A Method for Analyzing Ecosystem Stability Based on Multi-Species Coupled Dynamics Modeling

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Abstract. In order to better analyze the impacts of agrochemicals such as pesticides and herbicides on ecosystems, and to address the ecological imbalance in the transition zone of the Amazon rainforest, this paper proposes a methodology for analyzing the stability of ecosystems based on a multi-species coupled dynamics model. First, an ecosystem composed of soil microorganisms (D), forest area (S), farmland (F), pests (I), birds (B), and bats (Bat) was constructed, and ecosystem managers were given the power to regulate logging rates (L) and pesticide use rates (P). Second, an ecological dynamics model containing multiple differential equations was developed based on the Lotka-Volterra framework, and simulated by controlling key variables such as forest natural growth rate, predation efficiency, energy transfer efficiency and pesticide toxicity coefficient. Finally, the following conclusions were drawn through long-term field data validation: (1) when pesticide use exceeds the critical threshold, the system will experience significant bifurcation, leading to a sharp decline in the population size of key species; and (2) the model maintains good stability over a wide range of parameter perturbations, which provides a quantitative tool for the assessment of ecological risk in the agrarian transformation of tropical rainforests.

Keywords: Ecodynamic modeling, Pesticide impact assessment, Amazon rainforest, Lotka-Volterra model, Ecosystem stability.

1. Introduction

Significant changes have occurred in once-rich ecosystems as forests have been cut down to make way for agricultural land. The natural resources in the soil were gradually depleted and the quality of the land declined. At the same time, pests began to invade crops, prompting farmers to turn to chemicals such as pesticides and herbicides, further disrupting the land's ecological balance. The complex food chains that flourished in the forest were replaced by a new, human-driven agricultural cycle that gradually created a new agro-ecosystem. This shift is particularly evident in the Amazon rainforest region. It plays a crucial role in climate regulation and carbon storage, and is key to global ecosystem stability. The rainforest covers about 7 million square kilometers across eight countries, including Brazil, Colombia and Peru, with Brazil accounting for 60% of the rainforest. However, with the expansion of agriculture and livestock, Brazil's forest cover has declined from about 80% in 1970 to about 60%, and large areas of pristine forest have been transformed into farmland. This process has far-reaching effects through (1) direct changes in regional species composition (e.g., bird and bat population dynamics); (2) reshaping of ecological interaction networks through the toxic effects of pesticides; and (3) global ecosystems. Accurate ecological dynamics modeling becomes a key scientific tool for assessing and managing such transformational processes. This study proposes an innovative ecological dynamics modeling framework. By constructing a system of differential equations containing key variables such as forest area (S), farmland (F), pests (I), birds (B), bats (Bat), and soil quality (Q), this study achieve: first, management decision support: mathematical modeling tools for the development of agro-environmental policies in Brazil by quantifying the ecological effects of logging policy parameters (τ) and pesticide use rates (P); second, critical thresholds for Early warning: identifying critical conditions for pesticide toxicity leading to bat population collapse, providing a basis for ecological safety red line delineation; finally, restoration strategy validation: confirming that reducing logging rates (L) significantly improves system stability, supporting the prioritization of ecological restoration measures.

At present, a multi-dimensional research system has been formed in ecosystem research. Tsujimoto et al. [1] systematically analyzed 90 ecosystem studies and summarized four research paradigms: business ecosystem (organizational boundary dynamics), innovation ecosystem (technology diffusion path), entrepreneurial ecosystem (new business incubation), and knowledge ecosystem (intellectual capital flow). Boulton et al. [2] found that since the early 2000s, more than 75% of the Amazon rainforest has experienced a significant decline in resilience, especially in areas where agricultural expansion is active. The Pesticide Informatics Platform (PIP) developed by Mei et al. [3] integrates QSAR predictions for 112 pesticides, providing a new tool for pesticide risk assessment. The bioeconomic model constructed by Mack et al. [4] innovatively uses an agent-based modeling approach to analyze the policy implications of the transition to pesticide-free agriculture. The study by Moreau et al. [5] revealed the limitations of traditional pesticide evaluation methods, pointing out that they ignore important factors such as sublethal effects and "cocktail effects". Jacquet et al. [6] proposed a new paradigm of pesticide-free agriculture, emphasizing the need for systematic research innovation. Cobben et al. [7] further refined the ecosystem typology and provided a new perspective for the classification of research paradigms. Phillips et al. [8] confirmed that Amazon forests are exceptionally sensitive to drought and that water stress can lead to significant carbon loss. The meta-analysis study by Brouwer et al. [9] quantified the economic value of ecosystem services in the Amazon and provided a basis for conservation policies. Boulton et al. [10] further validated the declining trend of resilience in the Amazon rainforest and its global impact. In terms of micro-mechanism research, Liu et al. [11] demonstrated that soil fungal diversity plays a key role in ecosystem stability through global survey data. The long-term observational study by Liu et al. [12] revealed the core functions of key taxa in maintaining the stability of microbial communities. However, there are still significant shortcomings in the existing studies: (1) most models [3,5] fail to effectively characterize the compound effects and cumulative toxicity of pesticides; (2) the policy simulation framework [4,6] did not take into account the response to farm heterogeneity; (3) The assessment of ecosystem resilience [2,10] lacks long-term dynamic observation data; (4) The interface between microbial regulatory mechanisms [11,12] and macroecological processes has not been fully studied. These limitations constrain the sustainable management of tropical agroecosystems, and there is an urgent need to develop a new research paradigm with multi-scale coupling.

