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Endogenous Transmission Mechanism and Spatial Effect of Forest Ecological Security in China

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Abstract: Forest ecological security is an important component of ecological security and national security, and it is a requirement for the sustainable development of the forestry economy. In this study, based on the pressure–state–response (PSR) model, an evaluation index system of forest ecological security was constructed regarding three aspects: the pressure on the forest ecosystem caused by human activities, the state of the forest ecosystem, and the response measures taken by humans to protect the forest ecosystem. The forest ecological security and its pressure, state, and response in 31 provinces (municipalities and autonomous regions) in China from 2004 to 2018 were evaluated. Furthermore, with the help of a mediating effect model, the Moran index, and a spatial econometric model, the interaction relationship, spatial correlation effect, and spatial spillover effect of the pressure–state–response of forest ecological security were analyzed. The results showed the following: First, during the study period, the forest ecological security of most provinces was at sensitive and critical safety levels, and the forest ecological security level in Northeast and Southwest China was generally higher than that in Northwest and East China. Second, regarding the pressure, state, and response of forest ecological security, the pressure was generally low but with an increasing trend, the state was relatively good with continuous improvement, and the response was clearly insufficient and showed a fluctuating downward trend. Third, there were six different transmission mechanisms between pressure, state, and response of forest ecological security, among which there were significant transmission barriers between pressure and response. Given these findings, we propose suggestions to promote the improvement of forest ecological security in China.

Keywords: forest ecological security; pressure–state–response; endogenous transmission mechanism; spatial correlation effect; spatial spillover effect

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1. Introduction

Strengthening ecological construction and maintaining ecological security are common challenges facing humans in the 21st century, and they are an important basis for the sustainable development of the economy and society. Forests are an important part of the ecosystem that not only provides forest products and maintains biodiversity but also plays an irreplaceable role in regulating the climate and maintaining ecological security [1,2]. However, due to the advancement of industrialization, a series of problems, such as ecological environmental pollution, excessive consumption of resources, and abnormal climate change, have seriously threatened forest ecological security and restricted the sustainable development of the economy and society [3,4]. To alleviate this problem, China has implemented a series of forestry ecological projects, such as the Natural Forest Protection Project and Grain for Green Project. However, the overall level of forest ecological security in China still needs to be improved, and regional differences are obvious. In essence, the problem of forest ecological security lies in the coordination between human beings and forest ecosystems [5], that is, the matching problem due to the pressure on the forest ecosystem caused by human activities (the "pressure"), the state of the forest ecosystem (the "state"), and the response of human beings to the forest ecosystem (the "response"). In addition, because of the flow of the elements in geographical space, the forest ecological security in different regions affects each other. Therefore, the study of the interaction between pressure, state, and response and their spatial effects is conducive to a profound understanding of the endogenous transmission mechanism of forest ecological security, which can provide a new path for ecological governance in China, other countries, and even the world, from the perspective of the endogenous system.

In the 1870s, American scholar Brett R. Brown expressed the meaning of ecological security for the first time in *Building a Sustainable Development Society*, which organically combined environment and safety [6]. At the end of the 1880s, the International Institute for Applied Systems Analysis (IASA) proposed the concept of ecological security for the first time, noting that ecological security includes the security of nature, society, and the economy. It was believed that ecological security refers to a state in which the ecological environment will not cause harm to human beings in the process of changes [7]. Norman Myers (1989), one of the pioneers in the study of the concept of ecological security, concluded in his book *The Last Security* that ecological environmental degradation would endanger economic and political security through a large number of empirical analyses of regional resource wars and ecological threats [8]. In 1998, scholars from all over the world expressed different views on the concept, causes, and effects of ecological security in *Ecological Security and the United Nations System*. Subsequently, the issue of ecological security has attracted the attention of a large number of scholars [9–11]. The problems related to ecological security in China were raised in the early 1990s, but they were not fully studied. In 2000, the concept of ecological security was first proposed in the *National Ecological Environmental Protection Report*. Subsequently, many domestic scholars expounded the connotation of ecological security from different perspectives [12] and, based on this, assessed the ecological security in different regions [13–16].

Ecological security includes forest ecological security [17–19], land ecological security [20–22], landscape ecological security [23–25], and water ecological security [26–28]. Among the numerous studies of forest ecological security, global research focuses mainly on forest health. The concept of forest health was first introduced in Germany in the 1970s and has since spread to other countries [29]. Following the development of forest health theory, empirical studies on forest health assessment have emerged [30–32]. Chinese studies of forest ecological security mainly focus on the evaluation of forest ecological security and the relationship between forest ecological security and the forestry economy. In the evaluation research, most scholars construct evaluation index systems based on pressure–state–response (PSR) and drive–pressure–state–impact–response (DPSIR) [19,33]. In addition, system dynamics (SD), fuzzy comprehensive evaluation, the ecological footprint, and data envelopment have been used to evaluate the forest ecological security at different scales, such as national [29], regional [18], and provincial [34]. On this basis, some studies use Geographic Information Science (GIS), the Moran index, and spatial convergence models to analyze the spatial characteristics [35–38], and some studies use spatial econometric, structural equation, and barrier degree models to analyze its determining factors [5]. Research centering on the relationship between forest ecological security and the forestry economy involve aspects such as the coordinated development of forestry management efficiency and forest ecological security [29], the coupling of forest ecosystem and the forestry industry [39,40], and the interaction mechanism of forest ecological security and forest food safety [41].

To summarize, existing studies have achieved rich results, which provide important implications for the current research. Nonetheless, the following deficiencies remain: First, existing studies adopt the same set of index weights in the evaluation of forest ecological security in different years, ignoring its changes over time. Second, existing studies mainly focus on the evaluation of forest ecological security and lack of discussion on the interaction mechanism of its subsystems. Therefore, to address the shortcomings of the existing research, we first constructed an evaluation index system and calculated the index weights in different years, using the entropy weight method. Then, the comprehensive evaluation model was used to evaluate the forest ecological security and its pressure, state, and response in 31 provinces of China. Furthermore, the mediating effect model was used to analyze the internal conduction mechanism among the pressure–state–response, and the Moran index and spatial econometric model were used to explore the spatial correlation and spatial spillover effects and to clarify the interaction relationship from the endogenous perspective of the system, thus providing a theoretical reference for the formulation of policies related to forest ecological security.

2. Materials and Methods

2.1. The Forest Ecological Security Evaluation Index System

Forest ecological security refers to a state in which the ecological services provided by the forest ecosystem can meet the needs of human survival and sustainable utilization of the social economy under the condition of complete structure and function, so that human production, life, and development are not threatened [1,5]. It can be seen that forest ecological security includes the state of the forest ecosystem itself and the impact of human activities on the forest ecosystem. Human influence can be divided into the pressure on the forest ecosystem caused by human activities and the response measures taken to improve the state of the forest ecosystem. Therefore, on the basis of relevant studies [17,18,38], in this study, we started from the conceptual connotation of forest ecological security and constructed an evaluation index system encompassing the three aspects of pressure, state, and response, with the support of the PSR model (Table 1).

