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Coupling and Long-term Change Characteristics of Forest Carbon Sink and Forestry Economic Development in China

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Abstract [**Objectives**] To analyze the changes in of forest carbon sink and forestry economic development, provide reference for relevant management decisions, ecological governance and resource and environment management, and promote the development of green low-carbon economy in China. [**Methods**] Based on the data of six forest resource inventories from 1989 to 2018 and related studies, the comprehensive evaluation model of forest carbon sink and forestry economic development, the coupling degree model of forest carbon sink and forestry economic development, and the coupling coordination degree model of forest carbon sink and forestry economic development were adopted. The coupling degree of forest carbon sink and forestry economic development from 1992 to 2018 was analyzed. Stepwise regression and ARIMA model were used to analyze the influencing factors and lagging characteristics of forest carbon sink. The coupling degree between forest carbon sink and forestry economic development in China from 2019 to 2030 was predicted by autoregression and ADF test. The coupling between forest carbon sink and forestry economic development in China and its long-term change characteristics were also discussed in this study. [**Results**] (i) The investment of ecological construction and protection, the actual investment of forestry key ecological projects, GDP and the import of forest products had a significant impact on forest resources carbon stock. The total output value of forestry industry, the actually completed investment of forestry key ecological projects and the export volume of forest products had a significant impact on the forest carbon sink, and the actually completed investment of forestry key ecological projects has the greatest impact on the two. (ii) The impact of actually completed investment of forestry key ecological projects had a lag of 2 years on the forest resources carbon stock and a lag of 1 year on the forest carbon sink. When investing in forest carbon sink, it is necessary to make a good plan in advance, and do a good job in forest resources management and time optimization. (iii) From 1992 to 2018, the coupling degree of forest resources carbon stock, forest carbon sink and long-term development of forestry economy in China was gradually increasing. Although there were some fluctuations in the middle time, the coupling degree of forest resources carbon stock and the long-term development of forestry economy increased by 9.24% annually, and the degree of coupling coordination increased from "serious imbalance" in 1992 to "high-quality coordination" in 2018. From 1993 to 2018, the coupling degree of forest carbon sink and long-term development of forestry economy increased by 9.63% annually, slightly faster than the coupling coordination degree of forest resources carbon stock and long-term development of forestry economy. The coordination level also rose from level 2 in 1993 to level 10 in 2018. (iv) The prediction shows that the coupling coordination degree of forest resources carbon stock, forest carbon sink and the long-term development of forestry economy would increase from 2019 to 2030. The coupling coordination degree (D) values of both were close to 1, the coordination level was also 10 for a long time, and the degree of coupling coordination was also maintained at the "high-quality coordination" level for a long time. [**Conclusions**] Forest has multiple benefits of society, economy and ecology, and forest carbon sink is only a benefit output. The long-term coupling analysis of forest carbon sink and forestry economic development is a key point to multiple benefit analysis. The analysis shows that the spillover effect and co-evolution effect of forest carbon sink in China are significant. From 1992 to 2018, the coupling coordination degree of forest carbon sink and forestry economic development was gradually rising. The prediction analysis also indicate that the coupling coordination degree between the forest carbon sink and the long-term development of forestry economy will remain at the level of "high-quality coordination" for a long time from 2019 to 2030. Therefore, improving the level of forest management and maintaining the current trend of increasing forest resources are the key to achieving the goal of carbon peaking and carbon neutrality in China.

Key words Forest resources carbon stock, Forest carbon sink, Coupling coordination degree, Forestry economic development, Long-term trend

1 Introduction

Forest is the main terrestrial ecosystem and the largest carbon pool of terrestrial ecosystem. Forests play a unique role in addressing climate change and are an important resource for economically feasible and low-cost reduction of greenhouse gas concentrations[1]. Relevant monitoring data indicate that the supply capacity of forest carbon sink in China has been steadily improved[2], and its contribution to greenhouse gas emission reduction is increasing. With the continuous development of key forestry ecological projects in China, forest carbon sequestration has not only become an important way to offset industrial greenhouse gas emissions, but also the best choice for the development of green low-carbon economy in China[3]. Therefore, analyzing the coupling and long-term change characteristics of forest carbon sink and forestry economic development in China and grasping the change trend of forest carbon sink and forestry economic development can provide reference for relevant management decisions, ecological governance and resource and environmental management, and promote the development of green low-carbon economy in China.

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The coupling relationship between forest carbon sink and economic development reflects the relationship and degree of interdependence and interaction between carbon sink and economic development. With the change in China's economic development from focusing on speed to quality, the development of green low-carbon economy has increasingly become the focus of attention[3]. Among them, increasing forest carbon sequestration capacity, strengthening forest carbon sink management, and improving the coupling coordination among economic system, social system and natural system have also become the focus of research[4]. Forests have ecological, economic, social, and other multiple benefits, not only have ecological benefits such as biodiversity conservation, water conservation, carbon sequestration and oxygen release, but also have economic and social benefits such as providing forest by-products, forest tourism, employment opportunities. At present, there are more studies on single forest benefit and few studies on multiple benefits, especially less studies on measurement and coupling of multiple benefits of forest carbon sink[5]. The economic benefit evaluation methods of forest carbon sink mainly include market value method, afforestation cost method, carbon tax method, artificial fixed CO_2 cost method, mean value method, willingness to pay (WTP) method and cost-benefit method[6-7]. The magnitude of forest ecological benefits and forest carbon sink are not only related to climate factors such as forest structure, rainfall, average temperature and biodiversity, but also related to risk factors such as forest fire, pest and rat damage and management level. Forest social benefits mainly refer to the employment opportunities, cultural values and the maintenance of indigenous livelihoods provided by forests[8], and social benefits are also related to biodiversity and forest health. Among these multiple benefits, forestry carbon neutrality and carbon are mainly affected by biodiversity[9], which not only affects the forest structure, but also affects the stability and size of the forest carbon sink. Therefore, the coupling relationship between forest carbon sink and economic and social benefits is a scientific issue that should not be ignored in the evaluation of carbon sink benefits.

