ISSN 2616-5910 Vol. 6, Issue 1: 102-109, DOI: 10.25236/AJALS.2025.060115

Research on the Causal Relationship between Agricultural Environmental Variables and Species Health Based on Structural Equation Modeling

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Abstract: *This study aims to analyze the effects of temperature, precipitation, soil quality, and chemical use on plant health, insect populations, and species such as birds and bats in agricultural ecosystems. By constructing a data-based agricultural ecosystem model, the complex relationship between environmental variables and agricultural practices was studied using exploratory data analysis (EDA) and structural equation modeling (SEM). The results showed that environmental factors such as temperature, precipitation, and soil quality had significant positive effects on plant health and insect populations, while the use of chemicals significantly reduced plant health and insect populations. In addition, organic agricultural practices helped to improve the health of insect populations by reducing the use of chemicals. The populations of birds and bats had less impact on plant health and insect populations, but played a key role in the stability of the ecosystem. The results highlight the importance of optimizing agricultural practices and reducing the use of chemicals, providing a theoretical basis for sustainable agricultural management.*

Keywords: *Agricultural Ecosystem, Species Health, Structural Equation Model, Ecosystem Stability, Organic Agriculture*

1. Introduction

With the continuous expansion of global agricultural production, human activities are increasingly influencing ecosystems. One of the most significant impacts comes from the widespread use of chemical pesticides and fertilizers. While these chemicals have contributed to increased agricultural productivity and economic benefits, their adverse effects on ecosystem stability, species diversity, and environmental quality are becoming more evident [1]. Forest ecosystems, in particular, are vulnerable to these impacts, as the application of chemicals can alter species interactions, reduce biodiversity, and disrupt ecological balance.

Several studies have explored the impact of chemical agents in agricultural ecosystems, highlighting their detrimental effects on individual species and ecosystem health. For instance, research has shown that pesticide use can lead to a reduction in insect diversity, which, in turn, impacts plant growth and pollination processes, triggering cascading effects throughout the ecosystem. Furthermore, studies have examined the broader implications of agricultural practices on soil quality and species populations [2]. Some research has also delved into the complexities of multiple environmental factors, such as temperature and precipitation, combined with agricultural practices, and their interrelationships with species health using methods like structural equation modeling (SEM). Organic agriculture, which aims to reduce chemical inputs, has been found to offer benefits for species diversity, although challenges still remain, such as the potential use of herbicides in some organic farming systems.

This study builds upon existing research by constructing a new agricultural ecosystem model that comprehensively analyzes the impact of environmental variables (temperature, precipitation, soil quality) and chemical use on the health of species, including plants, insects, birds, and bats. Using exploratory data analysis (EDA) and structural equation modeling (SEM), we aim to better understand the interrelationships and causal pathways between these factors. Our goal is to quantify the specific impacts of agricultural practices, particularly chemical use, on species health, and explore the resulting threats to

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ecosystem stability and biodiversity. This research aims to provide empirical support for developing more sustainable agricultural policies and improving ecosystem resilience.

2. Research status of agroecology and chemical use

The impact of chemical use in agricultural ecosystems on the ecological environment is a widely concerned issue. With the widespread use of chemical pesticides and fertilizers, many studies have shown that agricultural interventions not only affect plant health, but also affect the stability and function of the entire ecosystem by changing the species population structure.

Many studies focus on the impact of pesticides on single species, especially key species in ecosystems such as insects, birds and bats. Studies have found that pesticide use may lead to a reduction in insect diversity, which in turn affects plant growth and pollination functions, and also causes a chain reaction on other species in the food chain [3]. In addition, the use of pesticides and fertilizers will change soil quality, further affecting the growth environment of plants and ultimately affecting the stability of the entire ecosystem.

In recent years, some studies have begun to focus on the interaction between multiple variables, especially the impact path in complex ecosystems. For example, researchers used structural equation models (sem) to analyze the relationship between different environmental factors and agricultural practices, revealing how agricultural interventions affect various components of the ecosystem through multiple pathways. These models can more accurately reflect the causal relationship and interaction between variables in the ecosystem.

