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Assessment of the Synergy between Forestry Ecological Security and Forestry Industry Structure in Guangdong Province

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Abstract: *Against the backdrop of ecological civilization construction, forestry ecological security and forestry industry structure evolution have attracted increasing attention from the whole society. Based on the theory of composite system synergy and the DPSIR model, this paper constructs a composite system synergy model for forestry ecological security and forestry industry structure in Guangdong Province. The paper empirically analyzes the orderliness of each system and the synergy of the two systems from 2011 to 2021. The research results show that: (1) The orderliness of forestry ecological security system in Guangdong Province increased from 0.36 in 2011 to 0.514 in 2021, but it fluctuated and declined after 2016. (2) The orderliness of forestry industry structure system increased from 0.436 in 2011 to 0.689 in 2016, but it showed a downward trend after 2017, reaching 0.414 in 2021. (3) The synergy of the two systems presented a fluctuating trend from 2012 to 2021, but overall, the synergy showed a gradual increase, growing from -0.031 in 2013 to 0.068 in 2021. These results indicate the complexity and dynamics between forestry ecological security and forestry industry structure, as well as the overall improvement of their synergy. The study proposes policy implications such as strengthening forestry ecological security protection, optimizing forestry industry structure, enhancing the synergy of the two systems, formulating long-term strategies, and fully considering local characteristics to promote the sustainable development of forestry in Guangdong Province.*

Keywords: *Composite system synergy; DPSIR model; Forestry ecological security; Forestry industry structure*

1. Introduction

Forestry ecological security is an integral part of ecological environmental protection, closely intertwined with the evolution of forestry industry structure. It holds significant implications for both socioeconomic development and the human living environment. As the leading province in China's economy, Guangdong Province's forestry ecological security issues have garnered widespread attention. Establishing a new pattern of ecological construction for a beautiful and green Guangdong, creating a high-level integration of urban and rural green and beautiful environments, and harnessing ecological advantages for development strengths all contribute to crafting a model of harmonious coexistence between humans and nature, and paving the way for Guangdong to embrace a new era where "green mountains and clear waters are invaluable assets." This path will position Guangdong at the forefront of comprehensive socialist modernization, providing a solid ecological foundation for the province's journey towards new heights of success. In this context, comprehending and analyzing the developmental trends of Guangdong Province's forestry ecological security system and forestry industry structure system, as well as their interrelationships, holds crucial theoretical and practical significance for promoting sustainable forestry development in the region and even across the nation.

Previous studies have mainly focused on high-quality development of forestry *[1-4]*, total factor productivity of forestry *[5-8]*, and there have been few in-depth studies on the synergy between forestry ecological security and forestry industry structure. The related studies also tend to focus on individual systems *[9-11]*, with relatively limited research on the synergistic relationship between forestry ecological security and forestry industry structure. Additionally, the development of forestry ecological security and forestry industry structure systems may be influenced by various internal and external factors, and their developmental trends and interrelationships may exhibit complex and

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dynamic characteristics *[12]*. Therefore, accurately measuring and deeply analyzing the developmental trends and synergy between these two systems is an important research question.

Therefore, this study takes Guangdong Province as an example, using a composite system synergy model and DPSIR model to construct the forestry ecological security system and forestry industry structure system in Guangdong Province. The study evaluates the orderliness of each system and the synergy of the composite system between 2011 and 2021, and deeply explores their developmental trends and synergy. The research findings of this study can provide support for the management decision-making of forestry ecological security and forestry industry structure, and serve as a reference for promoting sustainable development of forestry.

2. Research Methods and Evaluation Indicator System

2.1. Composite System Synergy Model

The Composite System Synergy Model is a model used to assess and quantify the synergy effects among various components in a complex system, in order to evaluate the overall performance and level of synergy in the system [13]. In this study, the model is applied to the composite system of forestry ecological security and forestry industry structure in Guangdong Province, denoted as $S = (S_1, S_2)$. S_1 represents the forestry ecological security subsystem, and S_2 represents the forestry industry structure subsystem. $S_{kj} = \{S_{k1}, S_{k2}, \dots, S_{kj}, \dots, S_n\}$, where S_{kj} represents the j-th element of subsystem S_k and $j \in [1, n]$. Let $x_{ij} = (x_{1j}, x_{2j}, \dots, x_{ij})$ be the ordinal parameter of the subsystem, where x_{ij} is the i-th ordinal parameter of the j-th element. $\alpha_{ij} \le x_{ij} \le \beta_{ij}$,$i \in [1, n]$, where α_{ij} and β_{ij} are respectively the lower and upper limit coefficients of the ordinal parameter x_{ij}. In the model, $x_{1j}, x_{2j}, \dots, x_{mj}$ are defined as positive indicators, where higher values indicate higher order; $x_{m+1}, x_{m+2}, \dots, x_n$ are defined as negative indicators, where higher values indicate lower order.