Foreign scholars started the quantitative research on the coupling relationship between forest carbon sink and economic and social benefits and multiple benefits mainly starts from the expansion of its single benefit. For example, in the study of forest carbon sink, Sierra *et al.* [10] not only considered the carbon sink of forest biomass, underground biomass, litter, dead wood and soil organic matter carbon pool, but also paid attention to the changes in economic benefits and carbon pool caused by the harvest of woody forest products after forest management. Fern Fernάndez-Manjarr Manjarrés *et al.* [11] also considered the leakage and non-permanence of the forest carbon sink due to the reduction of emissions from deforestation and forest degradation, while considering the measurement of carbon sequestration under forest management activities. Roces-D Díaz *et al.* [12] suggested to measure the economic benefits of carbon sequestration projects in the life cycle of investment projects, and suggested to use BS option model to quantitatively evaluate the option value of carbon sequestration investment. The Intergovernmental Panel on Climate Change (IPCC) also recommended dynamic accounting of the multiple benefits of forest carbon sink[13]. Ratcliffe *et al.* [14] believed that forests have multiple benefits, and carbon sink is not the only goal, when measuring forest carbon sink benefits, other multiple benefits should be considered, especially the coupling optimization of carbon sink benefits. In recent years, domestic scholars have also paid attention to the research on multiple benefit measurement and coupling optimization of forest carbon sink. For example, Niu Ling[15] studied other benefits of forest carbon sink from a macroeconomic perspective; Hua Zhiqin[16] discussed the relationship between forestry carbon sequestration market and economic performance from the institutional arrangement when studying the multi-benefit measurement of carbon sequestration, and proposed optimizing the institutional arrangement of forestry carbon sequestration property rights. Hu Yuan *et al.* [17] studied the promotion of carbon sequestration afforestation projects to local economic development from the perspective of coupling benefits. Therefore, it is not only a scientific issue, but also in line with the needs of the construction of ecological civilization to carry out the coupling study of forest carbon sink and forestry economic development, and to develop some new methods and models to evaluate the benefits of carbon sequestration and multiple benefits under the multiple effects of forests. In addition, it is also the strategic requirement to implement the national goal of carbon peaking and neutrality, which is of great value and significance to improve the scientific management level of carbon sequestration, promote the development of carbon sequestration market management, and strengthen the management of ecosystem services, the construction of ecological civilization and green development[18].

2 Research methods and data sources

2.1 Research methods The research on the coupling of forest carbon sink and forestry economic development in China and its long-term variation characteristics mainly adopts the comprehensive evaluation model of forest carbon sink and forestry economic development, the coupling degree model and the coupling coordination degree model[19]. With reference to related data, the main indicators of forest carbon sink mainly include forest stock volume per unit area (m^3/ha), forest resources carbon stock(10^8 t), and forest carbon sink(10^8 t/yr); main indicators of forestry economic development mainly include GDP (10^8 yuan), total output value of forestry industry (10^8 yuan), amount of investment completed in ecological construction and protection (10^8 yuan), actually completed investment of forestry key ecological projects (10^8 yuan), import value of forest products (10^8 yuan), export value of forest products (10^8 yuan), producer price index (PPI) for forestry products (last year = 100), and annual growth rate of forestry output value[20]. The specific research method is as follows:

(i) The comprehensive evaluation model of forest carbon sink and forestry economic development:

$$N = \sum_{j=1}^{n} \lambda_j N'_{ijt} \quad (1)$$

$$E = \sum_{j=1}^{n} \lambda_j E'_{ijt} \quad (2)$$

where N and E separately denote comprehensive evaluation value of the forest carbon sink and the forestry economic development system; N'_{ijt} is the indicator value of the j^{th} forest carbon sink in area i in period t; E'_{ijt} is the indicator value of the j^{th} forestry economic development in area i in period t; λ_j is the weight of the evaluation indicator. In the study, the objective principal component analysis (PCA) method is generally selected to determine the indicator weight, and the average value of the weight is calculated to obtain the comprehensive weight, so as to narrow the difference[21].

(ii) Coupling degree model of forest carbon sink and forestry economic development:

Coupling degree reflects the degree of interdependence and mutual influence between forest carbon sink and forestry economy. The coupling degree model of forest carbon sink and forestry economic development is as follows:

$$C = \left[\frac{NE}{\left(\frac{N+E}{2} \right)^2} \right]^k \quad (3)$$

where C denotes the coupling degree of forest carbon sink and forestry economic development, $C \in [0, 1]$; the larger the C value, the higher the degree of correlation between systems, and the smaller the C value, the lower the degree of correlation between systems, and the system is in disorder; k is the adjustment coefficient, and only two subsystems of forest carbon sink and forestry economic development are involved in the study, so the value of k is 2[22].

(3) The coupling coordination degree of forest carbon sink and forestry economic development:

The coupling degree of forest carbon sink and forestry economic development can reflect the association degree between the two. However, the coupling degree can not measure the "integration effect" of the coordinated development of the system itself. Therefore, in order to effectively measure the comprehensive development level of the two, the coupling coordination degree is introduced to reflect the integration effect of the two[23]. The specific model is as follows:

$$\begin{cases} D = \sqrt{C}\sqrt{T} \\ T = aN + bE \end{cases} \quad (4)$$

where D denotes the coupling coordination degree, C denotes the coupling degree, T is the comprehensive evaluation indicator of forest carbon sink and forestry economic development, both a and b are taken as 0.5, in other words, forest carbon sink and forestry economic development have the same degree of importance.

In addition, according to the relevant reference[24], the 10 level classification standards for coupling coordination degree between forest carbon sink and forestry economic development are shown in Table 1.

