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Coupling coordination relationship of forestry industry development and ecological environment: evidence from Heilongjiang Province

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China's economy has entered a new period of transformation, and the development of various industries will become the backbone of promoting economic sectors. At the same time, it will also become a booster for promoting the transformation and development of various industries. As an essential component of China's economic construction, forestry will also enter a critical period of transformation. However, because the forestry industry mainly relies on forest resources as production factors, there is a certain contradiction between the forestry industry development and the ecological environment. Therefore, taking Heilongjiang Province as an example, this paper applies the PSR model to explain the mechanism of the relationship between forestry industry development and the ecological environment. The PSR model mainly consists of three indicators: Pressure, State, and Response, which analyze the interrelationships between elements within the system. On the other hand, the coupling coordination model is applied to analyze the coupling coordination relationship between the forestry industry development and the ecological environment in Heilongjiang Province from 2011 to 2018. The results show that the development of the forestry industry puts pressure on the ecological environment. At the same time, the environmental climate also imposes restrictions and constraints on the development of the forestry industry. The two promote, influence, and constrain each other. The development of the forestry industry was antagonistic, running in, coupled, and coordinated with the ecological environment in Heilongjiang Province from 2011 to 2018. However, there is still a particular gap in the level of coupling and coordination between the two, and they have yet to reach a state of good coordinated development. Therefore, Heilongjiang Province can promote the coordinated development of its forestry industry and the ecological environment through innovative forestry industry transformation models, policy-oriented rational development and utilization of forest resources, environmentally constrained clean production of the forestry industry, and complementary and shared development of the forestry industry and ecological environment.

KEYWORDS

forestry industry development, ecological environment, low-carbon, coupling coordination, PSR model, comprehensive index method

1 Introduction

The ecological environment is vital in achieving the United Nations Sustainable Development Goals (Zhang et al., 2024), while forestry will play an essential role in improving the ecological environment. In response to rising environmental concerns, China has shifted its wood supply policy to improve its ecological environment (Huang and Cao, 2022). Therefore, China proposed the construction of ecological civilization to create sustainable ecological outputs. As an essential component of modern economic construction and a significant gateway to ecological civilization construction, the forestry industry becomes an essential direction for optimizing and improving the economic structure and a meaningful way to switch between new and old economic forces. Then, as economic development and societies advance, human demands have become more diverse, especially the need to improve their ecological situations. The forestry industry meets a community's diversity demands and improves its ecological environment (Dong et al., 2013). However, the forestry industry has thus far been unable to satisfy people's ecological demand for a better life through simple product reproduction and services (Caves, 2002). Therefore, it is necessary to seek the balance of forestry development and natural ecosystem development and promote the coordinated and sustainable development of the forestry industry and ecological environment.

Heilongjiang Province is China's northernmost and easternmost province, with the highest latitude and easternmost longitude. It is essential for land transportation from Asia and the Pacific to the Far East of Russia and Europe. Heilongjiang Province has the most significant critical state-owned forest area in China, with a forest area of 24.5377 million hectares, a total standing timber volume of 1999.9941 million cubic meters, and a forest coverage rate of 43.78%, ranking ninth nationwide. The forest area, total forest volume, and timber production all rank among the top in the country, making it the most crucial state-owned forest area and the most extensive timber production base in the country. Over the past 70 years, Heilongjiang Province has contributed over 700 million cubic meters of timber to the government and completed artificial afforestation of 170 million acres. At the same time, as a significant forestry province, Heilongjiang Province has abundant natural forest resources, and the ecological status of forestry is critical, serving as a natural environmental barrier in northern China. Therefore, Heilongjiang Province plays an irreplaceable role in conserving water sources, regulating climate, maintaining biodiversity, maintaining regional ecological balance and security, and ensuring national timber's continuous and stable supply. It has made outstanding contributions to national economic construction, social progress, and ecological civilization construction and has also played an indispensable role in the economic development of Heilongjiang Province. However, for historical reasons, to meet the demand for wood in national economic construction, state-owned forest areas under the jurisdiction of Heilongjiang Province have formed a single industrial structure dominated by wood production by utilizing and exploiting natural forest resources. Long-term timber mining has led to a resource crisis, economic crisis, and ecological crisis in Heilongjiang Province, causing heavy damage to the forestry economic development of Heilongjiang Province. It has led to decreased vitality in the traditional forestry industry, economic development, and social progress efficiency. The contradiction between economic development and the ecological environment is becoming increasingly prominent. To promote the positive evolution of traditional forestry towards modern forestry, promote the gradual economic recovery of Heilongjiang Province, promote the continuous restoration of forestry resources, and achieve social harmony and stability in Heilongjiang Province, Heilongjiang Province is bound to carry out forestry industry transformation under the premise of ecological construction, to conduct coordinated and sustainable development of forestry industry economy and ecological environment protection. Therefore, compared to other forestry provinces, Heilongjiang Province, which considers the dual mission of economic development and environmental construction, has a certain uniqueness. By calculating the coupling coordination degree between the forestry industry and the ecological environment, we can understand the current relationship between the development of the forestry industry and the environmental climate in Heilongjiang Province, effectively alleviate the contradiction between the two, promote the transformation of the forestry industry in Heilongjiang Province, promote high-quality economic development in Heilongjiang Province, provide practical basis for the future forestry development in Heilongjiang Province, and provide reference for other forestry regions or countries. Therefore, it is of great significance to calculate the relationship between the development of the forestry industry and the ecological environment in Heilongjiang Province based on the coupling coordination model in this article.

The uniqueness of the Heilongjiang Province region makes it the innovation of this article to use it as the research object. Heilongjiang Province has abundant forest resources and has formed a relatively developed forestry industry system and a reasonably complete ecological system. The two promote and influence each other, making the study of the coupling relationship between the development of the forestry industry and the environmental environment in Heilongjiang Province more special than other regions. Meanwhile, due to the potential damage to the ecological environment caused by the excessive pursuit of forestry industry development, this article uses negative indicators to calculate the relationship between the two, while most scholars choose positive indicators.

This article takes Heilongjiang Province as the research object, analyzes the coupling coordination relationship between forestry industry development and ecological environment based on the coupling coordination degree model, and effectively promotes the high-quality development of forestry economy in Heilongjiang Province, promoting the transformation of forestry industry. The article first explains the particularity of the region in Heilongjiang Province, which makes it of great significance to study the coupling relationship between the development of the forestry industry and the ecological environment in Heilongjiang Province. Secondly, based on the PSR model, the mechanism of the relationship between forestry industry development and the environmental climate is elaborated, laying a theoretical and practical foundation for calculating the coupling and coordination relationship between the two. Thirdly, based on the coupling coordination degree model, calculate the coupling coordination

relationship between the development of the forestry industry in Heilongjiang Province and the ecological environment. Finally, based on the coupling and coordination results of the development of the forestry industry and environmental environment in Heilongjiang Province, an explanation and discussion will be conducted to illustrate the correlation and impact of different policy periods on the development of the forestry industry and ecological environment. At the same time, countermeasures and suggestions will be provided for the coordinated and sustainable development of the forestry industry and environmental environment in Heilongjiang Province, as well as the high-quality development of the forestry economy.