The order degree $u_k(x_{ij})$ of subsystem S_k's ordinal parameter can be calculated using formula (1):

$$u_k(x_{ij}) = \begin{cases} \dfrac{x_{ij} - \alpha_{ij}}{\beta_{ij} - \alpha_{ij}}, i \in [1, m] \\ \dfrac{\beta_{ij} - x_{ij}}{\beta_{ij} - \alpha_{ij}}, i \in [m+1, n] \end{cases} \tag{1}$$

where $\beta_{ij} = x_{max} * 1.05$, $\alpha_{ij} = x_{min} * 0.95$, $u_k(x_{ij}) \in [0,1]$.

The order degree $u_k(x_i)$ of a subsystem represents the degree of synergy among the elements within the subsystem. The order degree of subsystem S_k can be obtained by integrating the order degrees of each ordinal parameter using the corresponding weights through linear weighting method. The calculation method is shown in formula (2).

$$u_k(x_i) = \sum_{j=1}^{n} w_j \cdot u_k(x_{ij}) \tag{2}$$

In equation (2), w_j represents the weight of the j-th element in subsystem S_k. $w_j \ge 0$, and $\sum w_j = 1$. The following section will discuss the methods for solving the weights.

After obtaining the degrees of order for the forestry ecological security subsystem and the forestry industry structure subsystem in Guangdong Province, the composite system synergy of the two subsystems can be further calculated. The calculation method is shown in formula (3):

$$C = \lambda \cdot \sqrt[n]{\left| \prod_{k=1}^{n} [u_k(x_i) - u_k(x_{i-1})] \right|} \tag{3}$$

In the equation, C represents the composite system synergy, and $C \in [-1,1]$. As for λ, we have:

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$$\lambda = \begin{cases} 1, \prod_{k=1}^{n}[u_k(x_i) - u_k(x_{i-1})] > 0 \\ -1, \prod_{k=1}^{n}[u_k(x_i) - u_k(x_{i-1})] \le 0 \end{cases} \tag{4}$$

The composite system synergy represents the degree of synergy between the subsystems within the composite system. In the equation, $u_k(x_i) - u_k(x_{i-1})$ represents the difference between the current degree of order and the previous degree of order for the kth subsystem. It is used to determine the direction of change in the degree of order for the kth subsystem. If $u_k(x_i) - u_k(x_{i-1})$ is positive, it indicates an increase in the degree of order, while if $u_k(x_i) - u_k(x_{i-1})$ is negative, it indicates a decrease in the degree of order. $\prod_{k=1}^{n}[u_k(x_i) - u_k(x_{i-1})]$ is used to determine whether the trends of subsystem changes are the same. If its value is greater than 0, it indicates a positive synergy degree in the composite system. Otherwise, it is negative.

2.2. The CRITIC method

The CRITIC method determines the objective weights of criteria based on the comparative strength of indicators and the conflicts between indicators. Its characteristic is that it simultaneously considers the variability of indicators and the correlations between them *[14]*. The comparative strength refers to the degree of variation within each indicator, measured by standard deviation σ_j. The conflict is measured by the correlation between indicators, where higher correlation between two indicators indicates lower conflict and smaller weight. Let C_j represents the information content contained in the j-th indicator, then C_j can be expressed as:

$$C_j = \sigma_j \sum_{i=1}^{n}(1 - r_{ij}) \tag{5}$$

The higher the information content, the more important the indicator is, and it should be assigned a higher weight. The weight of an indicator w_j can be expressed as:

$$w_j = \frac{C_j}{\sum_{i=1}^{n} C_j} \tag{6}$$

2.3. Construction of Indicator System

The DPSIR model, derived from the Pressure-State-Response (PSR) model, further deepens the study of environmental issues by adding two dimensions: "Drivers" and "Impacts". In this model, "Drivers" reflect the socio-economic background that triggers environmental issues, while "Impacts" describe the specific consequences of environmental issues on human well-being. These two additional dimensions allow for a more comprehensive understanding and response to environmental issues, forming the analytical framework of the Driver-Pressure-State-Impact-Response (DPSIR) model.