In terms of agricultural practices, organic agriculture is considered an important way to reduce the use of chemicals, improve soil quality and increase species diversity [4]. However, organic agriculture in some areas still faces the problem of excessive use of herbicides and fertilizers, which leads to an imbalance in insect populations. Therefore, comprehensive consideration of the interaction between agricultural practices, environmental variables and species health has become an important direction of current research.

Although many studies have explored the impact of agricultural chemicals on the ecological environment, how to combine different environmental factors and agricultural interventions to comprehensively analyze their combined effects on species health remains a challenge. Based on existing literature, this study will construct an agricultural ecosystem model and deeply explore the impact of different environmental variables and agricultural interventions on ecosystem stability.

3. A study on the effects of chemical use on biodiversity in agroecosystems

3.1 Constructing indicators and data

Due to the complex initial forest environment and diverse species, a training set of 1,000 data was constructed. The data in the training set were divided into 16 variables, including bats, birds, plant health, season, temperature, precipitation, soil quality, pesticide use, herbicide use, fertilizer use, organic farming practices, crop rotation, agricultural selection, marginal habitats, and distance from the forest, according to animals and plants, natural weather, use of chemical drugs, and human intervention [5].

Add constraints to the variables and use the random function to simulate 1,000 data as a data set:

(1) Temperature and precipitation

$$T_s = \begin{cases} U(10,20) & (S = Spring) \\ U(20,35) & (S = Summer) \\ U(10,20) & (S = Autumn) \\ U(-5,10) & (S = Winter) \end{cases} \tag{1}$$

$$P_s = \begin{cases} U(50,150) & (S = Spring) \\ U(100,300) & (S = Summer) \\ U(50,150) & (S = Autumn) \\ U(20,100) & (S = Winter) \end{cases} \tag{2}$$

Among them, S represents seasonal changes, P_s represents precipitation, and its value changes according to seasonal changes, and T_s represents temperature, and its value changes according to

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seasonal changes.

(2) Number of insects

$$K = U(50{,}150) + 20O + 30\omega_s(Summer) - 20C_u \tag{3}$$

Where K represents the number of insects, O represents organic farming practices, ω_s is an indicator function that is 1 when $S = Summer$ and 0 otherwise, and C_u represents the amount of herbicide used.

(3) Number of birds and bats

$$B_r = U(10{,}50) + 20B_h + 15\omega(S_f < 5) \tag{4}$$

$$B = U(5{,}30) + 10O + 15\omega_s(Summer) \tag{5}$$

Where B_r represents the number of birds, B_h represents the edge habitat, S_f represents the distance from the forest, $\omega(S_f < 5)$ is the indicator function, which is 1 when $S_f < 5$ and 0 otherwise, B is the number of bats, and O represents organic agricultural practices [6].

(4) Plant health level

$$Z_h = \begin{cases} Excellent & (T = Rich) \\ Good & (T = Medium) \\ Poor & (T = Poor) \end{cases} \tag{6}$$

If $Z_u > 5$ or $C_u > 5$ then:

$$Z_h = Medium \tag{7}$$

If $O = 1$, then:

$$Z_h = \begin{cases} Medium & (Z_h = Poor) \\ Z_h & (otherwise) \end{cases} \tag{8}$$

Where Z_h represents the plant health level, T represents the soil quality, and Z_u and C_u represent the amount of chemical agents used.

(5) Amount of chemical agents used

$$Z_u = \begin{cases} U(3{,}8) & (S = Summer) \\ U(1{,}5) & (otherwise) \end{cases} \tag{9}$$

$$C_u = \begin{cases} U(3{,}8) & (G_t = Traditional) \\ U(1{,}5) & (G_t = No - \text{tillorRe}\,duced - till) \end{cases} \tag{10}$$

$$F_u = \begin{cases} U(150{,}300) & (T = Poor) \\ U(50{,}150) & (T = MediumorRich) \end{cases} \tag{11}$$

