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Research on Forest Farmland Ecosystems Based on ARIMA-LSTM and Lotka-Volterra Model

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ABSTRACT

This study integrates the ARIMA-LSTM and Lotka-Volterra model to construct a farmland evolution model simulating the process of forest-to-farmland conversion. By incorporating biological factors and human decision-making, the study further develops a forest-farmland ecosystem simulation model. The research first conducts a comparative analysis to determine that spatially differentiated management strategies are the optimal land reclamation method, and employs the ARIMA-LSTM hybrid model to enhance the accuracy of forest-to-farmland trend predictions. Second, the study constructs a forest-farmland ecosystem simulation model based on the Lotka-Volterra model, incorporating factors such as interspecific predation and competition, seasonal fluctuations, and pesticide interference. By introducing native species to expand the analysis to the community level, the study reveals the mechanisms maintaining ecosystem stability, achieving a leap from single land-use simulation to complex ecosystem modelling. This study integrates time series prediction with ecological dynamics mechanisms to establish a comprehensive analytical framework encompassing 'reclamation strategy screening - evolutionary trend prediction - ecosystem simulation.' This framework provides quantifiable and verifiable scientific tools for the sustainable management of agroforestry systems, aiding in the resolution of challenges related to harmonious human-land development.

KEYWORDS

ARIMA-LSTM Model; Lotka-Volterra Model; Time Series Forecasting; Ecological Dynamics.

1. INTRODUCTION

The growing contradiction between global population growth and agricultural demand has intensified, making the conversion of forests into farmland an important means of alleviating food pressure. However, the resulting issues such as biodiversity loss and ecosystem imbalance require urgent attention [1]. This study integrates the ARIMA-LSTM model with the Lotka-Volterra model to construct a farmland evolution model and a forest-farmland ecosystem simulation model. The study first conducts a comparative analysis to determine that spatially differentiated management strategies are the optimal land reclamation method, and employs the ARIMA-LSTM hybrid model to enhance the accuracy of predicting forest-to-farmland conversion trends [2]. Based on this, the study constructs an ecosystem simulation framework incorporating species predation-competition relationships, pesticide interference, and seasonal fluctuations using the Lotka-Volterra model [3]. By introducing native species to expand the analysis to the community level, the results indicate that synergistic interactions between species can achieve a balance between short-term pest control and long-term system stability, marking a leap from single land-use simulation to complex ecosystem modelling. This study integrates time series prediction with ecological dynamics models to provide a scientifically sound and practically applicable analytical framework for the sustainable management of agroforestry systems, thereby contributing to addressing the challenge of harmonious human-land development in the context of global change.

2. THE ESTABLISHMENT OF FARMLAND EVOLUTION MODEL

2.1. Choose Agroforestry Reclamation Method

Among the existing agricultural and forestry reclamation technologies, this paper selected three most classic reclamation methods (central reclamation, edge reclamation, and spatial differentiation management strategy) for comparison and selected the best one as the reclamation method for our model. This paper comprehensively scored the ecological benefits (biological connectivity, soil conservation capacity, and species recovery rate), agricultural benefits (yield volatility and management costs), and sustainability (recovery costs, runoff coefficients). The specific formula is as follows:

$$CI = \frac{\sum_{i=1}^{n} a_i^2}{A_{\text{total}}^2} \times 100\% \tag{1}$$

Where CI represents Clustering Index, a_i is the area of the i-th habitat patch and A_{total} is the total landscape area.

$$\sigma_y = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(y_i - \bar{y}\right)^2}}{\bar{y}} \times 100\% \tag{2}$$

Where y represents the yield, $\bar{y}$ is average yield, σ_y is yield volatility.

$$R_c = \frac{Q}{P} \tag{3}$$

Where Q represents the restoration cost, P is revenue, Rc is cost ratio.

Combining other data and formula calculation results, it can be seen that the spatial differentiation management strategy achieves a dynamic balance between ecological protection and agricultural production by scientifically dividing functional areas and implementing differentiated management. Compared with single center reclamation (centralized development) and edge reclamation (gradual expansion), the spatial differentiation management strategy has more advantages in reclamation agricultural production, so our model chooses the reclamation method of the spatial differentiation management strategy.