In the DPSIR model, "Drivers" refer to the fundamental causes that drive environmental issues, typically involving socio-economic factors. "Pressures" represent the specific impacts of drivers on the environment, including emissions of pollutants and land use changes. "State" refers to the specific condition of the environment. "Impacts" refer to the effects of changes in environmental conditions on human well-being, including health issues, productivity decline, and loss of ecosystem services."Response" is the feedback from society to environmental issues, which can be individual, community, government, or global responses, such as legislation, policy-making, and behavior changes.

In summary, based on the DPSIR model, this study selects 17 relevant indicators from the five aspects of drivers, pressures, state, impacts, and responses to construct the evaluation indicator system for forestry ecological security in Guangdong Province (Table 1). This indicator system comprehensively covers various dimensions of the DPSIR model, effectively connecting social-economic activities, environmental pressures, ecological state, natural impacts, and social

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responses, providing a scientific analytical framework for in-depth research on the synergy between forestry ecological security and forestry industry structure in Guangdong Province.

Table 1: Evaluation Indicator System for Forestry Ecological Security in Guangdong Province.

Criterion Level	Element Level	Indicator Level	Unit	Indicator Type	Weight
Driving force	Economic drive	Per Capita GDP (A1)	yuan	Positive	0.0663
		The proportion of the output value of the secondary industry(A2)	%	Negative	0.0441
	Social drive	Urbanization level(A3)	%	Negative	0.0477
		Population density(A4)	People per square kilometer	Negative	0.0586
Pressure	Environmental pressure	Solid waste emission intensity(A5)	Tonnes per square kilometer	Negative	0.0684
		Sulfur dioxide emission intensity(A6)	Tonnes per square kilometer	Negative	0.0954
		Nitrogen oxide emission intensity(A7)	Tonnes per square kilometer	Negative	0.0753
	Social pressure	Forest tourism development intensity(A8)	%	Negative	0.0427
State	Resource status	Forest stocking volume per unit area(A9)	Cubic meters per hectare	Positive	0.0496
		Forest coverage rate(A10)	%	Positive	0.0151
Influence	Natural impact	Forest fire incidence rate(A11)	%	Negative	0.0637
		Forest pest infestation rate(A12)	%	Negative	0.0704
Response	Response deployment	The proportion of ecological construction and protection in the total investment amount of forestry(A13)	%	Positive	0.0492
		The density of forestry personnel(A14)	People per ten thousand hectares	Positive	0.0751
		The proportion of new afforestation(A15)	%	Positive	0.0601
	Governance response	The comprehensive utilization rate of solid waste(A16)	%	Positive	0.0378
		The rate of forest pest control for harmful organisms(A17)	%	Positive	0.0805

According to the theory of industrial economics, the forestry industry structure reflects the economic and technological links and proportion relationships within the forestry sector and between forestry and other industries. The changes in this structure to some extent can reflect the development stage of forestry and the degree of optimization of its economic structure in Guangdong Province. In this paper, the value-added structure is used as the core indicator to measure the forestry industry structure. The value-added structure reflects the status and influence of various sectors within the forestry industry in economic activities. Among them, an increase in the proportion of value-added from the primary sector of forestry may bring more ecological pressure, so we consider it as a negative indicator. On the other hand, an increase in the proportion of value-added from the secondary and tertiary sectors of forestry may bring more economic benefits and employment opportunities, which is beneficial for the sustainable development of forestry, so we consider them as positive indicators. The evaluation indicators for the industrial structure of forestry in Guangdong Province are shown in Table 2.

Table 2: Evaluation Index System for Forestry Industry Structure in Guangdong Province.

Criterion Level	Indicator Level	Unit	Indicator Type	Weight
Value-added structure	Proportion of value-added from the primary sector in forestry (B1)	%	Negative	0.2490
	Proportion of value-added from the secondary sector in forestry (B2)	%	Negative	0.3272
	Proportion of value-added from the tertiary sector in forestry (B3)	%	Positive	0.4238

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Researching the above two indicator systems can provide a deeper understanding of the synergy between forestry ecological security and industry structure in Guangdong Province. It can also help identify effective management strategies and solutions to promote the optimization and coordinated development of forestry ecological security and industry structure in Guangdong Province.

