allocation in european rice systems. *Science of The Total Environment*, 685:1139–1151, 2019.

[6] MD Summers, BM Jenkins, PR Hyde, JF Williams, RG Mutters, SC Scardacci, and MW Hair. Biomass production and allocation in rice with implications for straw harvesting and utilization. *Biomass and Bioenergy*, 24(3):163–173, 2003.

[7] Sunita Gakkhar and Brahampal Singh. Dynamics of modified leslie–gower-type prey–predator model with seasonally varying parameters. *Chaos, Solitons and Fractals*, 27(5):1239–1255, 2006.