Table 1 Data in the dataset

Category\Serial Number	1	2	3	4
Bats	1	0	1	0
Birds	0	0	0	1
Insects	50	49	70	67
Plant health	Good	Bad	Moderate	Bad
Seasons	Autumn	Summer	Summer	Winter
Temperature	17.2	16.4	10.8	14.5
Precipitation	105.9	119.5	120.1	61.5
Soil quality	Medium	Medium	Low	Medium
Pesticides	3.2	3.5	2.4	14.3
Herbicides	6.8	4.4	10.4	9.7
Fertilizers	197.5	220.7	154.2	45.4
Organic farming practices	0	0	0	0
Crop rotation	0	1	1	1
Farming choices	Tradition	Tradition	Tradition	Minimum tillage
Marginal habitats	4.4	1.8	2.9	1.4
Distance from forests	5.5	4.2	5.6	2.5

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Among them, Z_u represents the amount of pesticide used, C_u represents the amount of herbicide used, F_u represents the amount of fertilizer used, T represents the soil quality, and G_t represents the type of farming [7]. Some data in the dataset are shown in Table 1.

In the table, 0 represents the absence of bats and birds, and 1 represents the presence of bats and birds; 1 is used to represent organic agriculture, and 0 is used to represent traditional agriculture; 1 represents the implementation of crop rotation, and 0 represents the non-implementation of farming; agricultural choices are divided into three methods: traditional, reduced tillage, and no tillage; plant health is divided into three types: good, medium, and poor; soil quality is divided into three types: high, medium, and low [8].

3.2 Establish a new agricultural ecosystem model

Perform EDA analysis on the data set to observe the distribution trend between variables. First, calculate the correlation between variables and draw a correlation matrix.

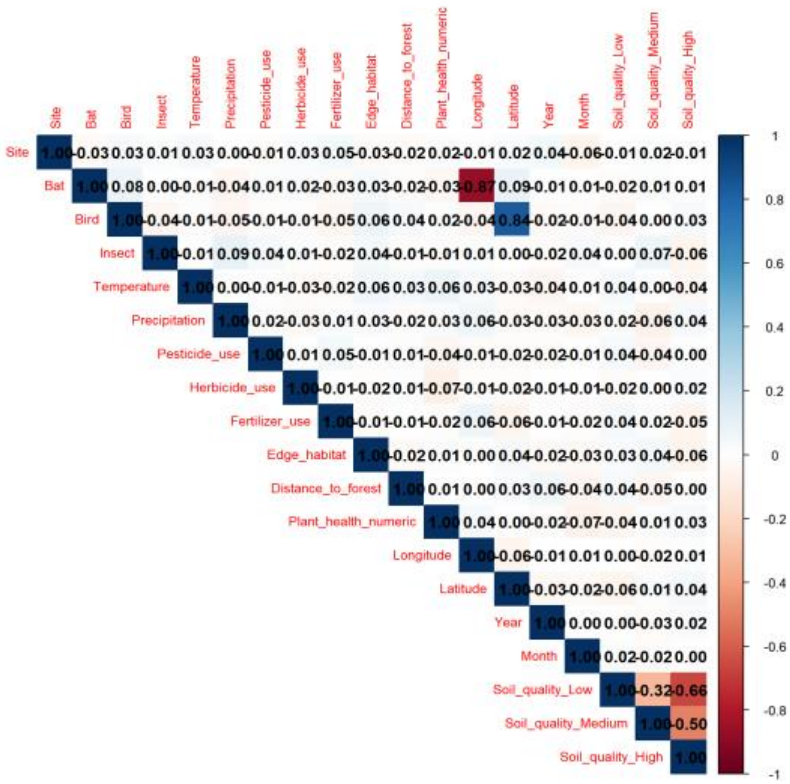

Figure 1 Correlation matrix between variables

From the analysis of Figure 1, we can conclude that a positive value indicates a positive correlation, and the change trends between the variables are the same, while a negative value indicates a negative correlation, and the change trends between the variables are opposite. For example, a positive correlation coefficient between Bat and Plant_health_numeric means that the better the plant health, the more bats there are. The closer the value is to 1 or -1, the stronger the correlation is, and the closer it is to 0, the weaker the correlation is. For example, if the correlation coefficient between Temperature and Bat is -0.01, the correlation between the two is weak. It also contains a specific relationship, and there is a complex connection between different levels of soil.