2 Literature review

Many studies related to this study consider the relationship between the forestry industry and the ecological environment. On the one hand, elaborating on the relationship between the forestry industry, ecological environment, and economy in different regions can effectively guide the development of regional forestry. On the other hand, the relationship between industry and ecology is evaluated through different methods.

First, it elaborates on the relationship between the forestry industry, the ecological environment, and the economy. The forestry industry is a resource-constrained industry with certain resource limitations. The quantity and richness of forest resources determine the scale of the forestry industry. The development of the forestry industry and the adjustment of forestry industry institutions have always been aimed at promoting the economic development of forest areas while maximizing the ecological function of forest resources, and there is inevitably a correlation between economy and ecology (Costanza, 1989). Norgaard (1992) proposed that there is a specific coordination relationship between the ecological environment and socio-economic development; it can avoid the consequence of disrupting the relationship through circular development (Glen et al., 2007). The forestry industry is an economic sector and the main body of environmental conservation. By studying the relationship between the forestry industry and ecology in Sweden and the United States at the beginning of the 21st century, it was found that these two countries usually focus on ecology, paying more attention to the ecological environment while also caring about the forestry industry (Mårald et al., 2016). A healthy development between the ecological environment and the economy can effectively achieve a win-win situation for both the ecological and economic systems (Glen et al., 2007). Therefore, it is possible to effectively promote the development of the forestry industry by studying and implementing management policies based on ecological intensification (Montesinos, 2019). At the same time, strengthening and deepening research on the ecological environment can also better guide forestry production practices (Blanco et al., 2022).

Second, it evaluates the relationship through various methods. The more influential methods of ecological evaluation include comprehensive index evaluation methods (Wei and Zimmermann, 2017) and landscape ecology evaluation methods (Kareiva et al., 2007; Taylor et al., 2007), economic evaluation methods (Sun et al., 2019), ecosystem service evaluation methods (Yan and Tang, 1984; Wang et al., 2015; Zhu et al., 2018), and ecological footprint evaluation methods (Yang and Zhu, 1999; Liu et al., 2005). The more influential methods of the forestry industry include development stages, Space dynamics (Xie et al., 2016), and comprehensive evaluation. The relationship between the forestry industry and ecological environment methods includes cooperation mechanisms, environmental Kuznets curves, and spatial econometric models (Zhang et al., 2020). Most of them are coupling coordination. Couping refers to a measure of the interdependence between two entities on each other. Ma Shijun, as a pioneer of ecological research, designed principles and optimization methods from systems engineering, which can reflect the ideas of ecology, economics, geography, and sociocultural study (Eshun et al., 2010). In 1986, the publication of *Ecological Economics* became the symbol of the ecological and economic systems theory suitable for the Chinese context (Hammett et al., 2001). Price and Keppo (2017) built the global energy economy model, which was constructed based on the relationship between resource environment, energy consumption, and economic development to achieve stable and coordinated development of industry and ecological environment (Price and Keppo, 2017).

In summary, existing research at home and abroad has researched the relationship between economy and ecology, the forestry industry, and forestry ecological construction. However, there needs to be more calculation of the coupling and coordination relationship between forestry industry development and the ecological environment, especially in areas with rich forest resources. Then, its industry development has used forest resources as production factors. As a significant forestry province, the contradictory relationship between the forestry industry development and the ecological environment in Heilongjiang Province will make it more important to analyze the coupling coordination relationship between the two. Therefore, this article takes Heilongjiang Province as the research object, exploring the comprehensive situation of the forestry industry development and the ecological environment by comprehensive index method and coupling coordination model. Analyzing the degree of coupling coordination between the two provides a valuable reference for promoting the transformation and development of the forestry industry, sustainable forestry development, and high-quality economic development in Heilongjiang Province.

3 The coupling mechanism between forestry industry development and the ecological environment

The coupling relationship between forestry industry development and the ecological environment includes the pressure that forestry industry development brings to the ecological environment and the limitations and constraints that the latter imposes on the former. The forestry industry development and ecological environment mutually promote, influence, and constrain each other. Therefore, based on the PSR model, this article elaborates on the mechanism of the relationship between forestry industry development and the ecological environment. The

PSR model consists of three indicators: Pressure, State, and Response. It was initially proposed by Canadian statisticians Rapport (1979). Later, it was jointly developed by the Organization for Economic Cooperation and Development and the United Nations Environment Programme to study environmental issues. It is now widely used in the sustainable development of the ecological environment, evaluation index system of agricultural development, and analysis of sustainable development (Dai and Yousaf, 2023).

3.1 Analysis of the pressure of forestry industry development on ecological environment

The forestry industry is a processing object focusing on forest resources, including cultivation, collection, and production activities. It can improve the forestry economic benefits, promote industrial economic development, and drive rural labor employment, making it the most important economic source in forest areas. At the same time, developing the forestry industry can also improve the ecological environment and promote ecological balance. However, while the rapid development of the forestry industry brings significant economic benefits and improves the environment, it will inevitably cause particular damage to forest resources. While pursuing the economic benefits of forestry industry development, it will ignore the impact of forestry industry development on the ecological environment. The forestry industry takes forest resources as processing objects, forming a primary industry dominated by resource cultivation, a secondary industry dominated by resource processing, and a tertiary industry dominated by forest tourism. The secondary industry brings the most significant pressure on the environment among them. Through the development and utilization of forest resources, on the one hand, after forest resources are harvested and utilized, their ecological service functions will gradually weaken and eventually disappear. On the other hand, some resource processing industries can cause unavoidable environmental damage during production processes.

3.2 Analysis of the limitations and constraints of ecological environment on the development of forestry industry

With the increasingly prominent global ecological and environmental issues, the forestry ecological service function and its ecological benefits have been further valued. The forestry ecological benefits reflect the effectiveness of forest ecosystem services. In 2008, the National Forestry Administration issued the Forest Ecosystem Service Function Evaluation Specification, which refers to the natural environmental conditions and utility that forest ecosystems and ecological processes form and maintain for human survival. Ma et al. (2017) evaluated China's Gross Ecosystem Product (GEP) for terrestrial ecosystems 2015. GEP for terrestrial ecosystems in 2015 was ¥72.81 trillion (Ma et al., 2017). However, if forest resources are destroyed, it will bring environmental problems that cannot be ignored. Therefore, as a fundamental industrial sector formed by relying on forest resources with significant ecosystem service value, managing and utilizing forest resources well will promote the development of the forestry industry, but on the contrary, it will bring certain obstacles to the development of the forestry industry. Therefore, the state of the ecological environment will bring certain limitations and constraints to the development of the forestry industry. When the ecological environment is damaged, forestry production activities relying on it will face severe losses.