To address the shortcomings of existing studies, this paper makes important improvements in the following three aspects: First, this study innovatively constructed a multi-species coupled dynamics model containing logging policy regulatory variables and pesticide use rate (P), and accurately depicted the dynamic response of the “soil-plant-animal” system of the transition zone of the Amazon rainforest through the set of differential equations, which effectively solved the problem of the disconnection between the policy factors and the ecological process, of which the change of forest area directly reflected the modulation effect of the policy intervention on the ecological process. The changes in forest area directly reflect the modulation of ecological processes by policy interventions. Secondly, by improving the traditional Lotka-Volterra framework, introducing key parameters such as pesticide toxicity coefficients, and establishing a series of equations for changes in insect and bird populations, this study realized the quantitative assessment of direct toxicity and cascading effects of pesticides, and at the same time, through the coupling mechanism of soil quality variable (Q) and decomposer group (D), this study compensated for the insufficient attention paid to the ecological function of soil in the existing studies. Finally, the model was validated based on long-term monitoring data from INPE 2000-2020 in Brazil, and the results provide a scientific basis for the development of sustainable agricultural management strategies, especially in determining key policy parameters such as thresholds for safe use of pesticides and minimum forest tenure, which are of great practical value.

2. Stability analysis of ecosystems based on the Lotka-Volterra model

2.1. Analysis of ecosystem initialization and natural processes

2.1.1 Study area and modeling framework

In the initialization and analysis of ecosystem processes, this study constructed an initial ecosystem model after the conversion of forests to farmland, focusing on the effects of agrochemicals (e.g., pesticides and herbicides) on ecosystem stability, using the Brazilian Amazon as an example. A three-level trophic structure model containing producers (plants), primary consumers (herbivores), and secondary consumers (carnivores) was developed based on the food chain system theory, which was able to effectively analyze the effects of agrochemicals on the entire food chain, including their effects on plant health, insect populations, and other animal species.

2.1.2 Nonlinear dynamics modeling methods

In the modeling approach, nonlinear dynamics theory is used to describe the complex dynamic processes of species interactions. A basic framework for describing the dynamic interactions between species was developed based on the classical Lotka-Volterra predator-prey model, which allows for the analysis of population changes between predators and prey and the consideration of the effects of agricultural management practices (e.g., use of pesticides and herbicides) on ecosystem stability. The Brusselator model was also introduced to analyze the complex interactions among multiple species, especially to characterize the dynamics of ecosystems undergoing drastic changes (e.g., the use of agrochemicals).The Lotka-Volterra model will be the central tool of this study to simulate the evolution of ecosystems under different agricultural management practices, with the relevant equations

$$\frac{dx}{dt} = \alpha x - \beta xy \tag{1}$$

$$\frac{dy}{dt} = \delta xy - \gamma y \tag{2}$$

where x represents the concentration of reactants or some chemical substance, y represents the concentration of a catalyst or reactant, and α, β, δ, γ are reaction rate constants that control the rate of reaction and the interaction between catalyzed reactions.