Table 1 Classification of coupling coordination degree between forest carbon sink and forestry economic development

Coupling coordination level	Coupling coordination degree interval	Degree of coupling coordination
1	$0.0000 < D \leq 0.1000$	Extreme imbalance
2	$0.1001 < D \leq 0.2000$	Serious imbalance
3	$0.2001 < D \leq 0.3000$	Moderate imbalance
4	$0.3001 < D \leq 0.4000$	Mild imbalance
5	$0.4001 < D \leq 0.5000$	On the verge of imbalance
6	$0.5001 < D \leq 0.6000$	Barely coordination
7	$0.6001 < D \leq 0.7000$	Primary coordination
8	$0.7001 < D \leq 0.8000$	Intermediate coordination
9	$0.8001 < D \leq 0.9000$	Good coordination
10	$0.9001 < D \leq 1.0000$	High quality coordination

NOTE D denotes the coupling coordination degree. The data were selected from the reference[24].

The calculation method of forest carbon sink mainly adopts the calculation formula of the volume expansion method, and the specific formula is as follows:

$$TC_F = S_i C_i + \alpha S_i C_i + \beta S_i C_i \quad (5)$$

$$C_i = V_i \delta \rho \gamma \quad (6)$$

where TC_F denotes forest resources carbon stock, including carbon sequestration of forest, carbon sequestration of understory vegetation and carbon sequestration of forest land; S_i is the area of the i^{th} class forest; C_i is the carbon density of the i^{th} class forest; V_i is forest stock volume per unit area of the i^{th} class forest; α is the carbon conversion coefficient of understory vegetation; β is the carbon conversion coefficient of forest land; δ is the biomass expansion coefficient; ρ is the coefficient of biomass accumulation converted into biomass dry mass, namely, bulk density; γ is the coefficient of conversion of biological dry mass into carbon sequestration, namely, carbon content[25]. In actual calculation, various conversion factors are generally determined according to the default parameters required by IPCC. δ is generally taken as 1.90; ρ is generally taken as 0.45 – 0.50 t/m^3, and 0.50 t/m^3 is taken in this study; γ is generally taken as 0.5; α is taken as 0.195; and β is taken as 1.244[26].

2.2 Data source The data used in this study are mainly from *China Forest Resources Inventory*, *China Forestry Statistical Yearbook*, *China Statistical Yearbook* (2021)[27–29], as well as published literature and data[25–26]. The specific data include forest area, volume, area, growth and volume of different forest stands, and the main data are shown in Table 2.

In addition, in the calculation of carbon sink, the data of forest resources carbon stock and forest carbon sink are mainly at the end of each forest resource inventory period, that is, the data of the last year of each inventory period. In order to facilitate the comparison with the statistical data of forestry economic development[30], we used the interpolation method to convert the forest resources carbon stock and carbon sink data of different inventory periods after 1992 into annual data. The fourth to ninth forest inventory periods are 1989 – 1993, 1994 – 1998, 1999 – 2003, 2004 – 2008, 2009 – 2013, and 2013 – 2018. The calculation formula of the interpolation method is:

$$y = y_1 + (y_2 - y_1)\frac{(x - x_1)}{(x_2 - x_1)} \quad (7)$$

where y_1, y_2, x_1, x_2 are known statistical data; x is any number between x_1 and x_2; y is the interpolation data corresponding to x.

The two indicators of "forest stock volume per unit area" and "annual growth rate of forestry output value" "are mainly calculated according to" forest area "and" forestry output value ", and thus not directly listed in the data collection.

Table 2 Main data of coupling and long-term change characteristics of China's forest carbon sink and forestry economic development from 1992 to 2018

Year	Forest resources carbon stock//10^8 t	Forest carbon sink 10^8 t/yr	Total output value of forestry industry 10^8 yuan	Amount of investment completed in ecological construction and protection//10^8 yuan	Actually completed investment of forestry key ecological projects//10^8 yuan	GDP 10^8 yuan	Export value of forest products 10^8 yuan	Import value of forest products 10^8 yuan	PPI for forestry products (last year = 100)
1992	140.286	0.186 62	198.43	13.24	4.46	27 194.5			107.30
1993	140.710	0.173 90	994.56	15.88	11.89	35 673.2	38.861 96	37.938 27	111.10
1994	141.504	0.177 02	1 337.55	18.95	14.46	48 637.5	49.554 61	47.610 68	111.80
1995	142.298	0.180 14	1 577.24	20.85	16.26	61 339.9	60.585 00	54.200 50	105.10
1996	143.092	0.183 26	1 707.76	27.87	21.15	71 813.6	56.837 62	57.535 08	104.40
1997	143.886	0.186 38	1 918.24	38.47	25.51	79 715.0	61.216 67	66.413 40	98.90
1998	144.680	0.189 50	2 727.85	60.61	23.36	85 195.5	55.958 13	69.153 87	101.10
1999	147.298	0.366 40	3 187.73	91.55	81.58	90 564.4	61.247 30	95.884 74	101.40
2000	149.916	0.543 30	3 555.47	150.66	113.19	100 280.1	72.951 25	114.494 62	90.00
2001	152.534	0.720 20	4 090.48	191.62	166.44	110 863.1	78.550 79	109.825 86	94.15
2002	155.152	0.897 10	4 634.24	296.14	255.80	121 717.4	95.796 66	128.972 94	98.31
2003	157.770	1.074 00	5 860.33	388.47	333.92	137 422.0	122.359 84	166.419 87	107.01
2004	159.938	1.036 80	6 892.21	398.45	351.02	161 840.2	163.008 54	199.399 12	104.62
2005	162.106	0.999 60	8 458.74	439.78	361.63	187 318.9	205.741 72	221.021 07	104.79
2006	164.274	0.962 40	10 652.22	470.77	353.34	219 438.5	263.770 42	257.986 89	112.78
2007	166.442	0.925 20	12 533.42	615.11	348.04	270 092.3	319.309 93	323.601 69	104.37
2008	168.610	0.888 00	14 406.41	827.72	420.24	319 244.6	334.883 10	384.394 66	108.47
2009	172.132	0.999 20	17 493.43	1 109.52	508.73	348 517.7	363.163 17	339.024 86	94.88
2010	175.654	1.110 40	22 779.02	1 170.96	472.00	412 119.3	463.166 86	475.065 54	122.78
2011	179.176	1.221 60	30 596.73	1 302.49	532.51	487 940.2	550.337 14	652.991 00	114.92
2012	182.698	1.332 80	39 450.91	1 604.12	528.38	538 580.0	586.907 87	619.480 82	101.23
2013	186.220	1.444 00	47 315.44	1 870.57	536.15	592 963.2	644.546 14	640.883 32	99.09
2014	191.854	1.617 20	54 032.94	1 947.97	665.95	643 563.1	714.120 07	676.052 23	99.44
2015	197.488	1.790 40	59 362.71	2 110.00	705.65	688 858.2	742.625 43	636.037 10	97.88
2016	203.122	1.963 60	64 886.04	2 016.29	675.41	746 395.1	726.766 70	624.257 44	96.11
2017	208.756	2.136 80	71 267.07	2 016.29	718.01	832 035.9	734.059 06	749.839 84	104.86
2018	214.390	2.310 00	76 272.76	2 125.75	717.20	919 281.1	784.913 52	818.729 84	98.90