3.3 The coupling mechanism based on the PSR model

In the forestry industry development and the ecological environment system, with the rapid development of the forestry industry and the continuous development and utilization of forest resources, the forestry industry is gradually growth. The forestry industry development system is causing pressure on environmental resources, such as forest resources (P). At the same time, due to the rapid development of the forestry industry, the structure is constantly changing, and the industrial scale is gathering, leading to intensified pollution emissions, a gradual imbalance in the industrial structure, and a gradual reduction in exploitable resources. The demand for the ecological environment in the forestry industry development is increasing, and the ecological service function of the ecological environment is decreasing, resulting in a change in the state of the ecological environment system (S), which causes limitations and constraints to the forestry industry development from resource constraints and control environmental pollution. Then, it makes the forestry industry development system slow down, adjusts resource utilization methods, and strengthens environmental governance (R), providing corresponding conditions for the improvement of the ecological environment, thereby improving the governance level of the ecological environment system, improving the ecological environment, enhancing it is carrying capacity, and better promoting the forestry industry development. The forestry industry development system and the ecological environment system interact and couple with each other, transforming from disharmony to coordination. The relationship gradually reaches a coordinated and unified level, achieving coupling, coordination, orderly, and healthy development. The coupling mechanism between forestry industry development and the ecological environment is shown in Figure 1.

4 Materials and methodology

4.1 Research methods

4.1.1 Comprehensive index method

The basic idea of the comprehensive index method is to use the mean method to perform dimensionless processing on the values of each indicator so that indicator data of different units or magnitudes can be analyzed under more equal conditions. The index values obtained through dimensionless processing range from 0 to 1, and then the unquantified index values are multiplied by the weight values of each index to obtain the comprehensive evaluation scores.

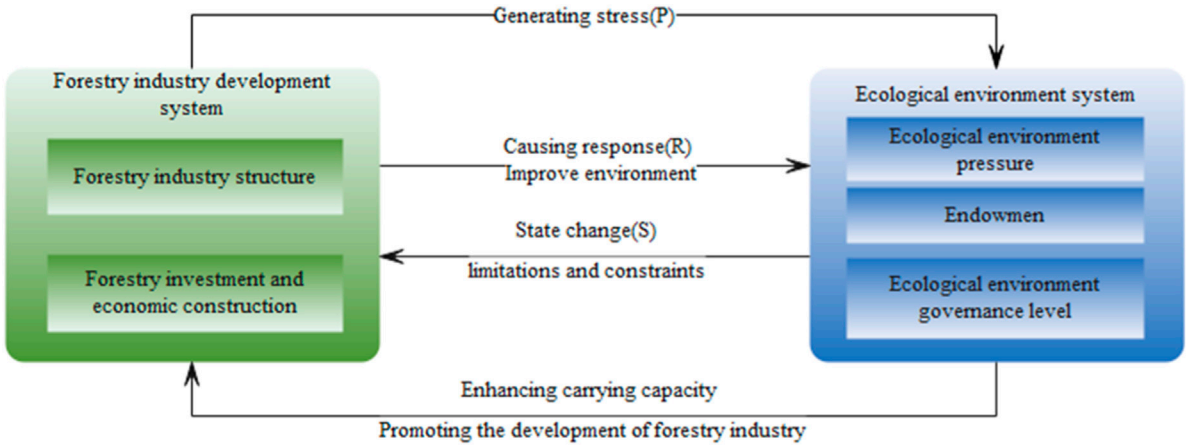

FIGURE 1
The coupling mechanism between the forestry industry and the ecological environment.

First, select the target sequence. According to the direction of the selected indicator, if the indicator is positive, the more significant indicator value is better. The selected target sequence is the maximum value of each indicator. If the indicator is negative, the smaller indicator value is better; the selected target sequence is the minimum value of each indicator. It is generally expressed as Eq. 1.

$$x_0 = \{x_0(1), x_0(2), \cdots x_0(n)\} \tag{1}$$

Second, calculate the initialization matrix. The attribute matrix is formed between the solution set and the sequence, and initialization is performed on the attribute matrix to obtain the initialization matrix Y.

Third, calculate the judgment coefficient. According to the initialization matrix, the grey correlation degree judgment coefficient is calculated. It can be calculated from Eq. 2.

$$\xi_i(k) = \frac{\min\limits_i \min\limits_k |x_0(k) - x_i(k)| + \zeta \max\limits_i \max\limits_k |x_0(k) - x_i(k)|}{|x_0(k) - x_i(k)| + \zeta \max\limits_i \max\limits_k |x_0(k) - x_i(k)|}$$
$$\zeta = 0.5 \tag{2}$$

Fourth, determine weights. According to the grey correlation degree judgment coefficient, the mean value of each indicator is determined, forming a matrix w. This matrix can reflect the proportion of each indicator in the entire indicator set. The matrix w is normalized to form W, which is the weight.

Fifth, calculate the comprehensive evaluation value. It can be calculated from Eq. 3.

$$Y_j = \sum_{i=1}^{n} X_{ij} \times W_i \tag{3}$$

Y_j is the comprehensive evaluation value in the j year.X_{ij} is the statistical value of the i indicator in the j year.W_i is the weight of the i indicator.n is the number of evaluation indicators.

This article constructs an evaluation index system for developing the forestry industry and ecological environment system in Heilongjiang Province. It calculates the comprehensive evaluation value of the two based on the complete index method, which serves as the basis for calculating the coupling coordination degree of the two.

4.1.2 Coupling coordination model

The coupling coordination degree is usually used to measure the mutual influence and interaction between multiple systems or elements. It can generalize the coupling degree model for the interaction between multiple systems or elements, drawing on the capacity coupling coefficient model in physics (Zhao and Shi, 2023). The coupling coordination model has been widely applied in economics and geography as an effective tool for studying the coupling effects between social and economic systems (Wang et al., 2022). It is expressed as Eqs 4–6.

$$D = \sqrt{C \times T} \tag{4}$$

$$C = n \times \left[\frac{U_1 U_2 \cdots U_n}{(U_1 + U_2 + \cdots + U_n)^n}\right]^{\frac{1}{n}} \tag{5}$$

$$T = \alpha K_\omega + \beta H_\omega \tag{6}$$

D refers to the coupling coordination degree, C refers to Indicates the coupling degree, and T refers to coordination. C reflects the coupling relationship between variables, and K_ω and H_ω reflect the comprehensive evaluation value. T reflects the overall development level of variables. α and β are weight coefficients because the two systems are equally important. They take $\alpha = \beta = 0.5$. D represents the degree of coupling coordination, such that the more significant the value, the higher the degree of coupling coordination. Conversely, the lower the degree between the two. According to the coupling coordination model, it can be divided into ten levels and five types through the value of D shown in Table 1.