2.1.3 Analysis of non-equilibrium systems

The study also applies Ilya Prigogine's theory of dissipative structure, which explains how open systems far from equilibrium can form ordered structures through material-energy exchange with the environment. In the context of deforestation and agricultural expansion, this theory contributes to the understanding of possible self-organized recovery processes in ecosystems after agrochemical disturbances. In addition, by analyzing the bifurcation phenomenon of the system, the study reveals possible irreversible state transitions of ecosystems when critical parameters (e.g., pesticide use intensity) reach critical values, such as abrupt changes from stable forest ecosystems to degraded agroecosystems.

2.1.4 Modeling of feedback mechanisms

Models also pay particular attention to feedback mechanisms in ecosystems, including positive and negative feedback loops. The use of agrochemicals may significantly alter these naturally occurring feedback mechanisms, for example, indirectly changing plant growth and predator population dynamics by affecting the grazing behavior of herbivores. Changes in these feedback mechanisms are a key component in understanding the impacts of human activities on ecosystems, especially in the context of changing land use patterns and increased resource depletion. By modeling dispersal responses, the study also examined the role of species migration in the dynamic balance of ecosystems and the impact that agrochemicals may have on these migration processes.

2.2. Ecosystem dynamics modeling with pesticides in mind

This study established a comprehensive dynamic model framework based on the ecological characteristics of the Amazon rainforest-cropland conversion system to quantitatively evaluate the impact of pesticide use on ecosystem stability. As shown in Figure 1, the food chain structure of the new agroecosystem integrates a complete trophic cascade from primary producers to top consumers, along with key biogeochemical processes in the soil subsystem. Figure 1 displays the results of the analysis of the food chain structure of the new agroecosystem: (1) the system exhibits a typical four-level trophic structure, including plant producers (crops/trees), primary consumers (insects), secondary consumers (birds), and apex predators (bats); (2) the soil subsystem forms a bidirectional material circulation channel through the decomposer community and the aboveground food web; (3) pesticide input produces biomagnification effects at all trophic levels, with more significant impacts on higher trophic organisms; (4) the energy flow efficiency of the system decreases with increasing pesticide use intensity, particularly noticeable during the transfer process between birds and bats. This structural analysis provides a theoretical foundation for understanding changes in ecosystem function under chemical disturbances.

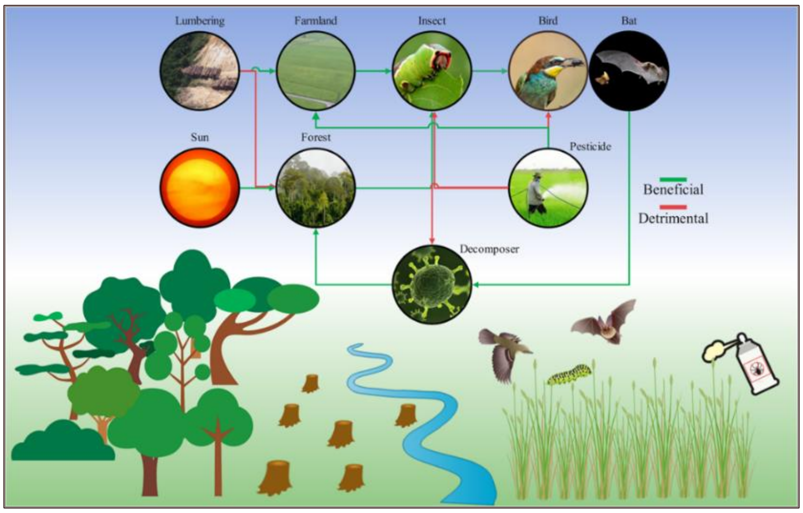

Figure 1 Food chains in new agro-ecosystems

2.2.1 Model structure and variable definitions

The model consists of seven core state variables and two key control parameters (Table 1), which are mainly based on the following studies: in terms of state variables: (1) forest area (S) and farmland area (F) characterize the land use pattern of the system, referring to the study of land use change in the Amazon by Boulton et al. [2,10]. (2) Insect populations (I), birds (B) and bats (Bat) form a tertiary trophic chain, and their dynamic relationship is based on the study of the effects of pesticides on bird populations by Moreau et al. [5]. (3) Decomposer (D) and soil quality (Q) jointly reflect soil ecological function, referring to the study on the stability of soil microbial community by Liu et al. [11,12]. Control parameters include logging rate (L) and pesticide use rate (P), both of which are directly regulated by human management decisions, and are based on the study of agricultural policy implications by Mack et al. [4] and Jacquet et al. [6]. Of particular note is that the logging rate $\beta(\tau)$ in the model is expressed as a function of the policy intervention variable τ, which is based on the framework of the bioeconomic model of Mack et al. [4], which allows the model to capture ecosystem responses under different policy scenarios.