NOTE The data were selected from the reference[25].

3 Analysis of coupling degree between forest carbon sink and forestry economic development

Firstly, we named the variable, specifically: year, period (yr); *frcs*, forest resources carbon stock (10^8 t); *fcs*, forest carbon sink (10^8 t/yr); *topf*, total output value of forestry industry (10^8 yuan); *ince*, amount of investment completed in ecological construction and protection (10^8 yuan); *fkein*, actually completed investment of forestry key ecological projects (10^8 yuan); *gdp*, GDP (10^8 yuan); *efp*, export value of forest products (10^8 yuan); *ifp*, import value of forest products (10^8 yuan); *ppi*, producer price index for forestry products (last year = 100). These variables reflect the coupling changes of forest carbon sink and forestry economic development from the aspects of carbon stock, carbon sink, forestry economic development, forest products trade and production price. Secondly, we used SPSSAU software to analyze the influencing factors of forest carbon sink and coupling coordination degree.

3.1 Analysis of factors influencing forest resources carbon stock and forest carbon sink

3.1.1 Influencing factors and lagging of forest resources carbon stock. Stepwise regression analysis was made with forest resources carbon stock as the dependent variable and other forestry economic development indicators as the independent variables, and the specific regression results are shown in Table 3. It can be seen from Table 3 that the stepwise regression analysis was performed with *topf*, *ince*, *fkein*, *gdp*, *efp*, *ifp* and *ppi* as independent variables and *frcs* as dependent variable. After the automatic identification of the model, the remaining four indicators of *ince*, *fkein*, *gdp* and *ifp* were kept in the model. The R^2 of the model is 0.998, $F = 3\ 137.812$, $P = 0.000 < 0.05$, and the Durbin - Watson (DW) value is 1.603, which is close to 2, indicating that *ince*, *fkein*, *gdp* and *ifp* could explain 99.8% of the changes in *frcs*, and the model passed the F test, so the model was effective. In addition, the multicollinearity of the model was tested, and it was found that the variance inflation factor (*VIF*) in the model was greater than 10, indicating that the model had multicollinearity problem. Finally, eliminating the multicollinearity problem, the final stepwise regression model was obtained as follows: $frcs = 138.292 - (0.008 \times ince) + (0.042 \times fkein) + (0.000\,084 \times gdp) - (0.015 \times ifp)$.

Table 3 Stepwise regression analysis results of *fcs* and changes in forestry economic development indicators

Item	Unstandardized coefficient		Standardized coefficient	t	P	VIF
	B	Standard error	Beta			
Constant	138.292	0.428		323.297	0.000**	
ince	−0.008	0.002	−0.300	−5.134	0.000**	42.873
fkein	0.042	0.003	0.469	15.703	0.000**	11.197
gdp	0	0	1.026	19.045	0.000**	36.490
ifp	−0.015	0.004	−0.183	−3.752	0.001**	29.758

NOTE *ince* denotes the amount of investment completed in ecological construction and protection, *fkein* is the actually completed investment of forestry key ecological projects, *gdp* is GDP, *ifp* is the import value of forest products, ** denotes the significance level of. The same below.

Therefore, the regression coefficient of *ince* was −0.008 ($t = -5.134$, $P = 0.000 < 0.01$), and the regression coefficient of *ifp* was −0.015 ($t = -3.752$, $P = 0.001 < 0.01$), indicating that *ince* and *ifp* had a significantly negative effect on *frcs*; the regression coefficient of *fkein* was 0.042 ($t = 15.703$, $P = 0.000 < 0.01$), and the regression coefficient of gdp was 0.000 84 ($t = 19.045$, $P = 0.000 < 0.01$), indicating that *fkein* and *gdp* had a significantlyly positive effect on *frcs*.

In addition, ARIMA (0, 2, 0) model and *ADF* test were carried out to analyze the lagging effect of each factor, and the coefficient was 0.091, the *AIC* value was 67.767, the *BIC* value was 71.194, the standard error was 0.082, z was 1.109, and p was 0.267, and the 95% *CI* was between −0.070 and −0.252.

For *frcs*, combined with Akaike Information Criterion (AIC) that the lower the *AIC* value, the better, SPSSAU automatically models and compares multiple potential candidate models, we finally found the optimal model was ARMA (0, 2, 0), indicating that the autoregressive order p was 0, the difference order d was 2, and the moving average order q was 0; the model formula is $y(t) = 0.091$, indicating that the lag period of each factor on forest resources carbon stock was 2. Accordingly, the *ADF* test was performed on the frcs, and the *ADF* test result of the data after the second-order difference showed that $P = 0.000 < 0.01$, with a confidence greater than 99% to reject the null hypothesis. At this time, the series was stable, which further indicated that the lag period of *frcs* was 2.

3.1.2 Influencing factors and lagging of forest carbon sink. Similarly, the stepwise regression analysis was carried out with the forest carbon sink as the dependent variable and other forestry economic development indicators as the independent variables, and the specific regression results are shown in Table 4.