This article is based on the comprehensive evaluation of the development of the forestry industry and the ecological environment system in Heilongjiang Province. The coupling coordination degree model is applied to calculate the coupling coordination relationship between the two, thoroughly verifying the mutual relationship between the two, analyzing the coupling coordination relationship between the two, and providing policy

TABLE 1 Coupling coordination level classification.

D	Coupling coordination degree	Coordination level	Coupling coordination stage
D∈(0.0~0.1)	Extreme imbalance	1	Imbalanced
D∈[0.1~ 0.2)	Severe imbalance	2	
D∈[0.2~0.3)	Moderate imbalance	3	Antagonistic
D∈[0.3~0.4)	Mild imbalance	4	
D∈[0.4~ 0.5)	Near imbalance	5	Running in
D∈[0.5~0.6)	Barely coordinated	6	
D∈[0.6~0.7)	Primary coordination	7	Coupled
D∈[0.7~0.8)	Intermediate coordination	8	
D∈[0.8~0.9)	Good coordination	9	Coordinated
D∈[0.9~ 1.0)	High-quality coordination	10	

FIGURE 2
Map of Heilongjiang province.

recommendations for developing the forestry industry and ecological environment construction in Heilongjiang Province.

4.2 Study area and data sources

This article takes Heilongjiang Province as the research area. Heilongjiang Province is located in the northeast of China and has the largest state-owned forest area in the country, with a forest coverage rate of 43.78%. It plays an irreplaceable role in protecting water sources, regulating climate, preserving biodiversity, and maintaining regional ecological balance. It is an essential environmental barrier in northern China. Heilongjiang Province has abundant forest resources, especially natural forest resources. Therefore, for a long time, Heilongjiang Province has formed a single industrial structure mainly focused on logging and utilizing natural forests, making outstanding contributions to national economic construction and social progress. However, the long-term dependence on timber resources has led to the destruction of the ecological environment in Heilongjiang Province, resulting in a resource and economic crisis. It has caused severe damage to the economic development of Heilongjiang Province, weakened the vitality of forestry sweat, reduced the efficiency of economic growth and social progress, and ultimately triggered a contradiction between the development of the forestry industry and the ecological environment. Heilongjiang Province is a microcosm of the development of state-owned forest areas in China and reflects the complex relationship between economy and ecology. Therefore, the selection of Heilongjiang Province as the research area in this article has certain representativeness and particularity. The map of Heilongjiang Province is shown in Figure 2.

According to the *China Forestry Statistical Yearbook*, *China Forestry and Grassland Statistical Yearbook*, and *Heilongjiang Province Statistical Yearbook* from 2011 to 2022, the related indicator values of forestry industry development and ecological environment in Heilongjiang Province. However, due to the absence of all indicator values for forestry investment and economic construction from 2019 to 2022, to ensure the accuracy of the calculation results, this article only calculates the coupling and coordination relationship between the forestry industry and the ecological environment in Heilongjiang Province from 2011 to 2018. The data is shown in Table 2, 3.

5 Results

5.1 Indicator and weight

The development of the forestry industry is interrelated with the ecological environment, and there is a specific coupling relationship

TABLE 2 Indicator values of forestry industry development in Heilongjiang Province from 2011 to 2018.

Time	Forestry industry development						
	Forestry industry structure				Forestry investment and economic construction		
	The proportion of forestry primary industry	The proportion of forestry secondary industry	The proportion of forestry tertiary industry	The ratio of total forestry output value to GDP	Investment in forestry industry development	Forestry support and guarantee investment amount	Investment in forestry infrastructure construction
2011	40.47	46.01	13.52	9.23	17305.00	1039119.00	-
2012	40.15	45.42	14.43	9.93	5247.00	45921.00	916943.00
2013	37.50	46.80	15.70	10.81	8658.00	88295.00	397123.00
2014	38.29	45.92	15.79	11.35	12437.00	34022.00	132519.00
2015	37.40	46.11	16.49	12.31	12198.00	37020.00	137879.00
2016	37.77	47.33	14.90	12.62	57291.00	168063.00	-
2017	40.38	44.98	14.64	11.91	86802.00	163297.00	121008.00
2018	38.78	45.09	16.13	11.43	27064.00	163834.00	48539.00
2019	45.03	27.77	27.20	9.49	-	-	-
2020	49.53	27.49	22.98	8.87	-	-	-
2021	50.12	27.35	22.53	8.63	-	-	-
2022	48.89	25.11	25.99	5.56	-	-	-

between the two. To accurately analyze the coupling and coordination relationship between the forestry industry development and the ecological environment in Heilongjiang Province, the paper is based on the coupling mechanism between forestry industry development and the ecological environment. It fully draws on relevant scholars related to the forestry industry development and ecological environment, evaluating index systems for the coupling and coordination of forestry industry development and ecological environment in Heilongjiang Province based on scientificity, rationality, feasibility, comprehensiveness, and operability principles. The forestry industry development includes two primary indicators: forestry industry structure and forestry investment and economic construction which includes seven secondary indicators of the proportion of forestry primary industry, the proportion of forestry secondary industry, the proportion of forestry tertiary industry, the ratio of forestry total output value to GDP, the investment in forestry industry development, the investment in forestry support and guarantee, and the investment in forestry infrastructure construction; The ecological environment includes three primary indicators: ecological environment pressure, endowment, and ecological environment governance level which includes nine secondary indicators of industrial wastewater discharge, industrial exhaust emissions, industrial solid waste generation, afforestation area, forest area, green coverage rate in built-up areas, *per capita* park green space area, comprehensive utilization of industrial solid waste, and domestic waste disposal volume. Together, they constitute the evaluation index system for the coupling and coordinating forestry industry development and the ecological environment in Heilongjiang Province, as shown in Table 4.

5.2 Analysis of comprehensive evaluation results

According to the calculation results of the comprehensive evaluation values of forestry industry development and ecological environment in Heilongjiang Province from 2011 to 2018, there are inevitable fluctuations in the comprehensive evaluation values of forestry industry development and ecological environment. However, the specific fluctuation range is a small size. The comprehensive evaluation values of the two systems are shown in Figure 3.

The comprehensive evaluation values of the forestry industry development and ecological environment in Heilongjiang Province showed varying degrees of fluctuation from 2011 to 2018, and the difference in the comprehensive evaluation values between the two was not significant; only the fluctuation amplitude was different, and the year when the turning point occurred was different.

From the comprehensive evaluation value of forestry industry development, the comprehensive evaluation value from 2011 to 2014 was on a continuous downward trend, with the lowest value reached in 2014 (0.82760). In 2014, the proportion of forestry secondary industry was relatively low, and the weight of forestry secondary industry was the highest in the forestry industry structure. The investment in forestry support and guarantee

TABLE 3 Indicator values of ecological environment in Heilongjiang Province from 2011 to 2018.