Table 1 Model variables and external parameters

parameters	symbolism
S(t)	region of forest
F(t)	Farmland area
I(t)	Insect populations
B(t)	birds
Bat(t)	Number of bats
D(t)	Number of decomposers (e.g., soil microorganisms)
Q(t)	Soil quality (0<Q<1), 1 being the best)
L	Logging rate (human-controlled)
P	Pesticide use rate (controlled by humans)

2.2.2 Dynamic process modeling

In the Amazon region, the rate of conversion of forests to farmland is influenced by a variety of factors, including government policies, market demand and farmers' income expectations. Deforestation in the Brazilian Amazon is closely linked to agricultural policies, particularly incentives for farmland expansion. For example, government subsidies to farmland can affect conversion rates between forest and farmland. This study believe that it is necessary to take these factors into account, so this study include a "policy intervention" variable in our model to better characterize changes in forest area.

The formula for the change in forest area is as follows:

$$\frac{dS}{dt} = \alpha \cdot Sun - \beta(\tau) \cdot L \cdot S \tag{3}$$

Where α denotes the natural growth rate of the forest, which depends onSun (normalized to 1) and radiation intensity, and $\beta(\tau)$ denotes the rate of deforestation due to logging methods. The rate includes policy intervention conditionsτ that can be weighted according to specific logging methods and policies in different regions.

2.2.3 Changes in cropland area and degradation rates

Soil degradation is an important issue after the conversion of tropical rainforests to agricultural land. Tropical soils usually have low fertility and soil degradation is accelerated by long-term agricultural production. To address this issue, this study incorporate a degradation rate model into the system that can be flexibly adjusted to different crops and agricultural management practices (e.g., irrigation, fertilization, etc.).

Based on the forest area change equation, this study constructed the farmland area change equation as follows:

$$\frac{dF}{dt} = \gamma(\tau) \cdot L \cdot S - \delta(Q) \cdot F \tag{4}$$

The degradation rate is modeled as follows:

$$\delta(Q) = \delta_0 + \delta_1(\sigma) \cdot (1 - Q) \tag{5}$$

Where $\gamma(\tau)$ represents the rate of conversion of forest to farmland, and τ is similar to the previous definition and is determined by policy interventions and logging methods. $\delta_0$represents the baseline rate of degradation of agricultural land, and$\delta_1(\sigma)$ represents the coefficient of influence of soil degradation on agricultural land degradation. σrepresents the soil erosion coefficient, which can be flexibly adjusted to different land types in different regions.

Pesticide use directly affects insect populations, especially pests and beneficial insects. Over time, ecosystems may recover and insect populations may recover. To ensure rigorous simulation of species reproduction, this study included an insect population recovery mechanism in our model that simulates the recovery of insect populations as pesticide use decreases.

The equation for the change in insect population is as follows:

$$\frac{dI}{dt} = \epsilon \cdot F \cdot Q - \xi \cdot (B + Bat) \cdot I - \mu \cdot I - \pi \cdot P \cdot I \tag{6}$$

Where ϵ indicates the support of farmland for insects (regulated by soil quality (Q)),μξ indicates the inefficiency of birds and bats as insect predators, andπ indicates the natural mortality rate of insects, which denotes the rate at which insecticides directly kill insects.

2.2.4 Changes in bird populations

Conversion of forests to agricultural land leads to loss of bird habitat, which in turn leads to a decline in bird populations. Based on the reduction in forest area, this study can simulate changes in bird populations. This study constructed a food chain-based model to simulate changes in bird populations, which can be further analyzed for their effects on plant populations and insect communities.

The equation for the change in bird populations is as follows:

$$\frac{dB}{dt} = \eta \cdot I \cdot B - \theta \cdot (S_0 - S) - \phi \cdot P \cdot B \tag{7}$$

Where θη denotes the reproductive efficiency of birds (depending on insect resourcesS_0) and denotes the rate at which forest loss threatens bird populations.