2.4. Data Sources

Considering the availability of data, this study selected relevant data from Guangdong Province from 2011 to 2021 for empirical analysis. The data sources mainly include the "China Statistical Yearbook" (2012-2022), "Guangdong Statistical Yearbook", "Guangdong Rural Statistical Yearbook", "China Forestry and Grassland Statistical Yearbook", and "China Forestry Statistical Yearbook". For missing data, linear interpolation was used for imputation, and the economic data were converted to comparable prices based on the year 2011.

3. Empirical Analysis

3.1. Calculation of Subsystem Orderliness

According to formula (1), the orderliness parameters of the forestry ecological security subsystem and the forestry industry structure subsystem were standardized. The results are shown in Table 3 and Table 4.

Table 3: Orderliness of Forestry Ecological Security Subsystem in Guangdong Province.

Orderliness Parameter	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
A1	0.063	0.13	0.21	0.291	0.382	0.471	0.562	0.648	0.734	0.756	0.895
A2	0.145	0.666	0.68	0.693	0.738	0.813	0.81	0.813	0.834	0.892	0.885
A3	0.78	0.742	0.679	0.644	0.585	0.543	0.504	0.433	0.378	0.279	0.247
A4	0.827	0.735	0.66	0.591	0.527	0.452	0.377	0.314	0.267	0.227	0.204
A5	0.842	0.807	0.823	0.898	0.915	0.915	0.125	0.607	0.559	0.51	0.219
A6	0.053	0.115	0.161	0.201	0.266	0.673	0.834	0.927	0.966	0.97	0.994
A7	0.079	0.175	0.288	0.381	0.523	0.698	0.792	0.842	0.905	0.965	0.941
A8	0.735	0.734	0.721	0.611	0.515	0.353	0.287	0.626	0.616	0.601	0.585
A9	0.102	0.242	0.377	0.49	0.579	0.631	0.677	0.667	0.657	0.681	0.86
A10	0.377	0.43	0.495	0.56	0.585	0.598	0.611	0.547	0.549	0.556	0.567
A11	0.057	0.927	0.689	0.504	0.228	0.989	0.645	0.453	0.337	0.747	0.412
A12	0.591	0.594	0.692	0.432	0.483	0.677	0.977	0.434	0.069	0.079	0.088
A13	0.082	0.489	0.878	0.537	0.746	0.622	0.339	0.328	0.302	0.3	0.298
A14	0.901	0.803	0.788	0.675	0.65	0.619	0.547	0.3	0.258	0.134	0.056
A15	0.201	0.145	0.228	0.261	0.945	0.68	0.597	0.609	0.538	0.594	0.008
A16	0.565	0.543	0.43	0.506	0.754	0.56	0.268	0.419	0.316	0.219	0.381
A17	0.033	0.213	0.099	0.189	0.367	0.583	0.675	0.771	0.923	0.889	0.854

Table 4: Orderliness of Forestry Industry Structure Subsystem in Guangdong Province.

Orderliness Parameter	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
B1	0.621	0.912	0.779	0.799	0.902	0.912	0.861	0.799	0.661	0.322	0.128
B2	0.854	0.327	0.312	0.304	0.26	0.183	0.188	0.184	0.163	0.108	0.112
B3	0.004	0.764	0.745	0.765	0.847	0.949	0.928	0.915	0.902	0.875	0.815

3.2. Results Analysis

Based on the weights of the subsystem orderliness parameters and formulas (2)~(4), the orderliness of the forestry ecological security system and forestry industry structure system in Guangdong Province, as well as the composite system synergy, were calculated. The results are shown in Table 5. The development trend of the orderliness of the subsystems is illustrated in Figure 1. It can be observed that since 2011, the orderliness of the forestry ecological security and forestry industry structure systems in Guangdong Province has exhibited significant fluctuations throughout the development

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process.

Table 5: Orderliness and Synergy of Forestry Ecological Security and Forestry Industry Structure in Guangdong

Year	Orderliness of Forestry Ecological Security System	Orderliness of Forestry Industry Structure System	Synergy
2011	0.36	0.436	—
2012	0.477	0.658	0.161
2013	0.498	0.612	-0.031
2014	0.473	0.623	-0.017
2015	0.553	0.669	0.061
2016	0.651	0.689	0.044
2017	0.59	0.669	0.035
2018	0.592	0.647	-0.007
2019	0.564	0.6	0.036
2020	0.577	0.487	-0.038
2021	0.514	0.414	0.068