2.2. Predicting Trends in Forest-To-Farm Conversion

(1) Model selection

After choosing the reclamation method, this paper can start predicting the trend of forest-to-farm conversion. The target prediction is to select unit linear regression, multivariate linear regression, and our innovative ARIMA-LSTM hybrid model. This paper selected the actual data of Amazon forest reclamation from 2001 to 2023 for analysis, and use residual analysis to determine which model can better accurately predict and calculate the annual increase in farmland area.

Simple linear regression (SLR):

$$y = \beta_0 + \beta_1 x + \epsilon \tag{4}$$

$$\epsilon_i = y_i - \hat{y}_i = y_i - \left(\beta_0 + \beta_1 x_i\right) \tag{5}$$

Multiple linear regression (MLR):

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_p x_p + \epsilon \tag{6}$$

$$\epsilon_i = y_i - \hat{y}_i = y_i - \left(\beta_0 + \beta_1 x_{1i} + \beta_2 x_{2i} + \cdots + \beta_p x_{pi}\right) \tag{7}$$

ARIMA-LSTM combined model [4]:

$$\epsilon_t^{\text{ARIMA}} = y_t - \hat{y}_t^{\text{ARIMA}} \tag{8}$$

$$\hat{\epsilon}_t^{\text{LSTM}} = \text{LSTM}\left(\epsilon_{t-1}^{\text{ARIMA}}, \epsilon_{t-2}^{\text{ARIMA}}, \ldots\right) \tag{9}$$

Combined with actual data, this paper used three models to predict the trend of forest-to-farm conversion, calculated the predicted data through formulas, and then calculated the residuals.

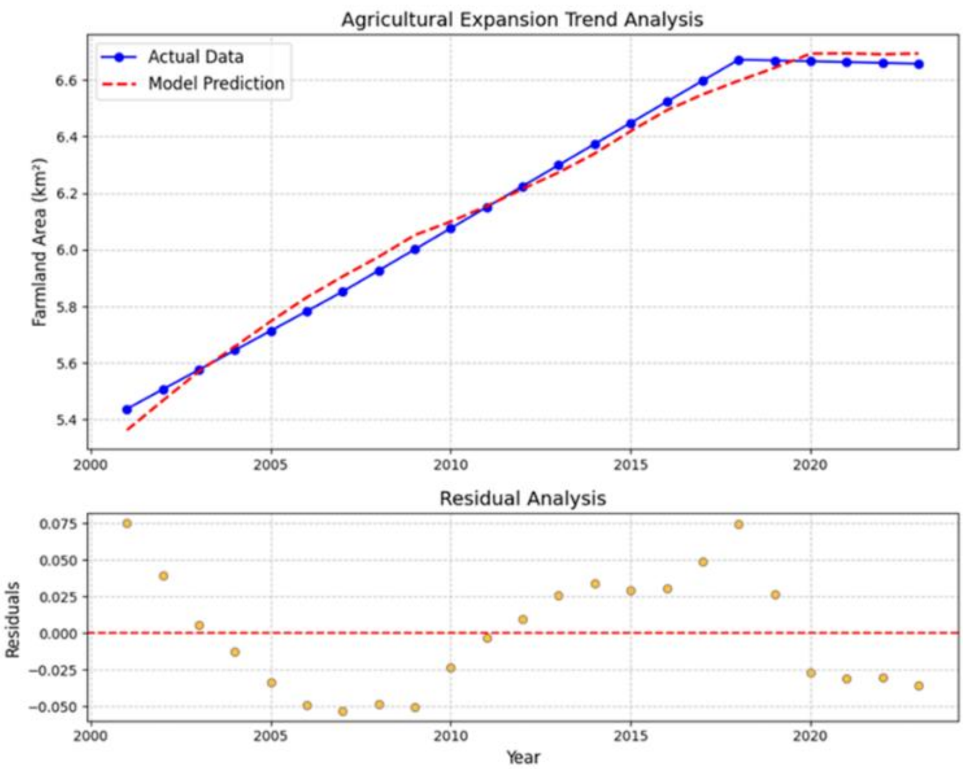

Figure 1. Predicted values and residual results of the ARIMA-LSTM hybrid model

The results show that the residual of the ARIMA-LSTM hybrid model is the smallest and the prediction effect is the best. The specific results are shown in Figure 1. Therefore, this paper chose the ARIMA-LSTM hybrid model to predict the trend of forest-farmland conversion.