Time	Ecological environment pressure			Endowment				Ecological environment governance level	
	Industrial wastewater discharge	Industrial exhaust emissions	Industrial solid waste generation	Planting forest area	Forest area	Green coverage rate in built-up areas	Per capita park green space area	Comprehensive utilization of industrial solid waste	Comprehensive utilization of industrial solid waste
2011	44072.00	10377.00	6017.00	124200.00	1926.97	36.30	11.50	4139.00	651.00
2012	58350.00	10445.00	6313.00	157000.00	1926.97	36.00	11.80	4642.00	710.00
2013	47796.00	10622.00	6094.00	124100.00	1962.13	36.00	12.10	4145.00	582.00
2014	41894.00	12091.00	6312.00	101100.00	1962.13	36.00	12.10	4069.00	553.00
2015	36410.00	10843.00	7495.00	42000.00	1962.13	35.80	12.00	4308.00	523.00
2016	23935.00	9599.00	6940.42	978051.00	1962.13	35.50	11.90	3582.09	535.00
2017	18058.97	10443.87	7069.56	121124.00	1962.13	35.50	11.80	3158.53	553.00
2018	19965.66	13335.22	8248.44	121705.00	1990.46	36.00	12.40	3444.21	525.00
2019	-	-	8754.00	120858.00	1990.46	36.40	12.43	3883.00	523.60
2020	15256.90	14058.40	6769.13	135479.00	1990.46	36.90	12.77	3166.23	497.60
2021	17965.42	21701.16	8315.93	95686.00	1990.46	37.40	13.60	3609.32	521.90
2022	12466.29	12736.36	10118.00	75470.00	1990.46	38.00	14.04	4110.00	507.90

10.3389/fenvs.2024.1375657

TABLE 4 Evaluation index system for the coupling and coordination of forestry industry development and ecological Environment in Heilongjiang province.

	Primary indicators	Secondary indicators	Unit	Indicator direction	Weight
Forestry industry development	Forestry industry structure	The proportion of forestry primary industry	%	+	0.1878
		The proportion of forestry secondary industry	%	+	0.1913
		The proportion of forestry tertiary industry	%	+	0.1765
		The ratio of total forestry output value to GDP	%	+	0.1682
	Forestry investment and economic construction	Investment in forestry industry development	Ten thousand yuan	+	0.0971
		Forestry support and guarantee investment amount	Ten thousand yuan	+	0.0884
		Investment in forestry infrastructure construction	Ten thousand yuan	+	0.0906
Ecological environment	Ecological environment pressure	Industrial wastewater discharge	10000 tons	-	0.0719
		Industrial exhaust emissions	Billion cubic meters	-	0.1101
		Industrial solid waste generation	10000 tons	-	0.1108
	Endowment	Planting forest area	hectare	+	0.0817
		Forest area	10000 ha	+	0.1313
		Green coverage rate in built-up areas	%	+	0.1320
		Per capita Park green space area	square meter	+	0.1292
	Ecological environment governance level	Comprehensive utilization of industrial solid waste	10000 tons	+	0.1180
		Domestic waste clearance volume	10000 tons	+	0.1150

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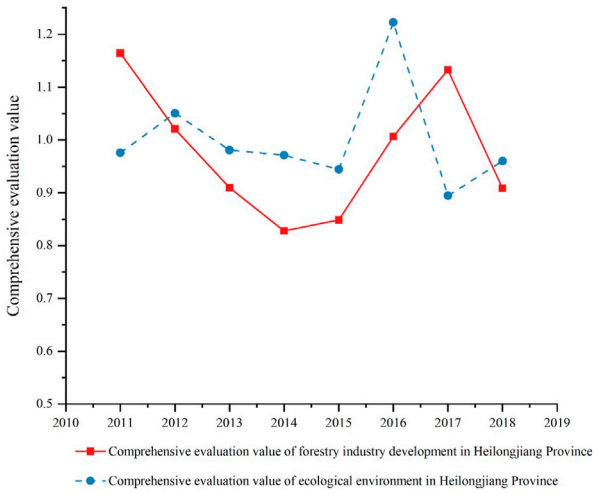

FIGURE 3
Comprehensive evaluation values of forestry industry development and ecological environment in Heilongjiang Province from 2011 to 2018.

and forestry infrastructure construction were relatively low, with a decrease of 61.47% and 66.63% compared to 2013. The significant decline resulted in the lowest comprehensive evaluation value of the forestry industry development in Heilongjiang Province in 2014. The comprehensive evaluation value of forestry industry development in Heilongjiang Province showed an upward trend from 2015 to 2017, which was more evident from 2016 to 2017. The investment in forestry industry development and forestry support and guarantee increased the most in 2016, 4.7 times and 4.54 times higher than in 2015, respectively, with a tremendous growth rate.

Meanwhile, between 2011 and 2018, the proportion of the forestry secondary industry was the highest in 2016, at 47.32978. The ratio of total forestry output value to GDP is also the highest, reaching 12.61958. The weights of these indicators are relatively high, resulting in a high comprehensive evaluation value for developing the forestry industry in Heilongjiang Province in 2016. In 2017, the comprehensive evaluation value of forestry industry development in Heilongjiang Province was the highest, an increase of 31.52% compared to 2016 and 1.37 times that of 2014, indicating a tremendous growth rate. In 2017, although the proportion of the forestry secondary industry decreased significantly, the proportion of the primary industry was relatively high, and all indicators of forestry investment and economic construction were high, making the comprehensive evaluation value of forestry industry development the highest in 2017. The comprehensive evaluation value of forestry industry development in Heilongjiang Province decreased in 2018, with a significant decrease of 19.77% compared to 2017. In 2018, there was a varying degree of decline in forestry investment and economic construction, especially in the investment in forestry industry development and forestry infrastructure construction. The investment in forestry industry development was only about one-third of that in 2017.

Moreover, the decline was more significant. From the comprehensive evaluation value of the ecological environment, from 2011 to 2012, there was an upward trend; from 2013 to 2015, it showed a downward trend, reached its highest value in 2016, experienced a significant decline in 2017, and then increased again in 2018. The fluctuation range of the comprehensive evaluation value of the ecological environment is more robust than that of the development of the forestry industry. In 2017, the comprehensive evaluation value of the ecological environment in Heilongjiang Province was the lowest, only 0.894616. The afforestation area decreased significantly in 2017, a decrease of 87.62% compared to 2016. The green coverage rate in built-up areas has also decreased. However, the decrease is not significant; the weight of this indicator is relatively high, ultimately leading to a lower comprehensive ecological environment evaluation value in 2017. Although the comprehensive evaluation value increased slightly in 2018, the magnitude is insignificant.

5.3 Analysis of coupling coordination relationship

According to the comprehensive evaluation index of forestry industry development and ecological environment in Heilongjiang Province from 2011 to 2018, the coupling coordination, coupling coordination degree, and coupling coordination stage types were calculated. The results are shown in Table 5. At the same time, the coupling coordination degree range of forestry industry development and ecological environment in Heilongjiang Province from 2011 to 2018 was drawn based on the coupling coordination degree, as shown in Figure 4.