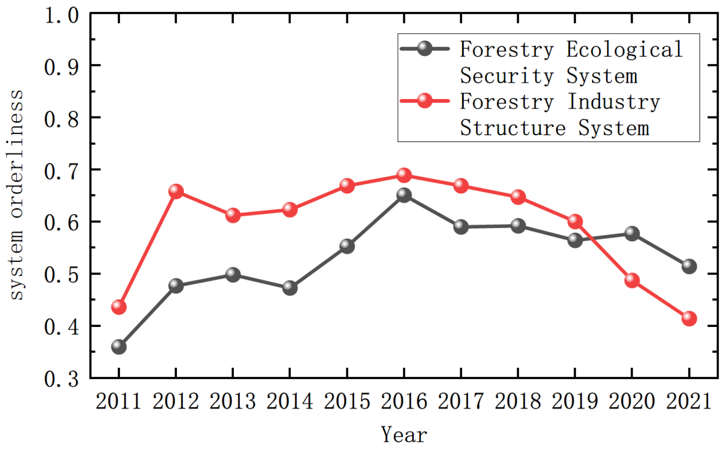

Figure 1: Forestry Ecological Security and Orderliness of Forestry Industry Structure System

According to Table 5, we can observe a fluctuating growth trend in the orderliness of the forestry ecological security system in Guangdong Province from 2011 to 2021. This is likely due to various internal and external factors affecting forestry ecological security, including but not limited to socio-economic development, environmental pressures, resource conditions, natural influences, and response measures. In 2011, the orderliness of the forestry ecological security system in Guangdong Province was at a relatively low level of 0.36. This could be attributed to lower levels of socio-economic development, higher environmental pressures, poorer resource conditions, stronger natural influences, and insufficient response measures at that time. However, as socio-economic development progressed, the government and society gradually increased their attention to forestry ecological security, leading to the implementation and improvement of relevant policies and measures. As a result, the orderliness of the forestry ecological security system has been increasing year by year. By 2016, the system's orderliness had reached 0.651, indicating significant progress. This could be attributed to increased government investment in forestry ecological protection, optimization of the forestry industry structure, improvement in the technical and managerial skills of forestry practitioners, and the implementation of a series of forestry ecological protection and governance measures. However, from 2016 to 2021, the system's orderliness experienced fluctuating declines, especially in 2020 and 2021, where the orderliness dropped to 0.577 and 0.514, respectively. This could be due to the occurrence of natural disasters such as forest fires and outbreaks of harmful pests during this period, which had a severe impact on forestry ecological security. Overall, although the orderliness of the forestry ecological security system in Guangdong Province has improved to some extent, it still faces challenges.

The orderliness of the forestry industry structure has undergone a fluctuating change from 2011 to 2021, with an initial increase followed by a decrease. In the initial stage (2011 to 2016), the orderliness of the forestry industry structure increased from 0.436 to 0.689, indicating a significant improvement

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and a trend towards a more orderly structure. This could be attributed to the combined effects of policy promotion, technological advancements, and stable growth in market demand. However, starting from 2017, the orderliness of the forestry industry structure began to decline and reached 0.414 by 2021. This could be attributed to changes in the market environment, intensified industry competition, and the impact of natural disasters and other internal and external factors. The decline in orderliness was particularly significant from 2019 to 2021, which could be associated with the impact of the COVID-19 pandemic. The significant economic impact of the pandemic likely led to a decline in forestry market demand and disruption in the industry structure.

According to Table 5 and Figure 2, we can observe a fluctuating trend in the synergy of the composite system between the forestry ecological security subsystem and the forestry industry structure subsystem from 2012 to 2021. Starting from 2012, the synergy reached 0.161, indicating a relatively good synergy and strong collaborative effects between the forestry ecological security subsystem and the forestry industry structure subsystem in that year. However, in 2013 and 2014, the synergy turned negative with values of -0.031 and -0.017, respectively, indicating a lack of synergy or even conflicts between the two subsystems during those years. From 2015 to 2017, the synergy returned to positive values and remained within the range of 0.061 to 0.035, indicating the restoration and maintenance of a certain level of synergy between the two subsystems during those three years. However, in 2018 and 2020, the synergy turned negative again with values of -0.007 and -0.038, respectively, suggesting the emergence of new non-synergistic phenomena between forestry ecological security and the forestry industry structure, possibly due to new environmental pressures, policy changes, or shifts in market demand.