In Figure 2, the data distribution of Insect, Pesticide_use, Herbicide_use, and Fertilizer_use is relatively dense, while the data distribution between the three variables Pesticide_use, Herbicide_use, and Fertilizer_use is relatively sparse.

Observing the relationship between various species in the ecosystem, and combining the above analysis, it is found that plants, insects, and birds can build a food chain, and there is a predator-prey relationship between these three species. Therefore, a food web model is established that includes producers such as plants and consumers such as insects, bats, and birds.

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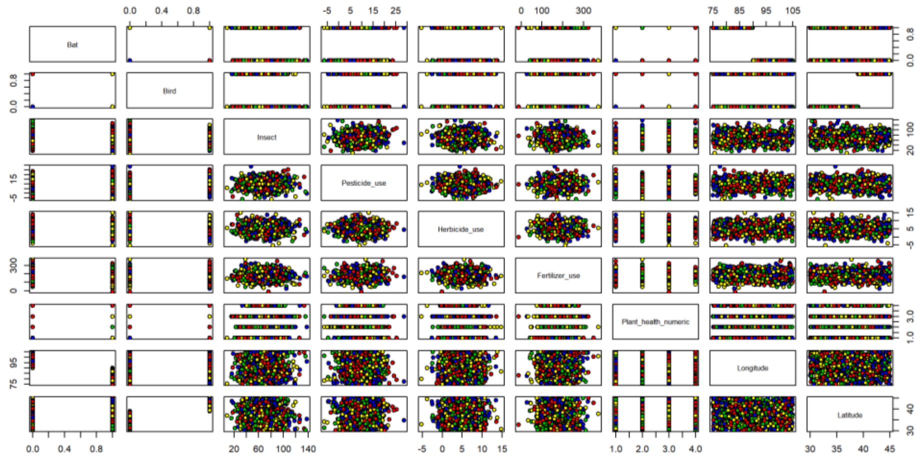

Figure 2 Dataset scatter plot matrix

3.3 The impact of chemical drugs on natural organisms and ecological stability

Assume that the relationship between the dependent variable and the independent variable is linear

(1) Measurement model:

Plant health:

$$Z_1 = \alpha Z_1 + \beta Z_1 \tag{12}$$

Bird population:

$$B_2 = \alpha B_2 + \beta B_2 \tag{13}$$

Bat population:

$$B_3 = \alpha B_3 + \beta B_3 \tag{14}$$

Insect quantity:

$$K_4 = \alpha K_4 + \beta K_4 \tag{15}$$

Among them, αZ_1 is the theoretical value of plant health, βZ_1 is the measurement error, αB_2 is the theoretical value of bird population, βB_2 is the measurement error, αB_3 is the theoretical value of bat population, βB_3 is the measurement error, αK_4 is the theoretical value of insect quantity, and βK_4 is the measurement error.

(2) Structural model

Plant health:

$$Z_1 = \beta_{10} + \beta_{11}X_1 + \beta_{12}X_2 + \beta_{13}X_3 + \beta_{14}X_4 + \beta_{15}X_5 + \beta_{16}X_6 + \beta_{17}X_7 + \beta_{18}X_8 + \omega_1 \tag{16}$$

Bird populations:

$$B_2 = \beta_{20} + \beta_{21}X_1 + \beta_{22}X_2 + \beta_{23}X_3 + \beta_{24}X_4 + \beta_{25}X_5 + \beta_{26}X_6 + \beta_{27}X_7 + \beta_{28}X_8 + \omega_2 \tag{17}$$

Bat population:

$$B_3 = \beta_{30} + \beta_{31}X_1 + \beta_{32}X_2 + \beta_{33}X_3 + \beta_{34}X_4 + \beta_{35}X_5 + \beta_{36}X_6 + \beta_{37}X_7 + \beta_{38}X_8 + \omega_3 \tag{18}$$

Insect quantity:

$$K_4 = \beta_{40} + \beta_{41}X_1 + \beta_{42}X_2 + \beta_{43}X_3 + \beta_{44}X_4 + \beta_{45}X_5 + \beta_{46}X_6 + \beta_{47}X_7 + \beta_{48}X_8 + \omega_4 \tag{19}$$

Among them, $\beta_{10}, \beta_{20}, \beta_{30}, \beta_{40}$ are intercept terms, $\omega_1, \omega_2, \omega_3, \omega_4$ are residual terms of the structural equation, $\beta_{1i}(i = 1, \cdots 8), \beta_{2i}(i = 1, \cdots 8), \beta_{3i}(i = 1, \cdots 8), \beta_{4i}(i = 1, \cdots 8)$ are the coefficients of the independent variable X_i on plant health, bird population, bat population and insect quantity respectively.