(2) Prediction results

To predict the trend of forest-to-farmland conversion, this paper used the ratio of forest and farmland area and calculate it through the ARIMA-LSTM hybrid model.

The results indicate that from 2000 to 2023, the Amazon region experienced significant changes in land cover dynamics, with forest area showing a gradual decline overall, while farmland area expanded steadily. Key data from 2023 revealed that forest loss reached 3.0%, while farmland growth rate stood at 11.3%. Additionally, the trend curve related to the forest-to-farmland conversion ratio showed an upward trend, peaking at 11.26% around 2019 before slowing down. This represents our model's prediction of the trend of forest-to-farmland conversion, as well as the calculated increase in farmland area year by year.

Next, calculate the environmental carrying capacity of farmland-related parameters according to specific requirements, and determine the stage of the farmland ecosystem.

$$K_{\text{total}} = K_{\text{unit}} \times A \tag{10}$$

Where K_{unit} represents K value per unit area (unit: kg/ha or t/ha), A is farmland area (unit: ha). K_{total} represents total K value (unit: kg or t).

As show in Figure 2, in order to make it more realistic, this paper added infection points to make the curve more similar to the real situation and more valuable for reference.

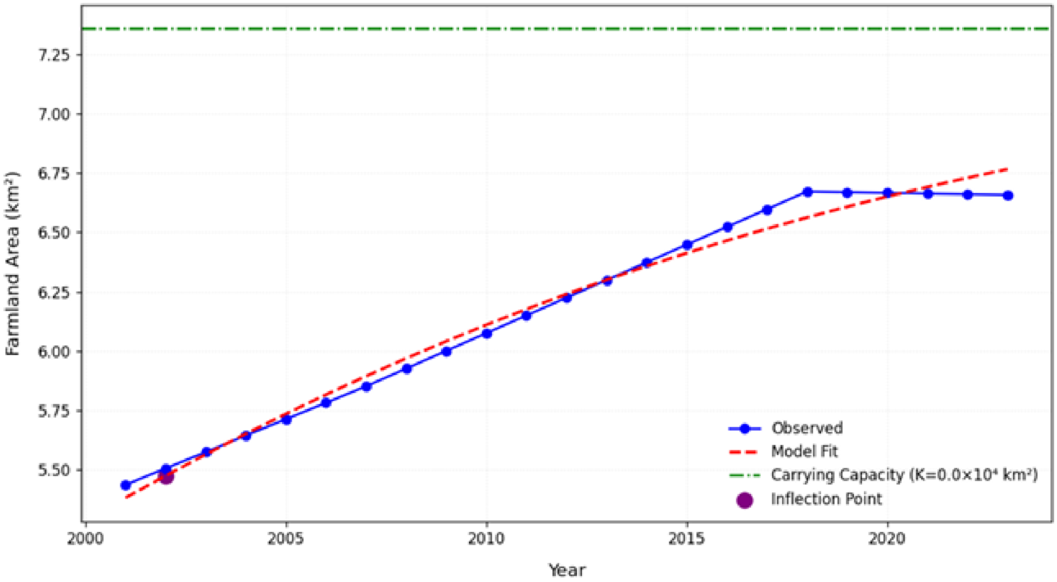

Figure 2. Amazon farmland expansion dynamics

Use Landsat satellite imagery to monitor changes in forest cover and farmland area. This paper roughly divided these four stages according to the rate of land use change at different stages: stabilization, moderate change, intensive deforestation, and stabilization. During the deforestation phase, forest areas are turned into flat land, and farmland reclamation gradually expands; after deforestation, the reclamation phase begins, where land is organized and reclaimed at an appropriate rate; once land preparation is complete, farmers focus on full-scale reclamation, rapidly increasing farmland area; finally, as most areas are developed, farmland area stabilizes.