Table 1. The evaluation index system of forest ecological security.

Level Indicators	Specific Indicators (Unit)	Formula	Direction	Weight
Pressure (P)	Population per unit forest area (person/ha)	Population/Forest area	-	0.0117–0.0136
	Human interference index (%)	(Area of construction land + Area of cultivated land)/Land survey area × 100%	-	0.0318–0.0509
	Forestry industrial structure index (%)	Output value of forestry secondary industry/Total output value of forestry × 100%	-	0.0383–0.0519
	Land desertification intensity (%)	Land desertification area/Land survey area × 100%	-	0.0204–0.0226
	Sulfur dioxide emission intensity (t/ha)	Sulfur dioxide emissions/Land survey area	-	0.0115–0.0477
	Discharge intensity of industrial wastewater (t/ha)	Industrial wastewater discharge/Land survey area	-	0.0119–0.0135
State (S)	Forest coverage rate (%)	Forest area/Land survey area × 100%	+	0.0765–0.0894
	Forest stock volume per unit forest area (m^3/ha)	Forest stock volume/Forest area	+	0.0694–0.1042
	Natural forest proportion (%)	Natural forest area/Forest area × 100%	+	0.0544–0.0670
	Forest fire rate (‰)	Area of forest fire/Forest area × 1000‰	-	0.0115–0.0387
	Forest pest and disease rate (%)	Area of forest diseases and pests/Forest area × 100%	-	0.0150–0.0295
Response (R)	New afforestation area per unit land area (%)	New afforestation area/Land survey area × 100%	+	0.0875–0.1272
	Closed mountain area for forestry per unit land area (%)	Closed mountain area for forestry/Land survey area × 100%	+	0.0793–0.1392
	Number of forestry employees (person)	Number of employed persons in forestry institutions at year-end	+	0.1779–0.2382
	Forestry investment (ten thousand yuan)	Total forestry investment since the beginning of the year	+	0.1025–0.2200

Pressure indicators were used to describe the negative effects of human activities on the forest ecosystem, including population per unit forest area, human interference index, forestry industrial structure index, land desertification intensity, sulfur dioxide emission intensity, and industrial wastewater discharge intensity. Among these, population per unit forest area, human interference index, and forestry industrial structure index reflect the occupation of forest land and the consumption of forest resources. Land desertification intensity, sulfur dioxide emission intensity, and industrial wastewater discharge intensity reflect the pollution and damage to the environment caused by human production and the development of the economy and society, that is, the environmental pressure faced by the forest ecosystem.

State indicators were used to evaluate the resource state and health state of forest ecosystem. Forest coverage rate, forest stock volume per unit forest area, natural forest proportion, forest fire rate, and forest pest and disease rate were selected in this study. Among these, forest coverage rate, forest stock volume per unit forest area, and natural forest proportion were used to describe the state of forest resources, that is, the quantity and quality of forest resources, and are the most direct indicators to evaluate forest ecological security. Forest fire rate and forest pest and disease rate were used to measure the health status of forests, which directly affect the quantity and quality of forest resources, and have an important impact on the safety of the entire forest ecosystem.

Response indicators were used to describe the measures taken by human beings to protect the forest ecosystem. New afforestation area per unit land area, closed mountain area for forestry per unit land area, number of forestry employees, and forestry investment were selected in this paper. Among these, the number of forestry employees and forestry investment were used to reflect the input intensity of labor and financial resources, and new afforestation area per unit land area and closed mountain area for forestry per unit land area were used to measure the protection of forest resources.

In terms of the interaction mechanism between pressure, state, and response, the influence of pressure on the state mainly includes three aspects. The first is the impact of social pressure on the state of the forest ecosystem, which is mainly reflected in the continuous occupation of forest land and the increasing disturbance of the forest ecosystem by human beings due to the increase in population and the advancement of urbanization, leading to a continuous decline in the quantity and quality of forest resources. The second is the impact of resource pressure on the state of the forest ecosystem, which is mainly reflected in the increased market demand for forest resources due to the increase in population, which leads to the continuous decrease in forest resources. The third is the impact of environmental pressure on the state of the forest ecosystem, which is mainly reflected in the continuous increase in pollutant discharge due to the development of the economy and society that destroys the soil, water, and atmosphere necessary for the growth of trees and then affects the state of the resource and health of the forest ecosystem. Simultaneously, the state of the forest ecosystem also affects the development of the economy and society through various means, such as macroeconomic policies. The effect of response on the state mainly includes two aspects. The first is the impact of input response on the state of the forest ecosystem, that is, the input of labor and capital strengthens forest management and protection, improves the efficiency of forestry production and the level of forestry science and technology, and thus saves and protects forest resources. The second is the impact of protection response on the state of the forest ecosystem; that is, measures such as closing mountains for forest cultivation and renewing afforestation protect forest resources, improve the forest coverage rate, and then improve the state of the forest ecosystem. Furthermore, the state of the forest ecosystem is also a key factor to determine the intensity of forestry investment and protection. In contrast, the interaction between pressure and response may be realized indirectly mainly through the state.

The original data of the indicators were derived from the *China Statistical Yearbook*, *China Forestry Statistical Yearbook*, *China Environmental Statistical Yearbook*, *China Land and Resources Statistical Yearbook* and the *China Forest Resources Inventory Report*. Among these, the data of forest area, forest stock volume, and forest coverage rate were taken from the results of the 7th to 9th National Forest Resource Inventory. The impact of price changes was eliminated from forestry investments according to the national consumer price index (2004 as the reference year), and the forestry investment and forestry output value of Heilongjiang included those of Daxing'anling. In addition, the spatial weight used was the first-order queen adjacent matrix W (adjacent is 1; non-adjacent is 0), in which Hainan was set as adjacent to Guangdong and Guangxi.

2.2. Methods

2.2.1. Comprehensive Evaluation Model

(1) Data standardization

To unify the dimensions of different indicators, it is necessary to standardize the original data of indicators before evaluation. The formulas are expressed as follows:

$$\text{Positive indicators}: \ {x_{ij}}' = (x_{ij} - x_{\min})/(x_{\max} - x_{\min}) \tag{1}$$

$$\text{Negative indicators}: \ {x_{ij}}' = (x_{\max} - x_{ij})/(x_{\max} - x_{\min}) \tag{2}$$

where x_{ij} is the original value of the jth index of the ith province, ${x_{ij}}'$ is the standardized value, and $x_{\max}$ and $x_{\min}$ are the maximum and minimum values of the jth index, respectively.