According to the PSR theory, the development of the forestry industry can not only promote the economic development of forest areas and improve the ecological environment. The two have a specific correlation, and the coupling and coordination results confirm the relationship. The development and growth of the forestry industry will pressure forest resources. At the same time, the development of the forestry industry will increase the demand for the ecological environment, leading to a decline in the environmental service functions and triggering a change in status. From the coupling coordination relationship between 2011 and 2014, it can be seen that the degree of coordination gradually became imbalanced, reaching the lowest level of coordination in 2014. In 2014, critical state-owned forest areas under the jurisdiction of Heilongjiang Province were selected as the pilot of the first batch of “stop logging” policies, which prohibited commercial logging of natural forests, resulting in a decrease in recoverable resources and hindered the development of the forestry industry. The protective policies of forest resources also impeded the development of the forestry industry. Therefore, to transform this state, the forestry industry development system will adjust its industrial structure, attempt industrial transformation, strengthen environmental governance, and other response measures to improve the ecological environment and promote the development of the forestry industry. It can be seen from the coupling coordination degree between the two that the coupling coordination degree has increased since 2015 and reached an

TABLE 5 Calculation results of the coupling coordination between forestry industry development and the ecological environment in Heilongjiang Province from 2011 to 2018.

Year	Coupling degree C value	Coordination index T-value	Coupling coordination degree D value	Coordination level	Coupling coordination degree	Type of coupling coordination stage
2011	0.805	0.621	0.707	8	Intermediate coordination	coupling state
2012	0.996	0.524	0.722	8	Intermediate coordination	coupling state
2013	0.999	0.258	0.508	6	Barely coordinate	Running in state
2014	0.393	0.124	0.221	3	Moderate imbalance	Antagonistic state
2015	0.925	0.115	0.326	4	Mild dysregulation	Antagonistic state
2016	0.953	0.76	0.851	9	Good coordination	Coordination status
2017	0.209	0.453	0.308	4	Mild dysregulation	Antagonistic state
2018	0.996	0.225	0.474	5	Near Dysfunction	Running in state

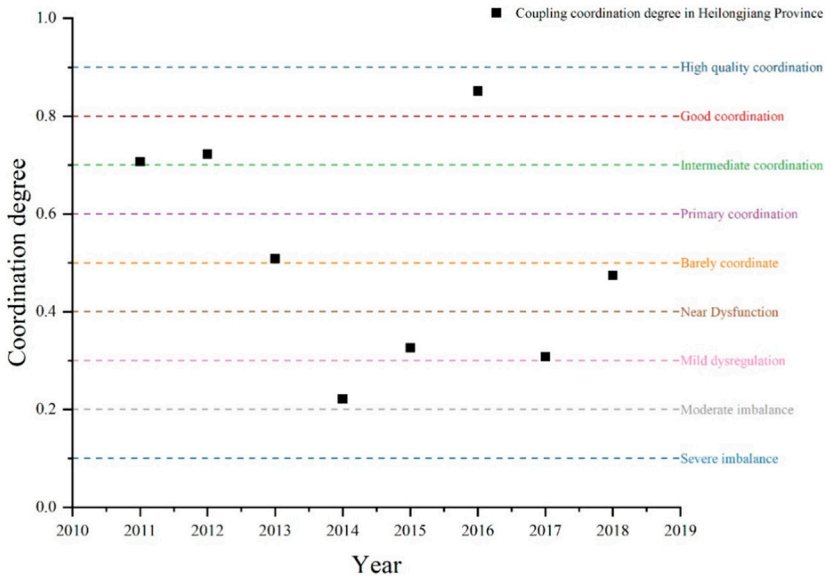

FIGURE 4
Coupling coordination interval of forestry industry development and ecological environment in Heilongjiang Province from 2011 to 2018.

excellent coordination state in 2016. After the implementation of the "logging cessation" policy in 2014, the relationship between the two has improved, and the transformation of the forestry industry and the adjustment of industrial structure have had significant effects. However, due to the similarity in the transformation mode of the forestry industry, the transformation process could be faster and more efficient, which leads to a mild imbalance in the relationship between the two. Therefore, Heilongjiang Province has begun to explore new ways of developing the forestry industry, such as clean production, green circulation, and low-carbon industries, effectively promoting the development of the forestry industry while protecting the ecological environment and coordinating the coupling relationship between the two.

Table 5 shows that the coupling and coordination degree between the development of the forestry industry and the ecological environment in Heilongjiang Province from 2011 to 2018 is between 3 and 9 levels, with a significant gap and apparent differences between different years. However, there is no extreme or severe degree of imbalance or high-quality coordination state, especially in 2014 and 2016, where the difference in coupling and coordination between the two is pronounced. 2011 was the first year of the second phase of the Natural Forest Protection Project, which aimed to curb the deterioration of the ecological environment, protect biodiversity, and promote sustainable social and economic development. Furthermore, it will change the increasingly deteriorating

ecological environment, solve the severe shortage of forest resources, and lead forestry construction to sustainable development. After implementing the natural forest protection project, the natural forest resources in Heilongjiang Province have been better protected, and the direction of forest resource management has been readjusted. From 2011 to 2012, the afforestation area gradually increased. At the same time, the forest area also continued to rise, resulting in a continuous increase in the ecological value of forest resources. However, the emissions of three wastes to the environment increased, and the investment in forestry and economic construction decreased. However, it has yet to impact the ecological climate of Heilongjiang Province severely. Therefore, the development of the forestry industry and the ecological environment are in intermediate coordination. In 2014, critical state-owned forest areas under the jurisdiction of Heilongjiang Province were included in the first batch of "stop logging" pilot projects, and commercial logging of natural forests was completely stopped. Heilongjiang Province entered a new stage of comprehensive protection of natural forests. Implementing the "logging cessation" policy has led to a sharp reduction in exploitable resources in Heilongjiang Province, hindering the development of the forestry industry. In 2014, the proportion of the forestry secondary industry decreased, indirectly affecting the coupling relationship between the development of the forestry industry and the ecological environment. Therefore, there was a moderate imbalance between the two in 2014. At this stage, Heilongjiang Province has entered a new stage of comprehensive protection of natural forests. It is necessary to fully tap into the ecological benefits of forest resources and pay more attention to the environmental efficiency of forests based on natural forest protection projects. It also makes its impact on the development of the forestry industry more significant.