3. THE ESTABLISHMENT OF THE FOREST-FARMLAND ECOSYSTEM SIMULATION MODEL

3.1. Interaction Analysis of Ecosystem Elements

This basic ecosystem takes farmland in the Amazon rainforest as an example. Initially, there are predator-prey relationships between insects and crops/weeds, as well as between birds and insects. Later, frogs are added to form a predator-prey relationship with insects, and snakes, as top predators, complete the food chain. The core competitive relationship is the nutrient competition between weeds and crops. In addition, farmers spray pesticides (insecticides and herbicides) to indirectly promote crop growth.

Considering that the use of herbicides may affect the soil microbial community by altering the types and quantities of microorganisms, thereby impacting the functionality of the soil ecosystem, herbicides may inhibit the growth and reproduction of some beneficial microorganisms while promoting the proliferation of harmful ones, leading to an imbalance in the soil microbial community structure. To address this, this paper innovatively introduced the factor of soil conditions, making the model more realistic and closer to real world scenarios.

3.2. Model Construction Based on Lotka-Volterra

Lotka-Volterra equations are also known as predator-prey equations. They consist of two first-order nonlinear differential equations [5]. They are often used to describe the dynamics of interactions between predators and prey in biological systems, that is, the rise and fall of the population size of both [6]. This is the basis of our model of biological interactions.

$$\frac{dN}{dt} = rN\left(1 - \frac{N}{K}\right) - \sum_j \alpha_j N_j N + \sum_k \beta_k N_k N \tag{11}$$

(1) Modeling the effects of time and chemical substances

a) Crop growth model:

$$\frac{dC}{dt} = r_c(t) \cdot C \cdot \left(1 - \frac{C}{K_c(t)}\right) - \alpha \cdot I \cdot C \tag{12}$$

Where $r_c(t)$ is the seasonal growth rate of crops:

$$r_c(t) = r_{c0} \cdot \left(1 + \beta \cdot \sin\left(\frac{2\pi t}{T}\right)\right) \tag{13}$$

r_{c0} is the base growth rate of crops, β is the amplitude of seasonal variation. T is the period length (typically 1 year). $K_c(t)$ is the seasonal carrying capacity of crops:

$$K_c(t) = K_{c0} \cdot \left(1 + \gamma \cdot \sin\left(\frac{2\pi t}{T} + \phi\right)\right) \tag{14}$$

K_{c0} is the base carrying capacity of crops, γ is the amplitude of carrying capacity variation, ϕ is the phase difference (reflects agricultural cycles). α is the consumption rate of crops by pests. I is the pest population.

The growth of crop biomass follows the principle of "self-regulation under resource constraints", similar to the growth pattern of population in a limited environment, but with the addition of seasonality and external disturbance factors. Crops will continue to increase their biomass at a fixed rate (such as 50growth per year) under ideal conditions (such as sufficient nutrients and water), but this growth cannot continue indefinitely because the resources and size of farmland are limited. When approaching this upper limit, crop growth will naturally slow down.

In practice, under undisturbed conditions, crop biomass will show an annual cycle fluctuation of "rapid growth in spring-peak in summer-slow decline in autumn and winter", and tend to fluctuate around the carrying capacity of farmland in the long term.

b) Pest population model

The dynamics of the pest population (I) are described by:

$$\frac{dI}{dt} = r_i(t) \cdot I \cdot \left(1 - \frac{I}{K_i(t)}\right) - \mu(t) \cdot I - \beta \cdot B \cdot I \tag{15}$$

Where $r_i(t)$ is the seasonal reproduction rate of pests:

$$r_i(t) = r_{i0} \cdot \left(1 + \delta \cdot \sin\left(\frac{2\pi t}{T}\right)\right) \tag{16}$$

r_{i0} is the base reproduction rate of pests, δ is the amplitude of seasonal variation, $K_i(t)$ is the seasonal carrying capacity of pests:

$$K_i(t) = K_{i0} \cdot \left(1 + \eta \cdot \sin\left(\frac{2\pi t}{T} + \phi_i\right)\right) \tag{17}$$