(2) Weight calculation

The entropy weight method is an objective weighting method to determine the index weight according to the degree of variation of each index value, and it can effectively avoid the deviation caused by human factors [42]. Therefore, it was used to calculate the weight of each index. Firstly, we need to calculate the information entropy value, e, and information utility value, d, of each index.

$$\text{The information entropy value of the } j\text{th index is as follows}: \ e_j = -K\sum_{i=1}^{m} {X_{ij}}' \ln {X_{ij}}' \tag{3}$$

$$\text{In the formula, } K \text{ is constant when } m \text{ samples are completely disordered, } K = 1/\ln m. \tag{4}$$

$$\text{The information utility value of the } j\text{th index is as follows}: \ d_j = 1 - e_j. \tag{5}$$

$$\text{Thus, the weight of the } j\text{th index can be obtained as follows}: \ w_j = d_j / \sum_{j=1}^{n} d_j \tag{6}$$

Because the effect of each index on forest ecological security changes over time, the weight of each index in different years was calculated in this study. The weight range of each index was shown in Table 1.

(3) Comprehensive evaluation

Standardized values and their weights were used to assess the forest ecological security of each province. The formula is as follows:

$$f_i = \sum_{j=1}^{n} w_j {x'}_{ij} \tag{7}$$

(4) Evaluation standard

According to the characteristics of forest ecological security, its evaluation criteria were divided into severe level ($0 \le f_i < 0.2$), sensitive level ($0.2 \le f_i < 0.4$), critical safety level ($0.4 \le f_i < 0.6$), comparative safety level ($0.6 \le f_i < 0.8$), and safety level ($0.8 \le f_i < 1$), using a uniform distribution function.

2.2.2. Mediating Effect Model

When analyzing the influence of independent variable X on dependent variable Y, if there is a variable M that makes X affect Y through M, then M is called an mediating variable [43]. When there is only one independent variable, dependent variable, and intermediate variable, the path relationship and regression equations are shown as follows:

$$\begin{gathered} Y = u_0 + cX + e_1 \\ M = u_1 + aX + e_2 \\ Y = u_2 + c'X + bM + e_3 \end{gathered} \tag{8}$$

where $u_i(i = 0, 1, 2)$ is the constant term, c is the total effect, c' is the direct effect, ab is the mediating effect, and $c = c' + ab$, $e_j(j = 1, 2, 3)$ is the regression residual.

The Sobel test is used to check whether the mediating effect is significant, $H_0 : ab = 0$, building the Z-statistic, $z = ab/\sqrt{a^2 s_b^2 + b^2 s_a^2}$, where s_a and s_b are standard errors of regression coefficients a and b, respectively.

2.2.3. Moran Index

The Moran index is an exploratory spatial analysis index to test whether variables have spatial correlation and spatial agglomeration characteristics. It was first proposed by Moran in 1950 to reflect the similarity between each region and its neighboring regions [44], and the calculation formula is as follows:

$$I = \frac{n \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij}(x_i - \overline{x})(x_j - \overline{x})}{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} \sum_{i=1}^{n} (x_i - \overline{x})^2} \tag{9}$$

where n is the number of regions, w_{ij} is the element value in the spatial weight matrix, and x is the value of the observational index.

Values of the Moran index are generally between -1 and 1. When the index value is greater than 0, it means there is a positive spatial correlation, that is, a high value is adjacent to a high value and a low value is adjacent to a low value; when the index is less than 0, it means there is a negative spatial correlation, that is, a high value is adjacent to a low value; when it is close to 0, it means there is no spatial correlation. Furthermore, the variance generated by a random combination can be used to construct a Z-statistic subject to the asymptotic standard normal distribution, so as to conduct a statistical test for the reliability of the Moran index.

2.2.4. Spatial Econometric Model

The spatial econometric model is a commonly used method to examine spatial spillover effects [45,46], and the formula is as follows:

$$\begin{cases} \mathbf{Y} = \mathbf{X}\boldsymbol{\beta} + \mathbf{W}\mathbf{X}\boldsymbol{\delta} + \rho\mathbf{W}\mathbf{Y} + \mathbf{u} + \mathbf{v} + \boldsymbol{\xi} \\ \boldsymbol{\xi} = \lambda\mathbf{W}\boldsymbol{\xi} + \boldsymbol{\varepsilon} \\ \boldsymbol{\varepsilon} \sim N(0, \sigma^2\mathbf{I}_n) \end{cases} \tag{10}$$

where $\mathbf{Y}$ is the dependent variable vector; $\mathbf{X}$ is the independent variable matrix; $\mathbf{W}$ is the spatial weight matrix; $\boldsymbol{\xi}$ is the residual vector; $\boldsymbol{\varepsilon}$ is normally distributed with mean of 0 and variance of σ^2; $\mathbf{I}_n$ is the identity matrix; $\boldsymbol{\beta}$ is the coefficient vector of the non-spatial term; and $\boldsymbol{\delta}$, ρ, and λ represent the spatial term coefficients of $\mathbf{X}$, $\mathbf{Y}$, and $\boldsymbol{\xi}$, respectively.

The following can be noted:

- When $\lambda = 0$, $\rho \neq 0$, $\delta = 0$, it is a Spatial Lagged Model (SLM);
- When $\lambda \neq 0$, $\rho = 0$, $\delta = 0$, it is a Spatial Error Model (SEM);
- When $\lambda = 0$, $\rho \neq 0$, $\delta \neq 0$, it is a Spatial Durbin Model (SDM);
- When $\lambda = 0$, $\rho = 0$, $\delta = 0$, the spatial econometric model will be simplified to a common panel regression model.

The Spatial Lag Model assumes that the spatial effect is only reflected in the dependent variable itself; the Spatial Error Model assumes that the spatial spillover effect is manifested in the form of errors; and the Spatial Durbin Model assumes that the spatial spillover effect is derived from the independent variable and the dependent variable, and that the spatial spillover effect of the dependent variable can be further explained by the spatial effect of the independent variable.

In addition, the Spatial Durbin Model divides the marginal effects of variables into non-spatial terms and spatial terms. Due to the feedback effect, lag effect, and other problems, the coefficient of a non-spatial term is often not equal to the value of the local effect, and the coefficient of a spatial term is not equal to the value of the spatial spillover effect, so it is necessary to decompose and reconstruct the marginal coefficient. Lesage and Pace (2009) decomposed the marginal effect into local effect and spatial effect, using the partial differential matrix [47].

3. Results and Discussion

3.1. Evaluation of Forest Ecological Security

The comprehensive evaluation model was used to quantitatively measure the pressure, state, response, and comprehensive index of forest ecological security in 31 provinces of China in 2004, 2011, and 2018 (Figures 1–4), and the regional differences and changing trends of the results were analyzed.