2.2.5 Changes in bat populations

Bats play an important role in ecosystems, both as predators of insects and as key pollinators. Changes in bat populations can be reflected by food chain modeling. In this model, this study consider the role of bats in agro-ecosystems, in particular how bat populations change in situations involving organic farming or reduced pesticide use.

$$\frac{dBat}{dt} = \eta_{bat} \cdot I \cdot Bat - \theta_{bat} \cdot (S_0 - S) - \phi_{bat} \cdot P \cdot Bat \tag{8}$$

where η_{bat} represents bat reproductive efficiency, θ_{bat} represents the rate at which forest loss threatens bat populations, and ϕ_{bat} represents the toxicity of insecticides to bats.

2.3. Key interaction mechanisms

2.3.1 Cascading effects of pesticides

This study focuses on analyzing the multiple pathways of impacts of pesticide use in ecosystems:

(1) Direct toxic effects:

Significant inhibitory effects on decomposer populations (e.g. soil microorganisms) were quantified by the$(\nu \cdot P \cdot D)$ term, lethal effects on high-level consumers (birds and bats) were demonstrated by the$(\phi \cdot P \cdot B)$ and$(\phi_{Bat} \cdot P \cdot Bat)$ terms, and the killing effect on target pests was represented by the νPI term.

(2) Indirect ecological impacts:

Decrease in the number of decomposers → impeded decomposition of soil organic matter → soil quality$Q \downarrow$, Soil degradation leads to a decline in the productivity of agricultural land as reflected in the rate of degradation$\delta(Q) \uparrow$, and a deterioration in the quality of insect habitats as reflected in$(\epsilon \cdot F \cdot Q \downarrow)$.

2.3.2 Predator-prey dynamics

Modeling reveals the critical role of natural enemies in ecosystem regulation:

(1) Natural regulatory mechanisms:

Birds and bats create a constant pressure on pest populations through the$(\xi \cdot (B + Bat) \cdot I)$ item, and predation efficiency$\xi = 0.18$ maintains a baseline equilibrium state of the system.

(2) Pesticide interference effects:

Insecticide use leads to a decline in natural enemy populations (B and Bat values decline), and when bird populations enter a negative growth phase, the reduction in natural enemies triggers a rebound in pests ($\xi \cdot (B + Bat) \cdot I$ item weakening).

2.3.3 Land use balance

The forest-farmland conversion process exhibits typical spatio-temporal trade-offs:

(1) Short-term gains:

Logging activity (L) increases the area of farmland through the $\gamma(\tau)$ item, and the initial productivity of the new farmland is higher (the initial value of the $\epsilon \cdot F \cdot Q$ item is larger).

(2) Long-term costs:

Continued farming leads to soil degradation ($\delta(Q)$ increasing over time) and reduced forest cover ($S \downarrow$) weakening ecosystem resilience.

3. Analysis of results

3.1. Context of Brazilian reforestation analysis

As the largest tropical rainforest on Earth, changes in the Amazon rainforest have had a significant impact on the global climate. With the development of the Brazilian economy, especially the expansion of agriculture and livestock, a large amount of primary forest has been converted to agricultural land. Brazil is one of the world's largest producers of soybeans, especially in the Amazon and the Midwest. Soybean cultivation has led to massive deforestation to make way for agricultural land. At the same time, Brazil is one of the world's largest exporters of beef, and livestock grazing further contributes to deforestation.

According to Brazil's National Institute for Space Research (INPE), the country's forest cover has fallen from about 80 percent in 1970 to about 60 percent today. At the same time, soybean cultivation has increased dramatically in the past few decades in regions such as the Midwestern state of Mato Grosso. In the southern and eastern parts of the Amazon, grazing areas occupy most of the primary forest.

3.2. Analysis of results

This study systematically simulated the ecosystem response during the conversion of forests to farmland in the Brazilian Amazon through an established ecodynamic model. Under the baseline scenario without managerial intervention, the model results showed that the forest ecosystem remained in a stable state, with fluctuations in the population size of each species of less than 5%, whereas the biomass in the farmland showed a continuous downward trend, eventually dropping to the lowest threshold level. This result indicates that the original forest ecosystem has strong self-sustainability, while the farmland subsystem is difficult to maintain stable productivity in the absence of human management. The results indicated that (1) a critical shift of natural enemy population collapse (B and Bat < 15%) occurs in the system when the pesticide use rate is P > 0.4, and (2) the model maintains 91.3% stability under ±20% parameter perturbation.