Table 4 Stepwise regression analysis results of *fcs* and changes in forestry economic development indicators

Item	Unstandardized coefficient		Standardized coefficient	t	P	VIF
	B	Standard error	Beta			
Constant	0.249 000	0.034		7.402	0.000**	
topf	0.000 026	0	0.871	7.996	0.000**	14.901
fkein	0.003 000	0	1.092	11.991	0.000**	10.403
efp	−0.002 000	0	−0.951	−6.119	0.000**	30.337

NOTE *topf* denotes the total output value of forestry industry and *efp* denotes the export value of forest products.

In the stepwise regression analysis, the regression model had $R^2 = 0.982$, adjusted $R^2 = 0.980$, model $F = 410.945$, $P = 0.000$, and D-W value was 1.609. In the regression, *topf*, *ince*, *fkein*, *gdp*, *efp* and *ppi* were used as independent variables, and *fcs* was used as dependent variable for stepwise regression analysis. After the automatic identification of the model, the remaining three items of *topf*, *fkein* and *efp* were left in the model, indicating that *topf*, *fkein* and *efp* can explain 98.2% of the changes in *fcs*. Besides, the model passed the F test, and the D-W value was close to 2, indicating that the model was effective. In addition, the multicollinearity of the model was tested, and it was found that the *VIF* value in the model was greater than 10, indicating that the model had a collinearity problem. Finally, after eliminating the closely related independent variables, the regression analysis was carried out again, and the final model was obtained as follows: $fcs = 0.249 + (0.000\,026 \times topf) + (0.003 \times fkein) - (0.002 \times efp)$. Therefore, the regression coefficient of *topf* was 0.000 26 ($t = 7.996$, $P = 0.000 < 0.01$), indicating that *topf* had a significantly positive effect on *fcs*; the regression coefficient of *fkein* was 0.003 ($t = 11.991$, $P = 0.000 < 0.01$), indicating that *fkein* had a significant positive effect on *fcs*; the regression coefficient of *efp* was −0.002 ($t = -6.119$, $P = 0.000 < 0.01$). Similarly, the ARIMA model was used to analyze the lagging of *fcs* factors, and the specific results are shown in Table 5.

Table 5 Parameter of ARIMA (1, 1, 0) model for *fcs*

Item	Symbol	Coefficient	Standard error	*z*	*P*	95% *CI*
Constant	*c*	0.071	0.044	1.618	0.106	−0.015 −0.157
AR parameter	α1	0.800	0.092	8.681	0	0.619 −0.981

In the analysis, $AIC = -107.335$ and Bayesian Information Criterion (BIC) $= -102.194$. For *fcs*, combined with the information criterion that the lower the *AIC* value, the better, SPSSAU was used to automatically model and compare multiple potential models, and finally we obtained the optimal model ARMA (1,1,0), and the model formula was $y(t) = 0.071 + [0.800 \times y(t-1)]$. Therefore, the autoregression order p was 1, the difference order d was 1, and the moving average order q was 0, indicating that the lag period of each factor on the forest carbon sink was 1. In addition, for *fcs*, the *ADF* test (unit root test) of the data after the first difference was performed, and the result showed that $P = 0.020 < 0.05$, with more than 95% confidence to reject the null hypothesis, and the series was stable at this time, which further shows that the lag period of *fcs* was 1.

3.2 Analysis of coupling degree of forest carbon sink and forestry economic development The coupling coordination degree better reflects the integration effect of the forest carbon sink and the changes in forestry economic development. Based on the coupling coordination degree model and the collected data, the coupling coordination degree of forest carbon sink and changes in forestry economic development was calculated.

3.2.1 The coupling coordination degree of *frcs* and changes in forestry economic development. SPSSAU software was applied to calculate the coupling coordination degree of *frcs* and changes in forestry economic development, as shown in Table 6.

Table 6 Calculation results of coupling coordination degree of *frcs* and changes in forestry economic development

Year	Coupling degree (*C*)	Coordination index (*T*)	Coupling coordination degree (*D*)	Coordination level	Degree of coupling coordination
1992	1.000	0.010	0.100	2	Serious imbalance
1993	0.975	0.017	0.127	2	Serious imbalance
1994	0.943	0.024	0.150	2	Serious imbalance
1995	0.905	0.031	0.167	2	Serious imbalance
1996	0.904	0.039	0.188	2	Serious imbalance
1997	0.917	0.046	0.206	3	Moderate imbalance
1998	0.935	0.052	0.221	3	Moderate imbalance
1999	0.945	0.086	0.285	3	Moderate imbalance
2000	0.954	0.115	0.331	4	Mild imbalance
2001	0.931	0.150	0.373	4	Mild imbalance
2002	0.908	0.204	0.431	5	On the verge of imbalance
2003	0.894	0.255	0.477	5	On the verge of imbalance
2004	0.907	0.276	0.500	6	Barely coordination
2005	0.924	0.298	0.525	6	Barely coordination
2006	0.946	0.315	0.546	6	Barely coordination
2007	0.975	0.351	0.585	6	Barely coordination
2008	0.977	0.421	0.641	7	Primary coordination
2009	0.970	0.504	0.699	7	Primary coordination
2010	0.988	0.527	0.722	8	Intermediate coordination
2011	0.990	0.596	0.768	8	Intermediate coordination
2012	0.992	0.655	0.806	9	Good coordination
2013	0.990	0.715	0.842	9	Good coordination
2014	0.990	0.801	0.891	9	Good coordination
2015	0.991	0.865	0.926	10	High quality coordination
2016	0.998	0.878	0.936	10	High quality coordination
2017	0.999	0.935	0.966	10	High quality coordination
2018	1.000	0.990	0.995	10	High quality coordination

For the calculation of coupling coordination degree of *frcs* and changes in forestry economic development, the interval processing was carried out on that couple coordination degrees of different years, wherein all the data after the interval processing were between 0 and 1, and then the coupling coordination degree was calculated. It can be seen from the calculation results in Table 7 that the coupling coordination degree of *frcs* and changes in forestry economic development was from serious imbalance in 1992, rising to the high quality coordination in 2018, although there were some fluctuations in the middle, it was in an upward trend on the whole. The coupling coordination degree (D) value and the coordination level also increased from 0.1 and coordination level 2 in 1992, they rose to 0.995 and coordination level 10 in 2018. Therefore, it can be seen from the calculation results that from 1992 to 2018, China's forest resources carbon stock and forestry economic development were coupled and coordinated, and the coupling coordination degree was also rising, with an average annual growth of about 9.24%, and the coordination level also increased from 2 to 10.