Heilongjiang province has been searching for a model for the transformation of the forestry industry to overcome the difficulties in the development of forestry, adjust the structure of the forestry industry, and alleviate the contradiction between forest resources and the development of the forestry industry. Heilongjiang Province has continuously proposed various measures to promote the development of the forestry industry, especially with ecological protection as the premise to reduce the damage of forestry industry development to the environment. The low-carbon, green, and circular industries have become the main drivers for transforming the forestry industry in Heilongjiang Province. In 2016, due to the transformation of the forestry industry, the emissions of three wastes in Heilongjiang Province decreased, reducing the damage to the ecological environment and effectively realizing the environmental function and value of the ecological environment. Therefore, in 2016, the development of the forestry industry in Heilongjiang Province was coordinated well with the ecological environment. After 2017, with the continuous adjustment of the forestry industry structure in Heilongjiang Province, the proportion of the primary forestry industry increased, the proportion of the secondary forestry industry decreased, and the contribution of the forestry industry output value to the economy of Heilongjiang Province decreased. Although the afforestation and forest areas have increased in 2018, the emissions of three wastes have been continuously growing, and the economic vitality has declined, which has also had a particular impact on the value of the ecological environment. Although the afforestation and forest areas increased in 2018, the emissions of these three wastes have been continuously growing. The decline in economic vitality has also had a particular impact on the value of the ecological environment, leading to a decrease in coupling coordination. The two are in a mild imbalance.

According to the degree of coupling coordination, the coupling coordination state between the development of the forestry industry in Heilongjiang Province and the ecological environment can be divided into four types, including antagonistic state, running in the state, coupling state, and coordination state, and there is no imbalance state. Only 2014–2015 and 2017–2018 were in the imbalance range, while the rest of the years were in the range of coordination. With the change of years, the coupling coordination degree has shown a two-stage trend from good to bad, namely, from 2011 to 2015 and from 2016 to 2018. The degree of coupling coordination is from intermediate to moderate imbalance and good coordination to mild imbalance from 2011 to 2015, respectively. From 2011 to 2013, the coupling and coordination relationship between the development of the forestry industry and the ecological environment in Heilongjiang Province was between the coupling state and the adaptation state, which was in line with their respective development levels. In 2012, it reached its highest level (0.722). From 2014 to 2015, the coupling and coordination relationship between the development of the forestry industry and the ecological environment in Heilongjiang Province was antagonistic. The ecological environment system hindered the development of the forestry industry, resulting in a minor coordination relationship compared to that of a single system. From 2016 to 2018, the coupling and coordination relationship between the development of the forestry industry and the ecological environment in Heilongjiang Province went from good coordination to near imbalance. In 2016, there was a good coordination between the development of the forestry industry and the ecological environment, belonging to a coordinated state. The coupling coordination degree reached its highest value (0.851), and the two achieved a relatively good coordination relationship. However, from 2017 to 2018, the coupling coordination relationship was imbalanced, with antagonism and adjustment, respectively, and the coupling coordination relationship between the two was average.

The interval distribution of the coupling coordination degree between the forestry industry development and ecological environment in Heilongjiang Province from 2011 to 2018 is almost distributed in various states from Figure 4, indicating that the coupling coordination relationship between the forestry industry development and ecological environment in Heilongjiang Province is not very stable. From 2011 to 2018, half were in a coordinated state, and the other half were imbalanced, with a relatively uniform distribution. However, the overall coupling coordination span is significant, and specific differences exist between years. Due to the adjustment of forestry development policies in Heilongjiang Province in other years and measures based on ecological environment protection, especially the impact of natural forest protection projects and the "logging cessation" policy on the ecological environment has led Heilongjiang Province to enter a new stage of comprehensive protection of forest resources, with

environmental construction as the main focus and full play to the ecological value of forest resources. Meanwhile, the continuous optimization and upgrading of forestry industry structure, and the exploration of forestry industry transformation models, the differences in the coupling and coordination relationship between forestry industry development and ecological environment in Heilongjiang Province will become the reasons. Overall, there is still a particular gap between the level of coupling and coordination between the forestry industry development and the ecological environment in Heilongjiang Province, and it has yet to reach a state of well-coordinated development.

6 Discussion

Based on the PSR model, this article uses Heilongjiang Province as the research object to explain the coupling mechanism between the development of the forestry industry and the ecological environment. At the same time, based on the coupling coordination degree model, the coupling coordination relationship between forestry industry development and the ecological environment in Heilongjiang Province from 2011 to 2018 is calculated. The coupling coordination status between the two is divided, effectively promoting the high-quality development of the forestry industry economy in Heilongjiang Province and promoting the transformation of the forestry industry. Heilongjiang Province has the most significant critical state-owned forest area in China, and its abundant forest resources have led to the formation of a single industrial structure dominated by wood production through the utilization and extraction of natural forest resources. It has resulted in a trade-off between the economic development of forest areas and the ecological efficiency of forests. Different dominant policies have led to certain contradictions between the two at different stages. Therefore, this article takes Heilongjiang Province as the research object to evaluate the development of the forestry industry and ecological environment construction, which has specific practical significance.

The research in the article shows that the degree of coupling coordination between the development of the forestry industry and the ecological environment in Heilongjiang Province from 2011 to 2018 ranges from 3 to 9, with a large span and specific differences between different years. Due to the continuous adjustment of forestry policies and the implementation of relevant ecological protection policies, Heilongjiang Province is actively adjusting the structure of the forestry industry, and the transformation of the forestry industry will lead to different degrees of coupling and coordination between the development of the forestry industry and ecological protection. Since the founding of the People's Republic of China, Heilongjiang Province has continuously provided timber for China's economic construction, and natural forest resources have been severely damaged. After the 1998 flood disaster, in response to the reality of ecological environment deterioration caused by excessive consumption of natural forest resources in China for a long time, the Central Committee of the Communist Party of China and the State Council implemented natural forest resource protection projects. The pilot program began in 1999 and was officially implemented in 2000. The natural forest protection project will curb the deterioration of the ecological environment, protect biodiversity, and promote sustainable development of society and economy as a national medium - and long-term plan project. Due to significant results, the second phase of the natural forest protection project was implemented in 2011. With the implementation of natural forest protection projects, the classification and zoning of natural forest resources will be reclassified, and the direction of forest resource management will be adjusted. In 2014, the critical state-owned forest areas under the jurisdiction of Heilongjiang Province implemented the "stop logging" policy, which led to a new stage of comprehensive protection of natural forests in the development of forestry in Heilongjiang Province. The "stopping logging" policy is consistent with the ecological civilization construction proposed by the 18th National Congress of the Communist Party of China. The Outline of the National Forestry Administration's Plan for Promoting Ecological Civilization Construction (2013–2020) clarifies the national ecological red line and regulates the systematic construction of the ecological and cultural system. Without the support of industries, implementing environmental protection policies will also lose vitality in ecological construction. Therefore, the development of the forestry industry and ecological protection interact and promote each other. Under the continuous adjustment of environmental protection policies, the forestry industry is also undergoing structural adjustment and upgrading, and the forestry industry is transforming. However, with the constant adjustment and upgrading of the forestry industry structure, it is easy to cause similarities in the transformation mode of the forestry industry. At the same time, the proposal of a low-carbon economy, green development, and clean production in the country makes it necessary for the development of the forestry industry to prioritize the protection of the ecological environment and actively explore the path of low-carbon, green, and sustainable forestry development. Therefore, with the changes in relevant policies, protecting the ecological environment in Heilongjiang Province has also had an inevitable impact on the development of the forestry industry. By calculating the coupling and coordination relationship between the two, it is found that the coupling and coordination relationship between the two is a repeated process from coordination to imbalance, and then to imbalance, which is also the process of continuous constraint, improvement, and coordinated development of China's ecological construction and forestry industry. At the same time, it also makes the overall span of the coupling and coordination relationship between the development of the forestry industry and the ecological environment in Heilongjiang Province extensive, and there are specific differences between different years.