Figure 1 showed that there were significant differences in the comprehensive index of forest ecological security among different provinces, and the forest ecological security level in Northeast and Southwest China was generally higher than that in Northwest and East China. Specifically, only Heilongjiang reached a comparative safety level in 2004. In addition, 16 provinces, including Jilin, Guangxi, Fujian, and Sichuan, reached critical safety level; 11 provinces, including Hebei, Shanxi, Gansu, and Qinghai, were always at sensitive level; and Tianjin, Shanghai, and Jiangsu were slightly below sensitive level. In terms of trends, the comprehensive values of forest ecological security in 18 provinces, such as Beijing, Zhejiang, Hunan, and Guangxi, increased in fluctuation, whereas they gradually decreased in 11 provinces, including Jilin, Shanghai, Shandong, and Hainan. However, the fluctuation range in all provinces was small.

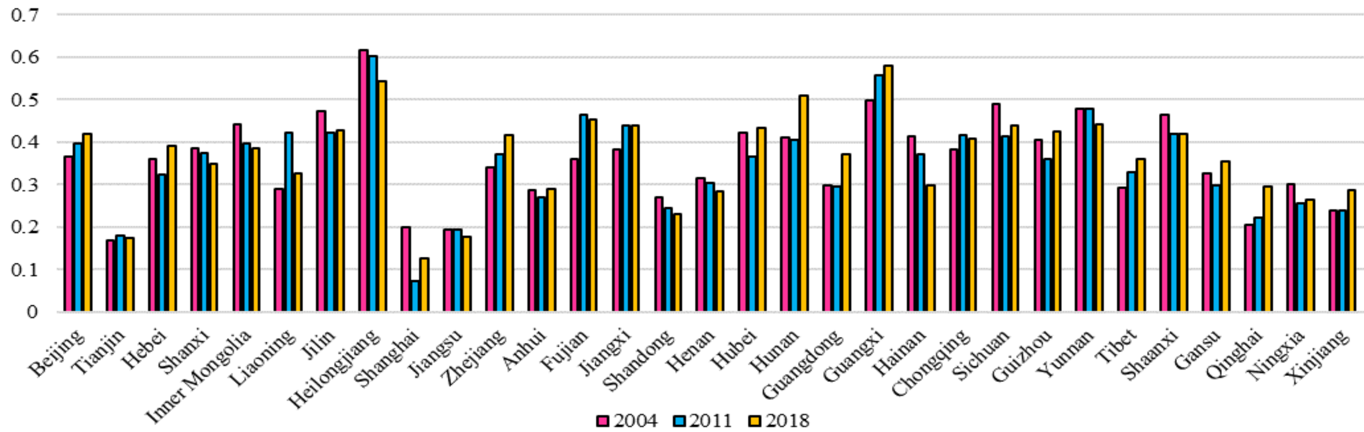

Figure 1. Comprehensive index of forest ecological security.

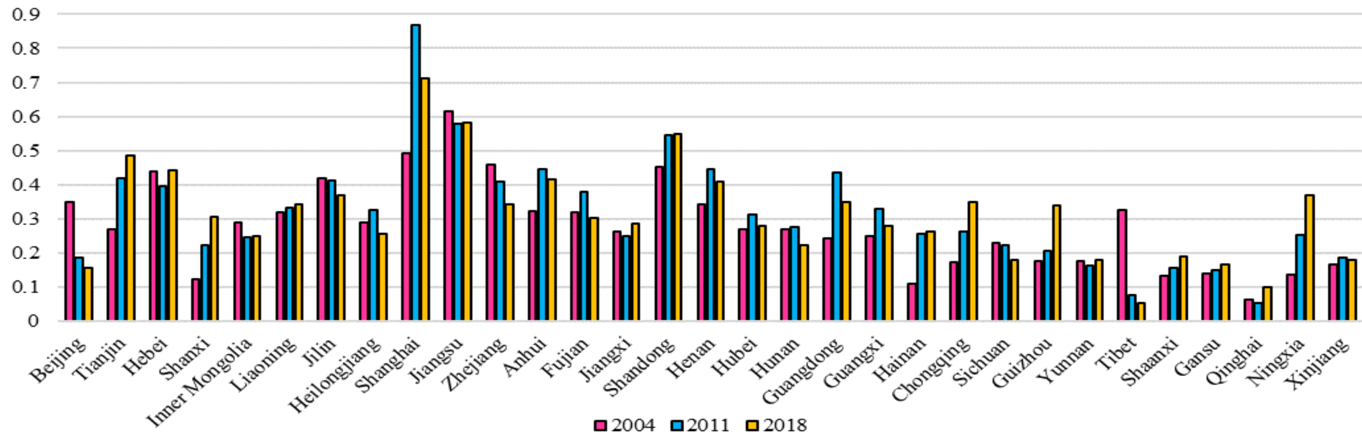

Figure 2. Pressure index of forest ecological security.

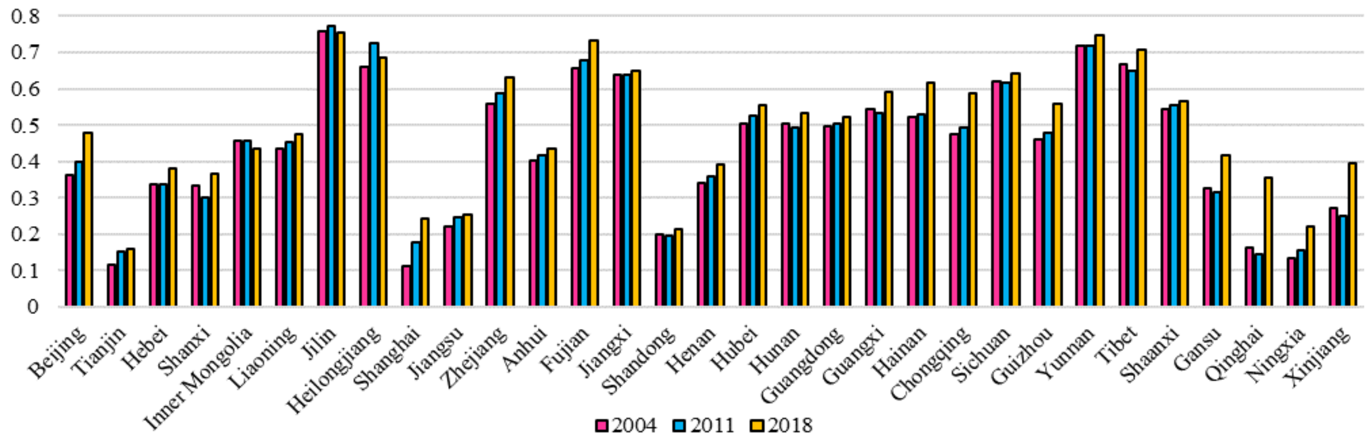

Figure 3. State index of forest ecological security.