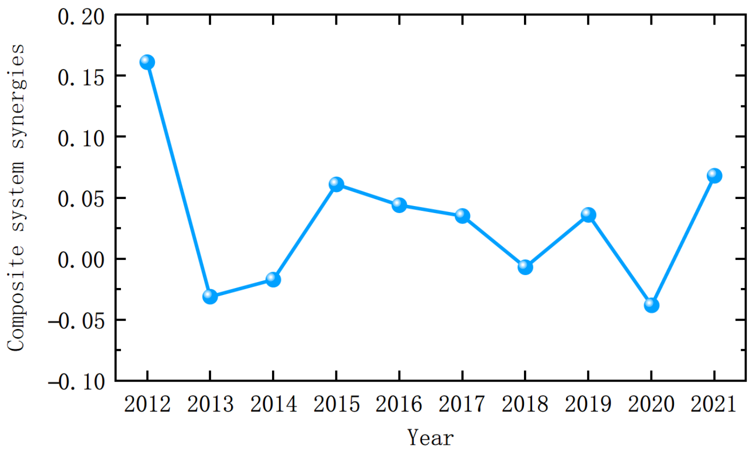

Figure 2: Synergy between Forestry Ecological Security and Forestry Industry Structural Composite System

It is worth noting that by 2021, the synergy has risen to 0.068, the highest value since 2012. This indicates an improvement in the synergy between the forestry ecological security subsystem and the forestry industry structural subsystem, suggesting that the interaction between the two may be moving towards a more harmonious and orderly state.

Overall, the fluctuations in the composite system synergy between the forestry ecological security subsystem and the forestry industry structural subsystem over the past decade demonstrate the complexity and dynamics of the relationship between these two subsystems. It is important to note that although negative values were observed in certain years, indicating conflicts and lack of synergy between the two subsystems, the overall trend shows a gradual increase in synergy. This suggests that when facing pressure and challenges, the two subsystems are gradually finding synergy and balance, which provides a positive signal for the future development of forestry.

4. Research Conclusions and Policy Implications

4.1. Research Conclusions

This article constructs a composite system synergy model of ecological security in forestry and industrial structure in Guangdong Province based on the theory of composite system synergy and the DPSIR model. It empirically analyzes the orderliness of the ecological security subsystem and the

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industrial structure subsystem, as well as the composite system synergy between the two systems. The research conclusions are as follows:

(1) The orderliness of the ecological security subsystem in Guangdong Province shows a fluctuating growth trend from 2011 to 2021. This indicates that despite facing various internal and external influences such as socio-economic development, environmental pressure, resource status, natural impacts, and response measures, the ecological security in forestry can gradually adjust and improve its orderliness, even though it faces challenges in certain years.

(2) The orderliness of the industrial structure in forestry undergoes a process of initial increase and subsequent decrease during this period. This may reflect the influence of factors such as policy promotion, technological progress, and market demand on the orderliness of the industrial structure in forestry. Especially in recent years, the orderliness of the industrial structure in forestry has declined, possibly due to the impact of the COVID-19 pandemic and changes in the market environment.

(3) The synergy between the ecological security subsystem and the industrial structure subsystem in forestry shows a fluctuating trend from 2012 to 2021. However, considering the overall trend, the synergy shows a gradual increase. This indicates that when facing pressure and challenges, these two subsystems can gradually find synergy and balance. Although conflicts and lack of synergy may occur in certain years, the overall synergy relationship has been improved.

4.2. Policy Implications

Based on the above conclusions, the following policy implications can be drawn:

(1) Strengthen the Symbiotic Relationship between Ecological Security and Industrial Structure: Given the confluence of environmental changes and anthropogenic factors, increased investment in ecological restoration and forestry pest prevention is imperative. Concurrently, realigning the forestry industrial structure in accordance with market demand and fostering technological innovation are necessary for bolstering industry competitiveness. Policy frameworks and institutional innovations should be developed to facilitate a synergistic relationship between ecological security and the industrial landscape in forestry.

(2) Formulate and Implement Longitudinal Strategic Frameworks: Governmental agencies and relevant stakeholders should craft comprehensive long-term strategic plans for forestry development. This encompasses both ecological and industrial objectives, with built-in mechanisms for regular evaluations and necessary adjustments throughout the implementation phase.

(3) Incorporate Regional Specificities: The formulation and implementation of forestry policies in Guangdong Province should be contextualized, taking into account local environmental conditions, socio-economic statuses, and cultural traditions. Targeted policies and adaptive measures should be employed based on these regional specificities.

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