This article uses the coupling coordination model to calculate the relationship between forestry industry development and the ecological environment. In contrast, other scholars use composite systems as evaluation objects to illustrate the relationship between the system or the various components that affect its operation. It includes water-energy-food, marine biopharmaceutical industry, multifunctional, complex land ecosystems, and economic development-social

development-government governance (Fu et al., 2023; Hu et al., 2023; Yin et al., 2023; Zhang et al., 2023; Zhao and Shi, 2023). Liu and Yang (2023) calculated the coupling coordination of forest ecology, economy, and social systems (Liu and Yang, 2023), but taking Changsha City as an example, the research area is relatively small. From the perspective of the forest economy and ecology, the overall trend also differs from the development of the forestry industry and ecological environment in Heilongjiang Province.

The variation of Probability of Connectivity is based on the coupling coordination model to calculate the coupling coordination relationship between forestry industry development and the ecological environment. The key is to construct evaluation indicators to evaluate the comprehensive level of the two systems and then measure the degree of coupling coordination between the two. Therefore, selecting indicators is essential for the final coupling coordination result. Especially for the ecological environment evaluation indicators, the article has selected indicator values that include both positive and negative directions to better interpret the bidirectional impact of ecology on the forestry industry, rather than only selecting positive indicators, which is different from other scholars when constructing indicator systems (Liu et al., 2022).

7 Conclusion and policy recommendations

7.1 Conclusion

This article takes Heilongjiang Province as the research object. It uses the comprehensive index method to calculate the comprehensive evaluation values of forestry industry development and ecological environment system in Heilongjiang Province from 2011 to 2018. Based on this, it explores the coupling coordination between forestry industry development and the ecological environment used on the coupling coordination degree model, and the conclusions are as follows.

(1) The comprehensive evaluation of forestry industry development and ecological environment in Heilongjiang Province show varying degrees of fluctuation, and the difference in the comprehensive evaluation values between the two is not significant; only the fluctuation amplitude is different, and the turning point occurs in different years.
(2) The comprehensive evaluation value of forestry industry development in Heilongjiang Province has continuously decreased from 2011 to 2014, with the lowest value reached in 2014. The comprehensive evaluation value showed an upward trend from 2015 to 2017, with the highest comprehensive evaluation value in 2017.
(3) The comprehensive evaluation value of the ecological environment in Heilongjiang Province showed an upward trend from 2011 to 2012 and a downward trend from 2013 to 2015, reaching the highest value in 2016 and the lowest level in 2017, with a more substantial fluctuation than the development of the forestry industry.
(4) The degree of coupling and coordination between the forestry industry and the ecological environment in Heilongjiang Province from 2011 to 2018 was between 3 and 9 levels, with a large span. However, no extreme imbalance, severe imbalance, or high-quality coordination state.
(5) The coupling coordination between the forestry industry development and the ecological environment in Heilongjiang Province has yet to reach an excellent coordinated development state. From 2011 to 2018, the forestry industry development was in a state of antagonism, adaptation, coupling, and coordination with the ecological environment. However, there is still a particular gap in the level of coupling and coordination between the two, and they have yet to reach an excellent coordinated development state.

7.2 Policy recommendations

(1) Innovate the transformation model of the forestry industry. The primary purpose of the transformation of the forestry industry in Heilongjiang Province is to coordinate and alleviate the relationship between the forestry industry development and the ecological environment, promote the economic development of the forestry industry, improve the status of forest resources, protect the ecological environment, and enhance the quality of people's life in forest areas. It can be achieved through the "ecological + green" industry development model, "ecological + low-carbon" industry development model, and "ecological + circulate" industry development model innovation of the antagonistic state of forestry industry development and ecological environment. Innovating the development and ecological environment of the forestry industry in a state of adaptation can build an ecological community, construct a modern forestry industry ecosystem, and establish an ecological industry park model. Innovate the coupled development of the forestry industry and ecological environment through a high-quality and adequate supply of forestry economy, high-quality cultivation and utilization of ecological resources, and PPP supply of high-quality social services.
(2) Policy orientation: rational development and utilization of forest resources. Through the guidance of forestry industry development and ecological environment-related policies, Heilongjiang Province aims to achieve practical and reasonable development and utilization of forest resources under the premise of protective development and utilization of forest resources to achieve moderate economic growth in the forestry industry.
(3) Environmental constraints: clean production in the forestry industry. It should reduce the discharge of waste into the external environment as much as possible through clean production in various forestry industry projects under the constraints of the ecological environment. Traditional and emerging industries should achieve clean production inside and outside the forestry industry under the constraints of the ecological environment.
(4) Literature review complements and shares to achieve coupling between the forestry industry and ecology. Heilongjiang Province can complement and share the

internal and external advantages of the forestry industry and ecological environment. In addition to leveraging the advantages of forest resources and the attractiveness of its industry development, it can also utilize other external solid advantages of the forestry industry. There are abundant forest resources in Heilongjiang Province that have high economic, social, and ecological value, and the development of the forestry industry has very high economic value, especially for its contribution to the economic development of Heilongjiang Province. Therefore, by complementing the advantages between the two, the forestry industry can fully utilize forest resources to achieve economic, social, and ecological benefits without affecting the quantity and quality of forest resources. It can also improve the quantity and quality of forest resources by developing the forestry industry.

The research in this article shows that although the coupling and coordination relationship between the development of the forestry industry and the ecological environment in Heilongjiang Province from 2011 to 2018 can be described, there are still certain shortcomings. The selection of evaluation indicators and research methods for developing the forestry industry and ecological environment may have specific limitations due to external factors, leading to biased research results. In addition, due to the author's limited ability and practical experience, this study may also need to be revised. There will be more progress through continuous learning and field investigation.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

QZ: Conceptualization, Formal Analysis, Funding acquisition, Methodology, Resources, Writing–original draft, Conceptualization, Formal Analysis, Funding acquisition, Methodology, Resources, Writing–original draft, Conceptualization, Formal Analysis, Funding acquisition, Methodology, Resources, Writing–original draft, CK: Data curation, Funding acquisition, Project administration, Writing–review and editing, Data curation, Funding acquisition, Project administration, Writing–review and editing, Data curation, Funding acquisition, Project administration, Writing–review and editing, WG: Methodology, Software, Writing–review and editing, Methodology, Software, Writing–review and editing, Methodology, Software, Writing–review and editing.

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Conflict of interest

Author WG was employed by Daqing Huali Biotechnology Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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