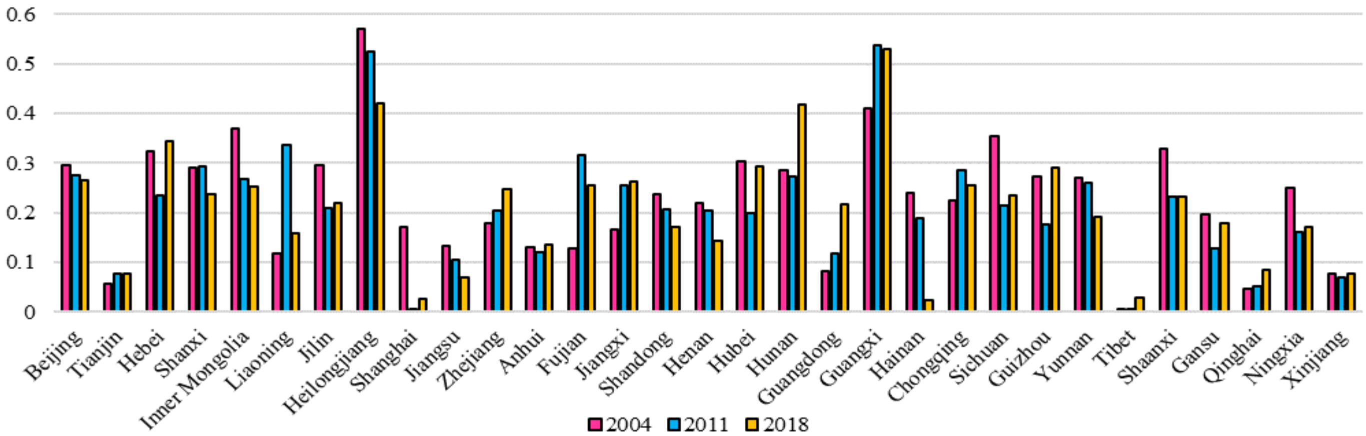

Figure 4. Response index of forest ecological security.

Figure 2 showed that the pressure values of nine provinces, including Shanghai, Jiangsu, Shandong, and Henan, were higher than 0.4 in most years. These provinces had a high level of economic development and large populations, so the production and living of human beings had a significant impact on the forest ecosystem. The pressure values of 15 provinces, including Liaoning, Heilongjiang, Fujian, and Jiangxi, were mostly between 0.2 and 0.4, with forest ecosystems facing the next highest pressure. Most of the pressure values in Yunnan, Gansu, Qinghai, Xinjiang, Tibet, Shaanxi, and Beijing were lower than 0.2. These provinces generally had a low level of economic development and less human disturbance, so the forest ecosystem faced less pressure. However, the pressure values of 21 provinces, including Shanghai, Shandong, Guangdong, and Chongqing, all fluctuated and increased, indicating that the impact of human activities on the forest ecosystem in most provinces was increasing.

Figure 3 showed that the state values of forest ecological security varied significantly between provinces. Among which, the state values of Jilin, Heilongjiang, Fujian, Jiangxi, Yunnan, Sichuan, and Tibet were always between 0.6 and 0.8, indicating that the state of the forest ecosystem was relatively good. In contrast, those of Tianjin, Shanghai, Shandong, and Ningxia were mostly lower than 0.2, indicating that the quantity and quality of forest resources in these provinces were relatively poor. Values for the remainder of the provinces were mostly between 0.2 and 0.6. In terms of changing trends, the forest ecological security state values of Inner Mongolia and Jilin decreased slightly, whereas those of all other provinces gradually increased.

Figure 4 showed that the response values of Heilongjiang and Guangxi were always higher than 0.4, indicating that the forestry investment and forest protection in these two provinces were better. The response values of Tianjin, Shanghai, Jiangsu, Anhui, and eight other provinces were always lower than 0.2, whereas those of other provinces were mostly between 0.2 and 0.4. In addition, the response values of most provinces showed a fluctuating decreasing trend during the study period, which indicated that afforestation, cultivation intensity, and forestry input intensity in most regions should be strengthened (Figure 4).

3.2. The Mediating Effect of Pressure–State–Response

Using the mediating effect model, we analyzed the interaction of pressure, state, and response of forest ecological security in 31 provinces of China from 2004 to 2018. Then, STATA15.0 was used to establish the panel mediation effect model, and the results showed that the mixed model was better than fixed and random models, thereby forming six transmission paths of pressure–state–response (Figure 5). The solid and dotted lines in the figures represent direct and mediating effects, respectively; $\surd$ means that direct or indirect effects are significant, and $\times$ means insignificant.