The structural equation model established above is used to analyze the various effects of chemical drugs including herbicides and pesticides on plant health and bird, bat and insect populations. Among them, temperature, precipitation, soil quality, insecticide use, herbicide use, fertilizer use, pesticide use

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and organic farming practices are independent variables, and plant health and bird, bat and insect populations are dependent variables.

After converting the categorical variables to factor types and converting Plant_health to the numerical variable Plant_health_numeric, the maximum likelihood estimation method is used for fitting, and the SEM path is drawn as shown in Figure 3 below:

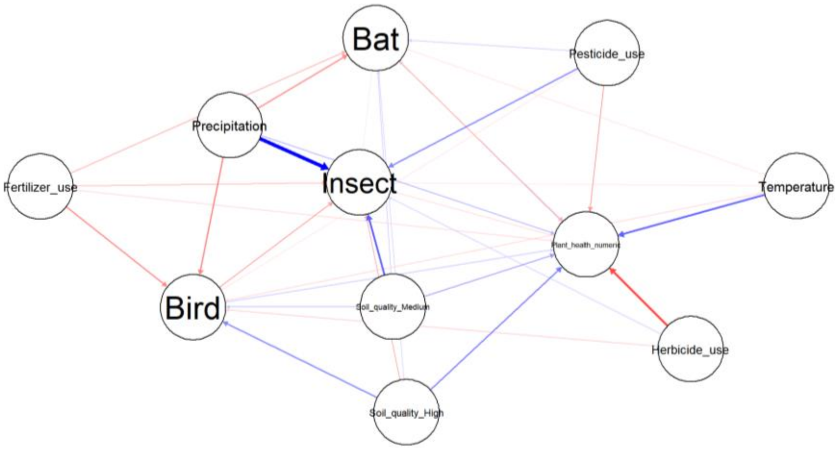

Figure 3 SEM path diagram between variables

In Figure 3 above, the factors on the right are independent variables, and the factors on the left are dependent variables. The thickness of the arrows represents the degree of influence, with blue arrows representing positive influences and red arrows representing negative influences. A unidirectional arrow indicates a direct effect of one variable on another variable or a causal relationship between the two, such as precipitation→Insect, which indicates that precipitation directly affects the number of insects. A bidirectional arrow represents a correlation or covariance relationship between two variables, not a causal relationship. For example, bats and plant health levels. If the arrow points from A to B and the path coefficient is positive, it means that an increase in A will lead to an increase in B, such as Herbicide_use→Insect, which means that an increase in the use of herbicides will also lead to an increase in the number of insects. If the arrow points from A to B and the path coefficient is negative, it means that an increase in A will lead to a decrease in B, such as Precipitation→Bird, which means that an increase in precipitation will lead to a decrease in birds.