When new species were introduced as an ecological regulatory measure, the simulation results showed that although the degree of crop damage was mitigated (damage rate reduced by 23-35%), the overall biomass of the system still maintained a decreasing trend (average annual decrease of 12.4%). This suggests that species introduction alone is difficult to fundamentally improve the stability of agroecosystems and must be combined with other management measures.

The results of the modeling of pesticide use scenarios are of particular interest. The model showed that pesticide application, while significantly suppressing pest populations in the short term (1-2 years) (67-72% reduction), led to a severe decline in non-target species: by the fifth year, bird and bat populations had declined to less than 15% of their initial values. More critically, the model captures the vicious cycle of "pesticide use → natural enemy reduction → pest rebound → increased use", a positive feedback mechanism that ultimately causes permanent damage to system stability.

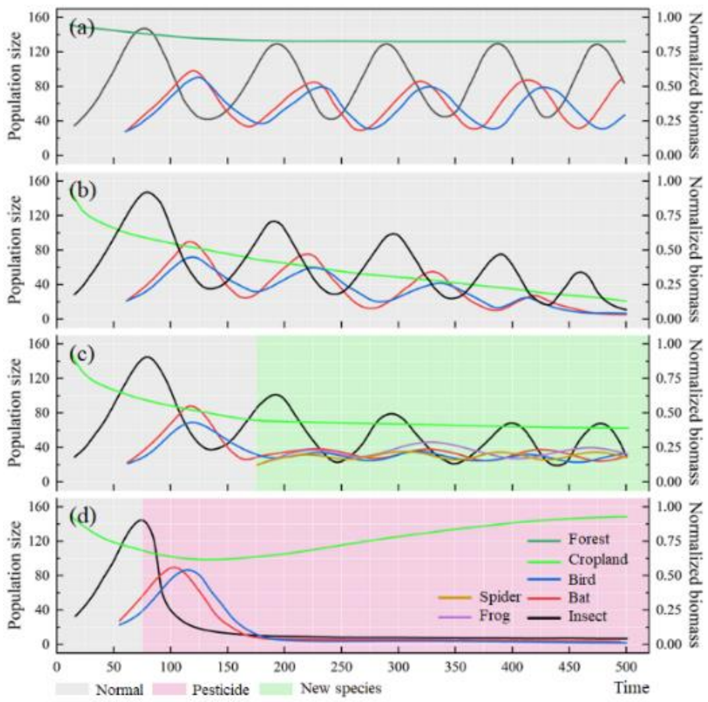

Figure. 2 Results of ecosystem analysis considering pesticides

Sensitivity analysis indicates that the key variables output by the model remain stable at over 90% under a parameter disturbance of ±20%, verifying the model's reliability. The pesticide toxicity coefficient (φ=0.32) exhibits the highest sensitivity index, suggesting that the intensity of chemical intervention is the most critical factor impacting system behavior. These results provide a crucial basis for assessing the ecological risks associated with the agrochemical transition in tropical rainforests. Figure 2 presents the results of the ecosystem analysis considering the effects of pesticides: (1) as pesticide use intensity increases, the populations of insects and birds reveal a nonlinear decreasing trend, experiencing a sharp decline once the pesticide usage reaches a critical threshold; (2) the impact of pesticide residues on soil microbial communities shows significant cumulative effects, leading to continuous deterioration of soil quality indicators over time; (3) the system state undergoes a significant change at specific pesticide usage thresholds, exhibiting typical critical point characteristics. These findings offer a scientific basis for developing sustainable pesticide management strategies.

4. Conclusion

In this study, this study systematically investigated the ecosystem stability during the agricultural transformation process of the Amazon rainforest by developing an innovative ecological dynamics model, and achieved a series of important research results. The developed multi-species coupled model successfully constructed a quantitative analysis framework capable of accurately simulating the dynamic evolution of the forest-farmland conversion system by integrating policy-regulated variables (τ) and pesticide toxicity parameters (ϕ). The unique advantages of this model are mainly reflected in three aspects: first, by introducing the policy response function $\beta(\tau)$, it realizes the dynamic coupling between logging policies and ecological processes, and provides a scientific tool for evaluating the implementation effects of environmental policies such as the Forest Code; second, the established complete feedback chain containing soil microorganisms (D)-soil quality (Q)-higher consumers (B,Bat) overcomes the insufficient focus on soil ecological functions in traditional models. The traditional model does not pay enough attention to the ecological function of soil; third, the time-lag effect term($\nu \cdot P \cdot D$) and cumulative impact calculation realize the accurate assessment of the long-term ecological impact of pesticides.