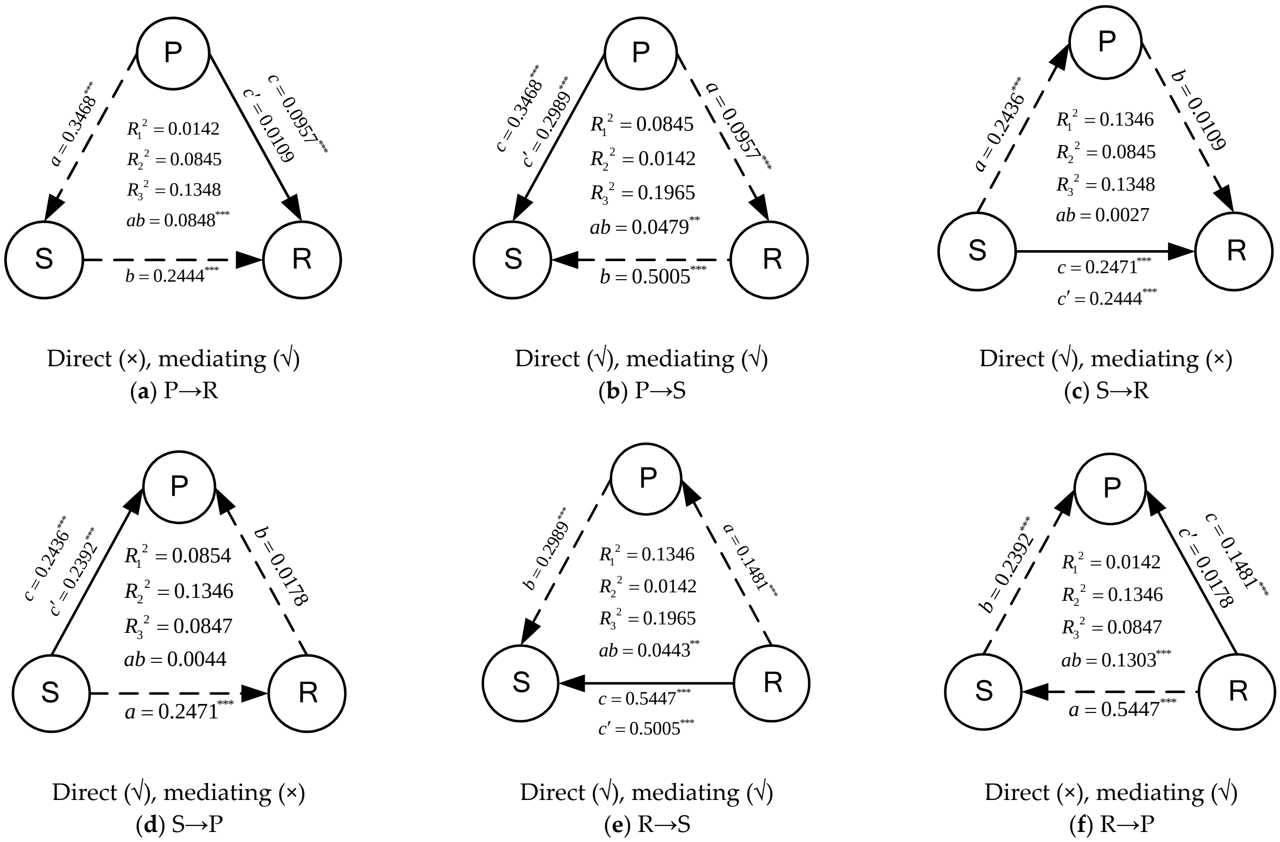

Figure 5. The transmission path of pressure–state–response.

As shown in Figure 5a, the total effect of pressure on response c = 0.0957 ($p < 0.01$), the direct effect c′ = 0.0109 ($p = 0.765 > 0.10$), the mediating effect of pressure through state on response ab = 0.0848 ($p < 0.01$), the mediating effect accounted for 88.61% of the total effect, and the direct effect was not significant. The results show that the pressure of human activities acts on the response mainly through the state of the forest ecosystem. In the same way, the contribution difference of the direct and mediating effects between pressure, state, and response in different conduction paths can be obtained.

In general, there is a significant interaction relationship (total effect) between any two subsystems of pressure–state–response. Among these, the direct and mediating effects of pressure on state (Figure 5b) and response on state (Figure 5e) are significant. The direct effects of pressure on response (Figure 5a) and response on pressure (Figure 5f) are not significant, but the mediating effect is significant. The direct effects of state on response (Figure 5c) and state on pressure (Figure 5d) are significant while the mediating effect is not. The results show that there is no perfect accessibility among subsystems of China's forest ecological security system, and there are circulation barriers in the process of information transmission. This reduces the transmission efficiency of China's forest ecological security system and restricts the improvement of China's forest ecological security.

3.3. The Spatial Correlation Effect of Pressure–State–Response

Using GeoDa software, the global Moran index of forest ecological security and its pressure, state, and response from 2004 to 2018 were calculated to reveal the spatial characteristics and changing trends (Figure 6). All Moran indices passed the significance test of at least 10%, which indicated that China's forest ecological security and its subsystems had significant spatial dependence. In addition, the comparison of the mean values showed that the spatial correlation effect of pressure and state was stronger, which improved the spatial correlation level of forest ecological security, whereas that of response was weaker, which reduced the overall correlation effect of forest ecological security. In addition, the spatial correlation of forest ecological security, pressure, and response gradually weakened, whereas that of state increased slightly.

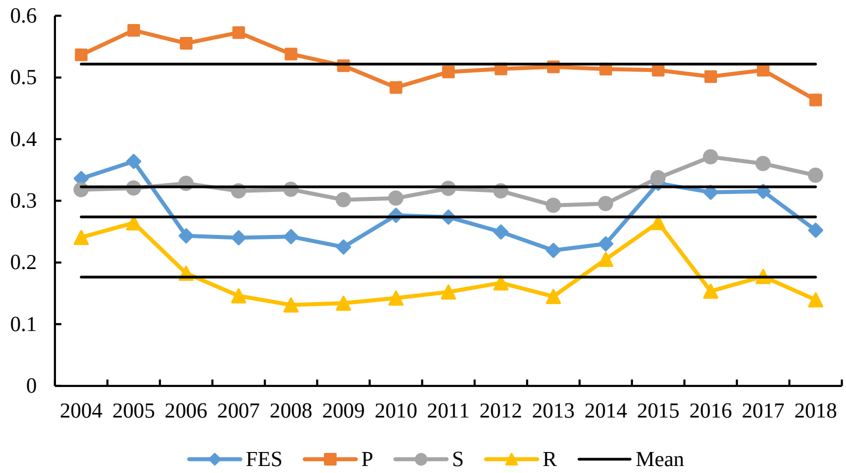

Figure 6. Moran index results.

Taking 2018 as an example, the local spatial correlation of forest ecological security, and its pressure, state, and response, were further analyzed (Figure 7). Figure 7a shows that 74.19% of the provinces are in the first and third quadrants, indicating that there is a positive spatial correlation of forest ecological security in most of the provinces. Specifically, the high–high adjacent provinces in the first quadrant include Heilongjiang, Jilin, Guangdong, Guangxi, and Yunnan. These provinces are mainly concentrated in Northeast and Southwest China, which are rich in forest resources, experience less external disturbance, and have a high level of forest ecological security. The low–low adjacent provinces in the third quadrant include Xinjiang, Gansu, Shandong, and Anhui. These provinces are mainly concentrated in Northwest and East China, where the quality of forest resources and ecological environment are weaker, and the level of forest ecological security is lower.