K_{i0} is the base carrying capacity of pests, η is the amplitude of carrying capacity variation. ϕ_i is the phase difference. $\mu(t)$ is the mortality rate due to pesticides:

$$\mu(t) = \mu_0 \cdot \exp\left(-\frac{(t - t_0)^2}{2\sigma^2}\right) \tag{18}$$

μ_0 is the Maximum mortality rate and t_0 is the time of pesticide application. σ is the duration of pesticide effect, β is the predation rate of pests by natural enemies and B is the natural enemy population.

The growth of pest populations is not only limited by their own reproductive capacity, but also strongly affected by predation by natural enemies and human intervention (such as pesticides).

c) Bat population model

$$\frac{dB}{dt} = r_B B\left(1 - \frac{B}{K_B(t)}\right) - d_B B + \epsilon_B \beta_B BI - \mu_B(t) B - \gamma_B P(t) B \tag{19}$$

Habitat and pesticide parameters:

$$K_B(t) = K_{B0}\left(1-\delta_B \sin\left(\frac{2\pi t}{T}+\phi_B\right)\right) \tag{20}$$

$$\mu_B(t) = \mu_{B0}\exp\left(-\frac{\left(t-t_{\text{spray}}\right)^2}{2\sigma_B^2}\right) \tag{21}$$

d) Bird population model

$$\frac{dQ}{dt} = r_Q Q\left(1-\frac{Q}{K_Q(t)}\right) - d_Q Q + \epsilon_Q \beta_Q Q I - \mu_Q(t)Q - \gamma_Q P(t)Q + M(t) \tag{22}$$

Migration and seasonal parameters:

$$K_Q(t) = K_{Q0}\left(1+\delta_Q \cos\left(\frac{2\pi t}{T}\right)\right) \tag{23}$$

$$M(t) = m_0 \sin\left(\frac{2\pi t}{T}+\phi_M\right) \tag{24}$$

e) Direct toxicity functions

For species $X \in \{B, Q, I\}$:

$$\mu_X(t) = \mu_{X0}\exp\left(-\frac{\left(t-t_{\text{spray}}\right)^2}{2\sigma_X^2}\right) \tag{25}$$

Specifically, when farmers stop using pesticides, the toxic effects on organisms will be reduced to zero.

(2) Models of the interactions of organisms and environment

a) Construction of community dynamics models

This paper extended the original Lotka-Volterra model by constructing a matrix-based framework to scale it up to describe the dynamics of entire communities.

For community with n species:

$$\frac{dN_i}{dt} = r_i N_i\left(1-\frac{\sum_{j=1}^{n} a_{ij} N_j}{K_i}\right) + \sum_{k=1}^{m} \phi_{ik} N_i N_k \tag{26}$$

Based on this model, this paper analyzed the roles of snakes and frogs. The introduction of these two new species enhanced the biodiversity of the farmland, accelerated the material cycle of the ecosystem, and provided a certain level of pest control through frogs. As a top predator, snakes promoted the balance of the entire food chain, enabling the farmland ecosystem to develop into a more stable state.

b) Extended models and species definitions

Taking the Amazon agricultural ecosystem as an example, the model incorporates the following key species:

Plants (N_3): Producers relying on pollination, suppressed by pests.

Pests (N_4): Herbivores consuming plants, controlled by bats.

Bats (N_2): Predators of pests (N_4) and pollinators for plants (N_3).

Bees (N_5): Diurnal pollinators enhancing plant diversity.