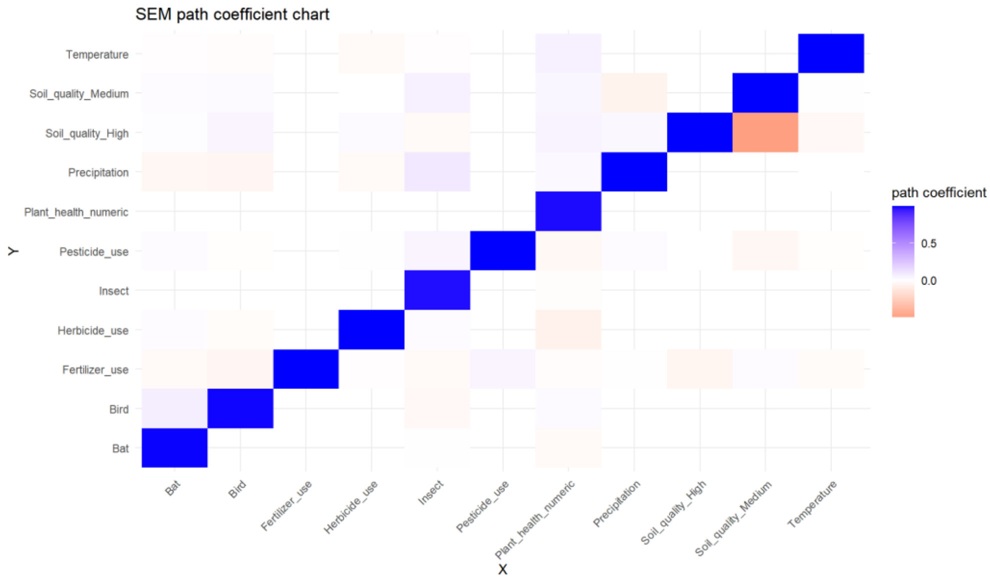

Figure 4 SEM path coefficient diagram of the effects of chemical agents on natural organisms

The path coefficient in Figure 4 above represents the intensity and direction of the influence between variables. The darker the color, the larger the path coefficient, which further indicates that the degree of influence on the path is stronger.

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Combining the above analysis, it is concluded that precipitation, temperature and soil quality have significant positive effects on plant health and insect populations; pesticide and herbicide use have significant negative effects on plant health and insect populations; organic farming practices have significant positive effects on insect populations; the number of birds and bats has little impact on plant health and insects, but they play an important role in maintaining the balance of the ecosystem.

4. Discussion and Conclusions

This study constructed an agricultural ecosystem model to deeply analyze the effects of temperature, precipitation, soil quality, and chemical use on species health within forest ecosystems. The results demonstrate that agricultural interventions, especially the use of chemicals, significantly affect plant health, insect populations, and the health of species such as birds and bats, which in turn have profound implications for ecosystem stability and biodiversity.

The study found that temperature, precipitation, and soil quality had significant positive effects on plant health and insect populations. As temperature and precipitation increased, plant health tended to improve, and insect populations grew accordingly. This phenomenon suggests that suitable climate conditions and sufficient precipitation provide a favorable environment for plant growth and insect reproduction. However, the effects of these variables on ecosystems are not simple linear relationships, as excessively high or low temperatures and precipitation may negatively impact species health, reflecting the complexity of species interactions within ecosystems. Notably, the use of chemical agents, especially pesticides and herbicides, showed a significant negative impact on both plant health and insect populations. The use of pesticides not only directly affects target species but also triggers a chain reaction by altering the food chain and interspecies relationships, further weakening the ecosystem's functions.

In contrast, the study found that organic agricultural practices had a positive impact on insect populations. Compared to traditional agriculture, organic farming reduces the use of chemicals, improves soil quality, and provides better habitats and food resources for insects. However, the benefits of organic agriculture are not universally applicable to all regions and crops, and its effects should be assessed based on specific regional and crop contexts. While organic farming has clear advantages in reducing environmental pollution, its sustainability in large-scale agricultural production still requires further research and verification.

Additionally, the study showed that natural enemy species, such as birds and bats, have relatively little direct impact on plant health and insect populations. This may be because the population changes of these species are primarily influenced by food resources and habitat conditions, rather than chemical use. Nevertheless, these species play a crucial role in maintaining ecological balance and controlling insect populations, underscoring the importance of protecting them in agricultural production.

In general, this study reveals the multiple effects of agricultural intervention on species health within ecosystems, and emphasizes the complex interactions between environmental factors such as temperature, precipitation, and soil quality, and agricultural practices. By optimizing agricultural production methods, reducing chemical use, and adopting more sustainable agricultural management measures, the negative impacts on ecosystems can be effectively minimized, and the protection of species diversity and ecological balance can be promoted. However, the study has some limitations, such as a relatively small dataset and a focus on specific regions' environments and agricultural practices. Future research could further validate the conclusions of this study by expanding the dataset and increasing regional diversity. Furthermore, the model used in this study assumes a linear relationship between environmental variables and species health, but in reality, this relationship may be more complex. Therefore, future research should employ more precise nonlinear modeling techniques to improve the accuracy of the study.

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