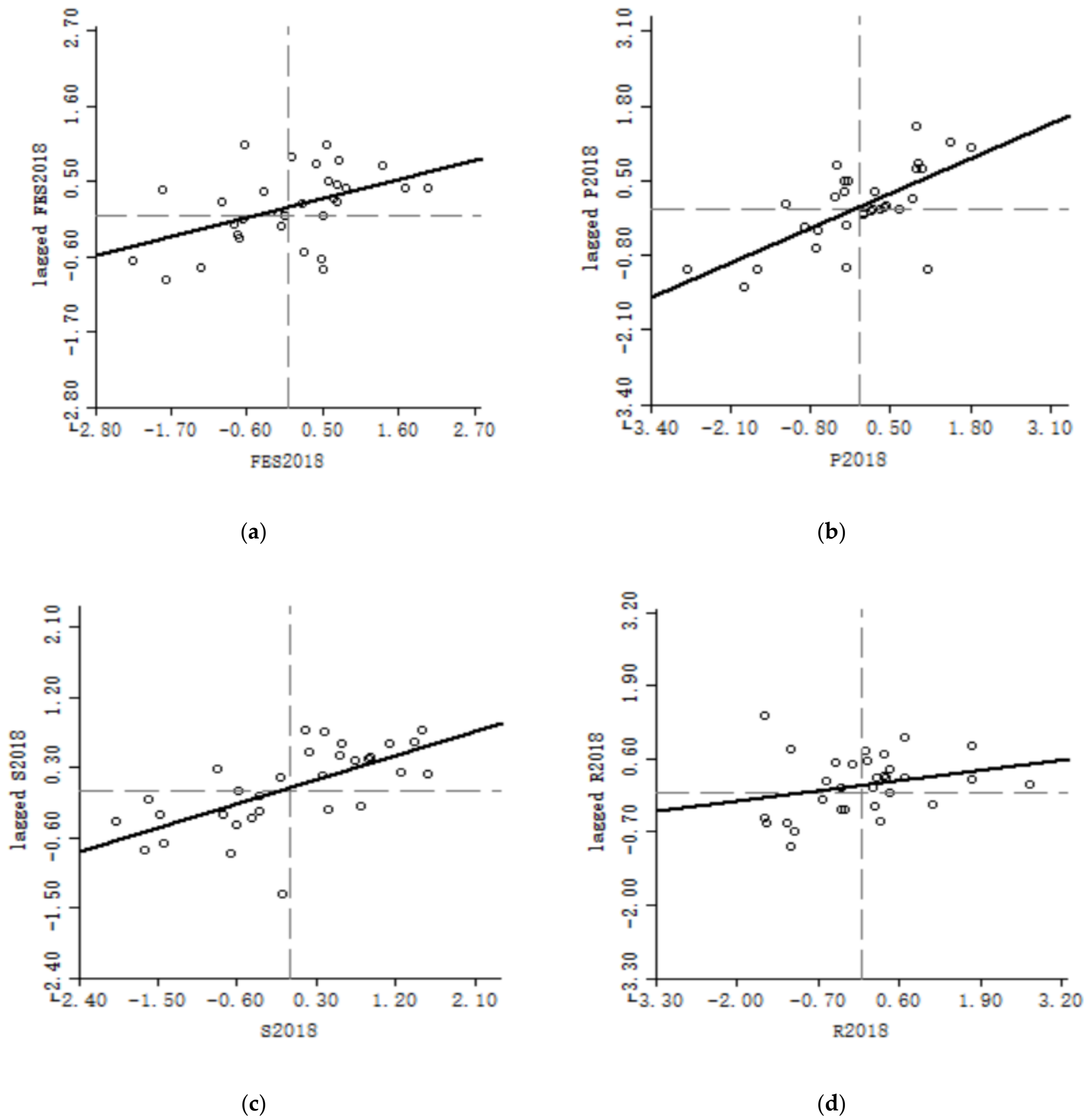

Figure 7. Moran scatter plot of pressure, state, response, and comprehensive index of forest ecological security. (**a**) Moran Scatter plot of comprehensive index; (**b**) Moran scatter plot of pressure index; (**c**) Moran scatter plot of state index; (**d**) Moran scatter plot of response index.

Similarly, Figure 7b–d shows that the pressure, state, and response of forest ecological security in most provinces have a positive spatial correlation. In terms of the pressure index, the high–high adjacent provinces are mainly concentrated in Eastern China, such as Zhejiang, Anhui, Shandong, and Jiangsu, where the human disturbance index and the proportion of secondary forestry industry are higher, which leads to greater pressure on the forest ecosystem. The low–low adjacent provinces include Yunnan, Xinjiang, Qinghai, Tibet, and other Western regions, where the forest population density is lower, and the disturbance of human activities is weaker, resulting in less pressure on forest ecological security. In terms of the state index, the high–high adjacent areas mainly appear in Northeast, Southwest, and South China, such as Heilongjiang, Yunnan, and Guangxi, where the forest resources are richer and the state of forest ecological system is better. The low–low adjacent areas are mainly distributed in Ningxia, Shanghai, Tianjin, and other areas in Northwest, Central, and Eastern China, where the quantity and quality of forest resources are lower, and there are fewer natural forests, so the state of forest ecological system is worse. In terms of the response index, the high–high adjacent areas mainly include Heilongjiang, Guangxi, Hunan, and other provinces with a higher proportion of mountain closure for forest cultivation and higher intensity of forestry investment, and adopted better response measures for the forest ecosystem. The low–low adjacent areas are mainly concentrated in Qinghai, Gansu, Shandong, Jiangsu, and other areas in Northwest and East China, where the forest protection measures and the input of labor and finance are relatively low.

3.4. The Spatial Spillover Effect of Pressure–State–Response

Based on the analysis of the spatial correlation effect, the Spatial Lag Model, Spatial Error Model, and Spatial Durbin Model were used to investigate whether there is a significant spatial spillover effect in the pressure–state–response system, to better understand the inter-provincial influence and action mechanism of forest ecological security (Table 2).

Table 2. Spatial econometric model results.

Variables	Pressure (P)			State (S)			Response (R)		
	SLM	SEM	SDM	SLM	SEM	SDM	SLM	SEM	SDM
Constant	0.0383 (1.5248)	0.5852 *** (18.4560)	0.1677 *** (5.2530)	−0.0057 (−0.1263)	0.1322 *** (3.2732)	0.0128 (0.2727)	0.0657 ** (2.1011)	0.0909 *** (3.3618)	0.1081 *** (2.8331)
P				0.2730 *** (5.4642)	0.3281 *** (5.9868)	0.3871 *** (6.1458)	0.0071 (0.1975)	0.0058 (0.1522)	0.1212 ** (2.2507)
S	0.1872 *** (6.0054)	0.1911 *** (5.9557)	0.2339 *** (6.5906)				0.2419 *** (7.9655)	0.2476 *** (8.0804)	0.2099 *** (5.3087)
R	0.0055 (0.1188)	−0.0155 (−0.3383)	0.0679 (1.585)	0.5006 *** (8.2634)	0.4910 *** (8.0443)	0.3525 *** (6.3534)			
W*P						−0.3010 *** (−3.3201)			−0.2008 *** (−2.5762)
W*S			−0.2321 *** (−3.3957)						0.0075 (0.0957)
W*R			−0.0093 (−0.1199)			0.1232 (1.2105)			
ρ	0.8130 *** (26.2298)		0.7410 *** (23.7573)	0.3690 *** (4.7402)		0.6080 *** (14.8753)	0.1320 (1.3826)		0.2690 *** (4.6124)
λ		0.8200 *** (26.9238)			0.3500 *** (4.1937)			0.1750 * (1.8100)	
R^2	0.4461	0.0431	0.5611	0.2380	0.1953	0.4466	0.1397	0.1342	0.2001
Log likelihood	340.3295	339.1361	373.7774	206.5023	206.0221	256.5186	365.2648	366.0043	377.9929
LM−SLM	121.4472 ***	4020.86 ***		4.8249 **	0.3749		0.5396	13.0346 ***	
R−LM−SLM	1546.86 ***	66115.27 ***		34.8746 ***	146.1625 ***		0.1746	29.3138 ***	
LM−SEM	5.6262 **	355.7022 ***		0.0966	24.6954 ***		0.7902	4.5951 **	
R−LM−SEM	1431.04 ***	62,450.11 ***		30.1463 ***	170.4829 ***		0.4253	20.8742 ***	
LR−SLM			9.5611 ***			10.5411 ***			7.9157 **
LR−SEM			−0.2059			12.6892 ***			6.3919 **
Wald−SLM			14.9821 ***			59.2719 ***			47.8731 ***
Wald−SEM			15.2756 ***			47.1624 ***			53.1985 ***

Note: *** significant at 0.01 level, ** significant at 0.05 level, and * significant at 0.10 level. Progressive T-statistics are shown in parentheses. The above models are all mixed-effect panel regression models. Software: MATLAB.