And the system is governed by:

$$\begin{cases} \dfrac{dN_2}{dt} = r_2 N_2\left(1-\dfrac{a_{22}N_2}{K_2}\right)+\phi_{24}N_2N_4, & \text{(Bats: predation + competition)} \\ \dfrac{dN_3}{dt} = r_3 N_3\left(1-\dfrac{a_{33}N_3}{K_3}\right)+\beta N_3\left(N_2+\gamma N_5\right), & \text{(Plants: growth + pollination)} \\ \dfrac{dN_4}{dt} = r_4 N_4\left(1-\dfrac{a_{44}N_4}{K_4}\right)-\phi_{24}N_2N_4, & \text{(Pests: growth - predation)} \\ \dfrac{dN_5}{dt} = r_5 N_5\left(1-\dfrac{a_{55}N_5}{K_5}\right), & \text{(Bees: pure pollination)} \end{cases} \tag{27}$$

Where ϕ_{24} is the bat predation efficiency on pests ($\phi_{24} > 0$), β is the pollination efficiency contribution to plant growth ($\beta > 0$) and γ is the relative efficiency of bees vs. bats ($\gamma = 0.8$ implies bees are 80% as efficient).

c) The impact of pesticide removal

Producer Stability: Enhanced plant diversity increases pollination dependency, reducing fluctuations:

$$\frac{dN_3}{dt} \propto \beta\left(N_2+\gamma N_5\right) \quad \Rightarrow \quad \text{Lower volatility in plant biomass.} \tag{28}$$

Consumer Stability: Pest control by bats ($\phi_{24}N_2N_4$) stabilizes the system; bees show minimal population fluctuations.

d) Coexistence equilibrium

Assuming pest suppression ($N_4^* \approx 0$):

$$\begin{cases} N_2^* = \dfrac{K_2}{a_2}, \quad N_5^* = \dfrac{K_5}{a_5}, \\ N_3^* = \dfrac{K_3\left(r_3+\beta\left(N_2^*+\gamma N_5^*\right)\right)}{r_3 a_{33}}. \end{cases} \tag{29}$$

Stability: Requires $\mathrm{Tr}(J) < 0$ and $\mathrm{Det}(J) > 0$, where J is the Jacobian matrix.

3) Comparative ecological roles

To assess the contribution of different biological factors to ecosystems, the study set standard parameters:

$$r_3 = 0.2, K_3 = 200, \beta = 0.05, \gamma = 0.8; \quad \phi_{24} = 0.1, K_2 = 50; \quad K_5 = 30 \tag{30}$$

The results showed that when only bats were introduced, the number of pests decreased by 60% and plant biomass increased by 40%. Bats directly suppressed pest outbreaks by feeding on them, while also pollinating plants through their nocturnal activity, quickly stabilising the ecosystem in the short term. When bats and bees were introduced together, pests decreased by 55% and plant biomass increased by 65%. Bats enhance stability through predation-pollination synergy, while bees support long-term biodiversity via specialized pollination. Combined implementation achieves short-term pest control and long-term resilience, requiring context-specific resource allocation.

4. CONCLUSIONS

This study employs an ARIMA-LSTM hybrid model and the Lotka-Volterra ecological dynamics framework to establish a comprehensive modelling system for simulating the evolution of farmland and forest-farmland ecosystems. The study first conducted a comparative analysis to determine that spatially differentiated management strategies are the optimal land reclamation method. It then introduced the ARIMA-LSTM hybrid model, integrating the advantages of time series analysis and machine learning, and combined residual analysis to construct prediction confidence intervals, effectively improving the prediction accuracy of the trend of forest-to-farmland conversion. Based on this, the study utilised the Lotka-Volterra model to construct an ecosystem simulation framework incorporating species predation-competition relationships, pesticide interference, and seasonal fluctuations. By incorporating native species to expand the analysis to the community level, the results indicated that synergistic interactions between species can achieve a balance between short-term pest control and long-term system stability. The model extends from single land-use simulation to complex ecosystem modelling incorporating multi-species interactions, enhancing the ability to characterise the dynamic mechanisms of agroforestry systems.

The research findings established a comprehensive research framework of ‘strategy screening - trend prediction - ecological simulation,’ revealing the interaction mechanisms between human intervention and biological factors in agroforestry systems. This provides a replicable model paradigm and quantitative analysis pathway for sustainable management of agroforestry land globally. Future research can further expand the spatial scale and species diversity dimensions of the model to more comprehensively support decision-making needs for harmonious human-land development.

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