3.2.2 The coupling coordination degree of *fcs* and changes in forestry economic development. Similarly, we calculated the coupling degree of *fcs* and changes in forestry economic development. In the calculation, since *fcs* is the change amount of forest resources carbon stock, the starting year was 1993 and the ending year was 2018. According to the calculation formula of the coupling coordination degree, the larger the value of the coupling degree (C), the greater the interaction between the systems; the larger the value of coupling coordination degree (D), the higher the degree of coordination between systems. The value of coupling coordination degree (D) value is typically between 0 and 1. Similarly, from Table 7, it can be seen that the coupling coordination degree of *fcs* and changes in forestry economic development increased from serious imbalance in 1993 to high quality coordination in 2018. Although there were processes such as moderate imbalance, mild imbalance, barely coordination, and primary coordination, the overall trend was upward. The value of coupling coordination degree (D) and coordination level also increased separately from 0.1, coordination level 2 in 1993 to 0.995 and coordination level 10 in 2018. Therefore, it can be seen from the calculation results that from 1993 to 2018, China's forest carbon sink and forestry economic development were coupled and coordinated, and the coupling coordination degree was also rising steadily, with an average annual growth rate of 9.63%.

Table 7 Calculation results of coupling coordination degree of *fcs* and changes in forestry economic development

Year	Coupling degree (C)	Coordination index (T)	Coupling coordination degree (D)	Coordination level	Degree of coupling coordination
1993	1.000	0.010	0.100	2	Serious imbalance
1994	0.960	0.016	0.123	2	Serious imbalance
1995	0.910	0.021	0.139	2	Serious imbalance
1996	0.953	0.023	0.146	2	Serious imbalance
1997	0.945	0.027	0.158	2	Serious imbalance
1998	0.969	0.027	0.162	2	Serious imbalance
1999	0.893	0.071	0.251	3	Moderate imbalance
2000	0.836	0.107	0.299	3	Moderate imbalance
2001	0.778	0.149	0.341	4	Mild imbalance
2002	0.746	0.208	0.394	4	Mild imbalance
2003	0.757	0.268	0.450	5	On the verge of imbalance
2004	0.812	0.287	0.482	5	On the verge of imbalance
2005	0.859	0.305	0.512	6	Barely coordination
2006	0.906	0.324	0.542	6	Barely coordination
2007	0.929	0.342	0.564	6	Barely coordination
2008	0.924	0.374	0.588	6	Barely coordination
2009	0.924	0.437	0.636	7	Primary coordination
2010	0.958	0.487	0.683	7	Primary coordination
2011	0.970	0.575	0.747	8	Intermediate coordination
2012	0.987	0.627	0.787	8	Intermediate coordination
2013	0.992	0.687	0.826	9	Good coordination
2014	0.990	0.797	0.888	9	Good coordination
2015	0.994	0.857	0.923	10	High quality coordination
2016	0.999	0.879	0.937	10	High quality coordination
2017	0.999	0.937	0.968	10	High quality coordination
2018	1.000	0.990	0.995	10	High quality coordination

4 Prediction of coupling coordination degree of forest carbon sink and changes in forestry economic development

Carbon peaking and carbon neutrality has become the future development strategy of China. The coupling coordination degree of forest carbon sink and changes in forestry economic development is directly related to the realization of goal of carbon peaking and carbon neutrality in China. In this study, exponential smoothing (ES) method was used to predict the coupling coordination degree of forest resources carbon stock and changes in forestry economic development. Exponential smoothing method is suitable for short-term prediction of data, and it can be divided into simple exponential smoothing method, double exponential smoothing method and triple exponential smoothing method (Holt – Winters). In the prediction, when the number of series is less than 20, the average value of the initial multi-period data is generally used as the initial value; when the number of series is larger than 20, the first period data is generally used as the initial value. In addition, the value of the smoothing coefficient α is generally between 0 and 1. If the data fluctuation is large, the value of α is between 0.6 and 0.8. On the contrary, if the data fluctuation is small, the value of α is generally between 0.1 and 0.5. In this study, the trend of the coupling coordination degree of the forest carbon sink and changes in forestry economic development was more considered, and the double smoothing method was used to predict. Specific to this study, for the data series more than 20 and the initial value S_0, the data of the first period was set as the initial value, and the best model parameters were: the initial value was 0.100, the α value was 0.800, the smoothing type is double smoothing, and the *RMSE* value was 0.017. Based on the parameters, the model was constructed to obtain the predicted value. The coupling coordination degree of *frcs* and changes in forestry economic development predicted by exponential smoothing is shown in Table 8.

Table 8 Predicted value of coupling coordination degree of *frcs* and changes in forestry economic development

Year	Original value	Predicted value	Absolute error
1992	0.100	0.100	0.000
1993	0.127	0.100	0.027
1994	0.150	0.143	0.007
1995	0.167	0.171	0.004
1996	0.188	0.186	0.002
1997	0.206	0.208	0.002
1998	0.221	0.225	0.004
1999	0.285	0.237	0.048
2000	0.331	0.330	0.001
2001	0.373	0.378	0.005
2002	0.431	0.417	0.014
2003	0.477	0.483	0.006
2004	0.500	0.526	0.026
2005	0.525	0.533	0.008
2006	0.546	0.552	0.006
2007	0.585	0.569	0.016
2008	0.641	0.617	0.024
2009	0.699	0.688	0.011
2010	0.722	0.754	0.032
2011	0.768	0.758	0.010
2012	0.806	0.809	0.003
2013	0.842	0.846	0.004
2014	0.891	0.879	0.012
2015	0.926	0.935	0.009
2016	0.936	0.965	0.029
2017	0.966	0.957	0.009
2018	0.995	0.991	0.004
2019		1.023	
2020		1.051	
2021		1.079	
2022		1.107	
2023		1.135	
2024		1.163	
2025		1.191	
2026		1.219	
2027		1.247	
2028		1.275	
2029		1.303	
2030		1.331	

From the prediction results in Table 8, it can be seen that from 2018 to 2030, the coupling coordination degree of *frcs* and changes in forestry economic development increased slowly, with an annual growth rate of 2.49%. Since the coupling coordination degree in 2019 – 2030 is greater than 1, it does not conform to the value range of coupling coordination degree. The predicted coupling coordination degree of frcs and changes in forestry economic development in 2019 – 2030, and the coordination level and degree of coupling coordination are shown in Table 9.