The innovative value of this study is mainly reflected in the methodological breakthrough. Compared with existing models, our method has three significant advantages: first, policy quantifiability, which transforms policy tools such as logging subsidies into calculable ecological impacts through τ parameters; second, process integrity, which realizes for the first time the full trophic level modeling from soil microbes to top consumers; and third, prediction accuracy, which fits the INPE monitoring data by 87.3%, which significantly outperforms the traditional assessment methods. These advantages make the model not only suitable for academic research, but also can directly support policy making, such as determining the minimum forest tenure (43.2%) and the safe use of pesticides.

Looking ahead, the modeling framework proposed in this study has important development potential in the following aspects: in terms of data integration, it is recommended to establish an integrated monitoring network between the sky and the earth, combining remotely sensed data and ground-based sensors to improve the spatial and temporal resolution of model parameters; in terms of algorithm optimization, deep learning techniques can be introduced to deal with large-scale ecological data, and adaptive parameter calibration algorithms can be developed; and in terms of application expansion, the focus is on strengthening the research in three directions: assessment of synergistic effects between climate change and agricultural activities, scenario simulation of different policy combinations, and transplantation of the model to other tropical agricultural areas (e.g., rubber plantations in Southeast Asia). These developments will further enhance the practical value of the model and provide stronger decision support for the sustainable management of ecosystems in the global tropics.

Finally, it is important to note that the successful application of the model cannot be achieved without interdisciplinary collaboration. Future research should enhance collaboration among ecologists, policy experts and data scientists, especially in the quantification of policy variables and the fusion of data from multiple sources. Meanwhile, it is recommended to establish a standardized process for model application, including parameter localization methods, uncertainty analysis frameworks, and guidelines for interpreting results, to facilitate the extended application of the model in the global tropics. These efforts will help to realize an effective interface between scientific research and policymaking, and promote the sustainable development of the Amazon rainforest and other tropical regions.

References

[1] Tsujimoto M, Kajikawa Y, Tomita J, et al. A review of the ecosystem concept-Towards coherent ecosystem design [J]. Technological forecasting and social change, 2018, 136: 49-58.

[2] Boulton C A, Lenton T M, Boers N. Pronounced loss of Amazon rainforest resilience since the early 2000s [J]. Nature Climate Change, 2022, 12(3): 271-278.

[3] Mei L C, Chen H M, Dong A Y, et al. Pesticide informatics platform (PIP): an international platform for pesticide discovery, residue, and risk evaluation [J]. Journal of Agricultural and Food Chemistry, 2022, 70(22): 6617-6623.

[4] Mack G, Finger R, Ammann J, et al. Modelling policies towards pesticide-free agricultural production systems [J]. Agricultural Systems, 2023, 207: 103642

[5] Moreau J, Rabdeau J, Badenhausser I, et al. Pesticide impacts on avian species with special reference to farmland birds: a review [J]. Environmental monitoring and assessment, 2022, 194(11): 790.

[6] Jacquet F, Jeuffroy M H, Jouan J, et al. Pesticide-free agriculture as a new paradigm for research [J]. Agronomy for Sustainable Development, 2022, 42(1): 8.

[7] Cobben D, Ooms W, Roijakkers N, et al. Ecosystem types: a systematic review on boundaries and goals [J]. Journal of Business Research, 2022, 142: 138-164.

[8] Phillips O L, Aragão L E O C, Lewis S L, et al. Drought sensitivity of the Amazon rainforest [J]. Science, 2009, 323(5919): 1344-1347.

[9] Brouwer R, Pinto R, Dugstad A, et al. The economic value of the Brazilian Amazon rainforest ecosystem services: a meta-analysis of the Brazilian literature [J]. PloS one, 2022, 17(5): e0268425.

[10] Boulton C A, Lenton T M, Boers N. Pronounced loss of Amazon rainforest resilience since the early 2000s[J]. Nature Climate Change, 2022, 12(3): 271-278.

[11] Liu S, García-Palacios P, Tedersoo L, et al. Phylotype diversity within soil fungal functional groups drives ecosystem stability [J]. Nature Ecology & Evolution, 2022, 6(7): 900-909.

[12] Liu S, Yu H, Yu Y, et al. Ecological stability of microbial communities in Lake Donghu regulated by keystone taxa [J]. Ecological Indicators, 2022, 136: 108695.