The results show that the mixed effect is better than the fixed and random effects. It can be seen that the Spatial Lag Model is better than the Spatial Error Model by comparing R^2, LM-SLM, and LM-SEM, whereas Likelihood Ratio (LR) and Wald tests show that the Spatial Durbin Model is best. Table 2 shows that the results of the Spatial Lag Model, Spatial Error Model, and Spatial Durbin Model are significant, indicating that the pressure, state, and response of forest ecological security have a significant spatial spillover effect, that is, the pressure, state, and response of forest ecological security in a province can significantly affect its neighboring provinces.

Through the comparison of the above three models, it can be seen that the Spatial Durbin Model has the strongest ability to explain the spatial spillover effect. The Spatial Durbin Model can decompose the spatial spillover effect into each independent variable and spatial lag term, and the independent variables are divided into spatial and non-spatial terms (Table 3).

Table 3. Marginal effect reconstruction of Spatial Durbin Model.

Dependent Variable	Independent Variable	Local Effect	Spillover Effect	Total Effect
Pressure (P)	State (S)	0.2154 *** (6.3124)	−0.2016 (−1.0022)	0.0138 (0.0660)
	Response (R)	0.0781 (1.5420)	0.1432 (0.5247)	0.2213 (0.7250)
State (S)	Pressure (P)	0.3723 *** (6.3746)	−0.1502 (−0.8952)	0.2221 (1.3493)
	Response (R)	0.4234 *** (7.1290)	0.7954 *** (3.5599)	1.2187 *** (4.8564)
Response (R)	Pressure (P)	0.1100 ** (2.1744)	−0.2236 ** (−2.4976)	−0.1136 (−1.5499)
	State (S)	0.2147 *** (5.7602)	0.0838 (0.8925)	0.2985 *** (3.6303)

Note: *** significant at 0.01 level, ** significant at 0.05 level. T-statistic is in parentheses.

The results show that the forest ecological security state index of a province increases by 1 unit, and its pressure index will increase by 0.2154 units on average, under the condition that other influencing factors remain unchanged. Because the pressure index is adjusted to the positive index in the normalization process, its increase here indicates that the pressure faced by the forest ecosystem is decreasing. The spatial spillover effect of the state on the pressure is not significant, that is, the forest ecological security pressure value of a province will not be significantly affected by the forest ecological security state of its neighboring provinces. The local and spillover effects of the response also have no significant effect on the pressure, that is, the local and adjacent forest ecological security response has no significant effect on the local forest ecological security pressure. Similarly, all local and spillover effects of pressure–state–response can be obtained.

The results of the spatial spillover effect show that there are significant spatial spillover effects in the three subsystems of pressure, state, and response of the forest ecological security system in China. The interaction between subsystems is mainly a local effect, and the spillover effect mainly focuses on response → state and pressure → response. In addition, some of the spillover effects are negative (state → pressure, pressure → state, pressure → response), which will offset the local effects, and ultimately reduce the interaction among the pressure–state–response subsystems. Therefore, it is not conducive to improving the overall level of forest ecological security in China.

4. Conclusions and Implications

The results of the endogenous transmission mechanism and spatial effect of forest ecological security in China showed the following: (1) China still faces severe challenges to forest ecological security. From 2004 to 2018, the forest ecological security in most provinces was at sensitive and critical levels, and there were significant differences among provinces. The forest ecological security in Northeast China and Southwest China was higher than that in Northwest China and East China, and the forest ecological security in most provinces was gradually improving. (2) In terms of the internal composition of forest ecological security, during the study period, the forest ecosystem in most provinces was under less human impact, but increased gradually. The state of forest ecosystem was generally good, and it was improving continuously. The protection and investment measures of humans on the forest ecosystem were obviously insufficient in most provinces, and showed a trend of fluctuation and decline. (3) There were six different transmission mechanisms among the pressure–state–response of forest ecological security. Among these, the transmission between pressure and response was weaker, indicating that response measures were insufficient or did not match the pressure on forest ecosystem, which means that ecological control measures cannot effectively offset the impact of pollution and destruction on the ecological system, and the pressure will be higher than the response for a long time, which restricted the improvement of forest ecological security. (4) There were significant spatial correlation and spatial spillover effects in the pressure, state, and response of forest ecological security. The spillover effects were mainly concentrated in the paths of R→S and P→R. The positive spatial spillover of the response to the state means that local ecological construction and environmental protection measures produce significant positive externalities, which improved the external state of forest ecological security. The negative spatial spillover of the pressure to the response means that the increase in external pressure leads to a local reduction of ecological construction and environmental protection, which was not conducive to the improvement of forest ecological security. The spatial spillover effects are mainly due to the convergence of ecological policies, the transfer of information and knowledge, and the mutual incentive of environmental governance. Therefore, the improvement of China's forest ecological security is the result of the joint effect of inter-provincial ecological construction and environmental protection.

The following implications result from the above research conclusions: (1) The overall level of forest ecological security in China is relatively low. To improve China's forest ecological security, we must first adhere to the baseline of pressure, strictly control pollution emissions, and actively adjust the forestry industry structure. At the same time, all regions can continuously improve the state of the forest ecosystem by increasing reforestation, closing hills for afforestation, and strengthening forestry investment, so as to effectively improve the overall level of forest ecological security. (2) Although there are transmission barriers among the pressure–state–response of forest ecological security, conductive paths still exist between the three factors. Therefore, it is necessary to choose an appropriate transmission path in the process of improving China's forest ecological security. Clearly P→R→S and R→P→S have significant path advantages. Thus, it is concluded that the focus of improving China's forest ecological security is to take appropriate measures for pressure and response, and ensure the pertinence of decision-making goals while expanding the scale of investment in ecological construction and environmental governance. (3) The spatial effect of the pressure–state–response means that forest ecological security can be improved through inter-provincial mutual influence. Therefore, in the process of forest ecological security management, we must formulate targeted forest ecological protection policies according to regional differences. This should be undertaken while fully taking advantage of regional forest resources, making full use of the spatial spillover effect of forest ecological security, and continuously improving the overall level of China's forest ecological security through inter-provincial resource complementation, imitating competition, and information transmission.

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