Table 9 Normalized coupling coordination degree, coordination level, and degree of coupling coordination of *frcs* and changes in forestry economic development from 2019 to 2030

Year	Coupling coordination degree (D)	Coordination level	Degree of coupling coordination
2019	0.991 8	10	High quality coordination
2020	0.992 5	10	High quality coordination
2021	0.993 3	10	High quality coordination
2022	0.994 0	10	High quality coordination
2023	0.994 8	10	High quality coordination
2024	0.995 5	10	High quality coordination
2025	0.996 3	10	High quality coordination
2026	0.997 0	10	High quality coordination
2027	0.997 8	10	High quality coordination
2028	0.998 5	10	High quality coordination
2029	0.999 3	10	High quality coordination
2030	1.000 0	10	High quality coordination

As shown in Table 9, according to the current development trend of forest resources carbon stock and forestry economy, from 2019 to 2030, the coupling coordination degree (D) values of frcs and changes in forestry economic development have been in a slowly increasing stage, and the coordination level of the two is also 10, and the degree of coupling coordination also belongs to the high quality coordination stage. Therefore, maintaining the current good development momentum of forestry economy and improving the management level and productivity of forest resources will help to promote the coupling and coordinated development of frcs and forestry economy. Similarly, the exponential smoothing method was used to predict the coupling coordination degree of *fcs* and changes in forestry economic development in 2018 – 2030. The prediction results after normalization are shown in Table 10. It can also be seen from the prediction results in Table 10 that the coupling coordination degree (D) values of *fcs* and changes in forestry economic development are in a slow increase stage from 2019 to 2030, the coordination level of the two is also 10, and the degree of coupling coordination also belongs to the high quality coordination stage. The change trend of coupling coordination degree of *fcs* and changes in forestry economic development and the coupling coordination between *frcs* and forestry economic development is consistent, which further illustrates that *frcs* and *fcs* are closely related. And that improvement of the management level and productivity of for resources is beneficial to the improvement of the coupling coordination degree of the two. Fig. 1 shows the coupling coordination degree predictions for *frcs*, *fcs*, and changes in forestry economic development.

Table 10 Normalized coupling coordination degree, coordination level, and degree of coupling coordination of *fcs* and changes in forestry economic development in 2019 – 2030

Year	Coupling coordination degree (*D*)	Coordination level	Degree of coupling coordination
2019	0.997 3	10	High quality coordination
2020	0.997 5	10	High quality coordination
2021	0.997 8	10	High quality coordination
2022	0.998 0	10	High quality coordination
2023	0.998 3	10	High quality coordination
2024	0.998 5	10	High quality coordination
2025	0.998 8	10	High quality coordination
2026	0.999 0	10	High quality coordination
2027	0.999 3	10	High quality coordination
2028	0.999 5	10	High quality coordination
2029	0.999 8	10	High quality coordination
2030	1.000 0	10	High quality coordination

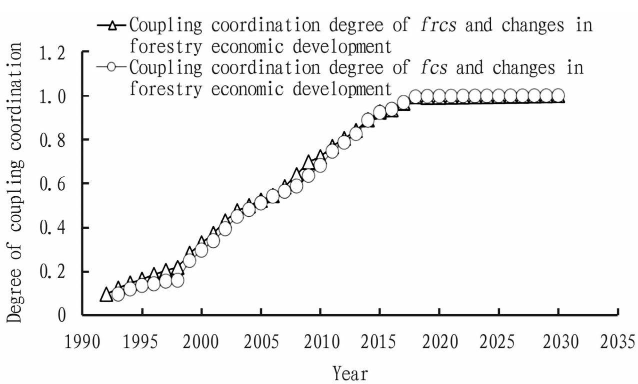

Fig. 1 Prediction for coupling coordination degree of *frcs*, *fcs* and changes in forestry economic development

5 Conclusions and discussion

The coupling degree reflects the degree of interdependence and mutual influence between systems. It also reflects the overall effectiveness of the system and is a comprehensive evaluation of the development level of the system. Forest carbon sequestration is an important way to reduce industrial greenhouse gas emissions, and it is also the best choice for China to develop a green low-carbon economy. The size of forest carbon sink is closely related to the area and volume of forest resources, as well as the economic and social development of forestry. The main purpose of this study is to seek the long-term symbiotic relationship between forest carbon sink and forestry economic development, to improve the value-added of their production and the symbiotic model of their future development, and then improve the allocation efficiency of forest resources in China, optimize the forestry industry system and promote the development of forestry economy. Through this study, we reached the following conclusions.

(i) The investment in ecological construction and protection, actually completed investment of forestry key ecological projects, GDP and import value of forest products have a significant impact on carbon storage of forest resources. Among them, both actually completed investment of forestry key ecological projects and GDP have a positive impact. The investment of ecological construction and protection and the import value of forest products are negative, and the influence of actually completed investment of forestry key ecological projects is the greatest. The total output value of forestry industry, actually completed investment of forestry key ecological projects, and export value of forest products have a significant influence on forest carbon sink. Specifically, export value of forest products has a negative influence, and the influence of actually completed investment of forestry key ecological projects has a negative influence and the influence is the greatest. Therefore, no matter from the perspective of carbon storage or carbon sink, we found that actually completed investment of forestry key ecological projects has a significant impact on both, and both are important factors. It also fully shows that the construction of key forestry ecological projects plays an important role in the realization of the goal of carbon peaking and neutrality in China.

(ii) The effect of forest resources carbon stock and forest carbon sink has a certain lag. Our findings indicate that whether it is the effect of other factors on forest resources carbon stock and forest carbon sink, or the effect of forest resources carbon stock and forest carbon sink on other factors, there is a certain lag. The lag period of forest resources carbon stock is 2 years, and the lag period of forest carbon sink is 1 year. Both of them also passed the tests of *AIC*, *BIC* and *ADF*, indicating that there was a lagging effect. Therefore, when investing in forest carbon sink, it is necessary to make well deployment in advance, and do a good job of forest resources management and time optimization.

(iii) From 1992 to 2018, the coupling degree of forest resources carbon stock, forest carbon sink and forestry economic development in China was gradually rising. Among them, the coupling degree of forest resources carbon stock and forestry economic development has an average annual growth of 9.24%, although there are some fluctuations in the middle. However, the coupling coordination degree rose from serious imbalance in 1992 to high quality coordination in 2018, and the coordination level also rose from 2 in 1992 to 10 in 2018. From 1993 to 2018, the coupling degree of forest carbon sink and forestry economic development increased by 9.63% annually. The growth rate was slightly faster than the annual average growth rate of the coupling coordination degree of forest resources carbon stock and forestry economic development. The degree of coupling coordination also rose from serious imbalance in 1993 to high quality coordination in 2018. The coordination level rose from level 2 in 1993 to level 10 in 2018.

(iv) For the long-term trend, the prediction shows that no matter the coupling coordination degree between forest resources carbon stock and forestry economic development, the coupling degree of forest carbon sink and forestry economic development is increasing and maintained at the level of high quality coordination and level 10 for a long time. From 2019 to 2030, the coupling coordination degree (D) values of both are close to 1, and the coordination level is 10 for a long time. The degree of coupling coordination is also maintained at the high quality coordination level for a long time. Therefore, how to improve the management level and maintain the current growth trend of forest resources is the key to achieve the goal of carbon peaking and carbon neutrality in China, and is also the basic condition for China's forestry to ensure the implementation of the commitment of "carbon peaking and carbon neutrality" strategic goal. Therefore, it is necessary to continue to optimize the structure of forestry industry, improve forest productivity, and ensure the continuous increase of forest resources.

In addition, the coupling coordination degree reflects the level of coordinated development of things, and also reflects the interaction and interaction between systems[31]. There is a strong correlation between forest carbon sink and forestry economic development. Relevant studies show that the correlation coefficient between the two is as high as 0.99[32], but the long-term interaction between forest carbon sink and economic growth and its impact mechanism are still not clear[33]. Therefore, it is necessary to discuss the following issues:

(i) The forest carbon sink has a lagging effect on the forestry economy. The forest carbon sink mainly absorbs CO_2 from the atmosphere through forest vegetation and fixes carbon in related organs, while the forestry economy is mainly through the input of land, labor and capital of forest resources to produce timber, forest by-products and ecological and social benefits. From the input of labor and capital to the output of timber, forest by-products and carbon sinks, it is not immediately effective, and there will be a certain lag period. Only by scientifically evaluating the lagging effect of forest carbon sink on forestry economy, or the lagging effect of forestry economy on carbon sink, can we optimize the input of forest carbon sink production process and the organizational form of forestry economic production. In this study, our findings indicate that there is a 2-year lagging effect of forest resources carbon stock on forestry economy in China, and a 1-year lagging effect of forestry economy on forest carbon sink. Therefore, in the production investment of forest carbon sink, it is required to make plan in advance, integrate and optimize the whole production process, and promote the optimal development of forest carbon sink and forestry economy.

(ii) The forest carbon sink has an important spillover effect on the forestry economy. Through stepwise regression analysis, it is found that forest carbon sink has an important positive effect on forestry output value and GDP, which indicates that forest carbon sink has an important spillover effect on forestry economy. Relevant research shows that the contribution of forest carbon sink to economic growth, especially GDP growth, is as high as 2.035 8, indicating that at this stage, every 1 percentage point increase in forest carbon sink will boost economic growth by 2.035 8 percentage points[34], also indicating that the spillover effect of forest carbon sink on economic growth is relatively large, which is conducive to stimulating economic growth. Therefore, promoting and improving the development of China's forest carbon sink plays a certain role in promoting the development of China's economy. In the process of implementing the national goal of carbon peaking and neutrality, it is necessary to speed up the development of forest carbon sink in China and further develop the spillover effect of forestry economy.

(iii) Economic growth is conducive to the scientific and technological innovation and progress of forest carbon sink. Economic growth will promote technological progress, make industrial structure, demand structure and regional structure more reasonable and optimized, and promote the increase of forest resources stock, thereby promoting the increase of forest carbon sink. Besides, the rapid economic development has changed the demand structure of forest products from resource-based consumption to ecological consumption, changed people's understanding of forest resources and forest products, and affected people's consumption tradition. In addition, the change of consumption structure promotes the gradual upgrading and rationalization of forestry industry, further promotes the innovation and technological progress of forestry science and technology, reduces the consumption of forest resources, increases forest area and forest stock, and then promotes the development of forest carbon sink[35], and facilitates the achievement of the goal of carbon peaking and neutrality.

(iv) The continuous improvement of coupling coordination degree is conducive to promoting the co-evolution of forestry industry. The production and management object of forestry industry is forest resources, and the independent economic organization in production is enterprises. The common production and management object of different enterprises-forest resources not only increases the efficiency of enterprises, but also promotes the development of industry. Therefore, forest resources or forest carbon sink and forestry enterprises can easily form a symbiote[31], which is also in line with the characteristics of industrial symbiosis theory. Therefore, the continuous improvement of coupling coordination degree is not only conducive to promoting the co-evolution of forestry industry, but also conducive to directly or indirectly promoting the improvement of forest resource allocation efficiency and industrial development[36].

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