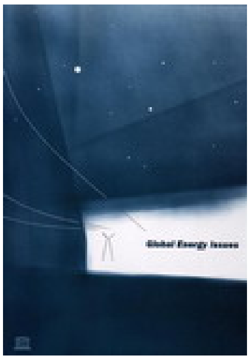

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Marine ecological governance and green development in Beibu Gulf of Guangxi under the digital context

Hefeng Song, Xue Wang*,
Junhui Zhao and Shuai Yuan

Nanning College of Technology,
Nanning, Guangxi, China
Email: songhefeng@nnct.edu.cn
Email: wangxue@nnct.edu.cn
Email: zhaojunhui@nnct.edu.cn
Email: yuanshuai@nnct.edu.cn
*Corresponding author

Jiayi Yu

College of Industrial Management,
Gyeongsang National University,
Jinju, South Korea
Email: mangguo1218@126.com

Abstract: With the rapid development of science, technology, and the economy, the Earth's ecosystem has suffered severe damage. The Guangxi Beibu Gulf Marine Region (GBGMR) is China's extremely important ecological barrier. This work aims to help formulate scientific and effective governance of the GBGMR and achieve Common Prosperity of the GBGMR to enable the high-quality and sustainable development of the GBGMR. This is achieved by constructing an integrated Ecological Carrying Capacity (ECC) model and introducing footprint breadth and depth analysis. The results show that the carbon and water ecological environments in the GBGMR show significant temporal and spatial differences. The ecological sustainability of Ningxia province along the GBGMR is the worst, while that of Henan is the strongest.

Keywords: carbon footprint; water footprint; Guangxi Beibu Gulf Marine Region; ecological governance; traditional regression analysis; organisational psychology.

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Biographical notes: Hefeng Song received his PhD from Gyeongsang National University, South Korea. Now, he works in the School of Business, Nanning College of Technology. His research interests include e-business and digital governance.

Xue Wang received her PhD from Gyeongsang National University, South Korea. Now, she works in School of Business, Nanning College of Technology. Her research interest include e-biz, business model.

Junhui Zhao received his Master's degree from Gyeongsang National University, South Korea. Now, he works in the School of Business, Nanning College of Technology. His research interests include e-business and green governance.

Shuai Yuan received the Master's degree in Business Administration from Renmin University of China. He is currently working at Nanning College of Technology, where he is affiliated with the Teaching and Research Section of Financial Technology and Digital Economy. His academic interests focus on financial technology, digital economy, and enterprise management.

Jiayi Yu is currently pursuing her PhD at Gyeongsang National University in South Korea, with research interests in industrial management, smart tourism, and related fields.

1 Introduction

As the 'Mother River' of the Chinese nation, the Guangxi Beibu Gulf Marine Region (GBGMR) provides a vast basin area, water resources and fishery resources for the nine provinces along its course (Shi et al., 2020). This region has a unique landform, ranging from glaciers in the west to loess in the central part and plains in the east (Sun et al., 2020). For a long time, it has been an important ecological barrier and a core economic zone in northwest and north China (Chen, et al., 2020a). However, the inherent ecological vulnerability of the river basin itself also brings crises to its environmental governance (Fang et al., 2021). Against the grand background of the country's vigorous promotion of ecological civilisation construction and the realisation of common prosperity, President Xi Jinping clearly pointed out in the government work report that priority should be given to ecology, and all regions should be encouraged to participate jointly and conduct coordinated governance (Li et al., 2021). Therefore, how to systematically solve the ecological and environmental constraints of the GBGMR and explore a green transformation path for the coordinated development of ecological protection, economy and society has become a major theoretical and practical issue that needs to be addressed urgently. This work is carried out against this background, aiming to provide scientific decision-making support for the sustainable development of the GBGMR.

In recent years, the academic community has conducted extensive research on the ecological governance of the GBGMR, such as evaluating its urban ecological level (Chen et al., 2020b) or analysing the coupling coordination between its economy and ecology (An et al., 2022). All these studies have found that the ecological health of the basin shows a slow improvement trend. However, there is still obvious room for deepening in existing research. In terms of evaluation systems, many studies tend to separate carbon emissions (such as carbon emission intensity, CEI) (Chen et al., 2022) from water resource consumption. They fail to comprehensively consider the regional Ecological Carrying Capacity (ECC) under the ‘carbon-water’ dual constraints within a unified analytical framework; this makes it difficult for the evaluation results to fully reflect the composite ecological pressure faced by the basin. At the same time, in the discussion of governance paths, existing studies mostly put forward suggestions from the perspectives of macro-policies or system dynamics simulation (Jiang et al., 2021). They rarely explore in depth how to integrate ‘green innovation’ into the governance system as an endogenous driving force; they also lack analysis on the dynamic mechanism of stimulating the collaborative cooperation of different governance subjects from micro perspectives, such as organisational psychology. For this reason, this work is committed to answering the following interrelated core scientific questions. What are the spatiotemporal differentiation characteristics of the Carbon Footprint (CF) and Water Footprint (WF) of each province and region in the GBGMR? How to construct an ECC evaluation system that integrates the dual constraints of carbon and water, and scientifically measure its dynamic changes? What are the key socioeconomic factors affecting the basin’s ECC? Based on the research findings, how to formulate differentiated ecological governance paths that balance theoretical innovation and practical feasibility for different regions?

Compared with existing literature, the contributions of this work are reflected in its unique theoretical perspective, integrated research methods, and prominent practical value. The innovation lies in introducing the organisational psychology analysis method into the ecological governance research framework in the GBGMR. It breaks through the traditional analytical paradigm that only relies on macroeconomics and environmental science. Thus, it provides a new micro perspective for understanding and promoting cross-regional and cross-departmental collaborative governance. In terms of research methods, this work constructs an ECC analytical framework based on the ‘CF-WF’ dual dimensions; it systematically identifies key influencing factors by combining panel regression models. Compared with single-dimensional ecological footprint research, the evaluation system of this work is more comprehensive and in-depth. The practical value is that it reveals the spatiotemporal heterogeneity of the GBGMR’s ecological pressure; it also puts forward more operable differentiated policy suggestions for the characteristics of different regions based on empirical results. It aims to offer accurate and effective scientific decision-making references for the green transformation and high-quality development of the GBGMR, thereby filling the gap in integrating theory and practice in existing research.

2 Literature review

The sustainable development of the GBGMR has long been a focus of attention in the academic community. Existing studies extensively explored the influence of natural and human factors on the ecosystem services of river basins (Lou et al., 2022; Zhu et al., 2022). They deeply analysed the coupling coordination degree of the ‘production-life-ecology’ three-life space and its influencing factors (Li et al., 2021). These studies generally suggest that there is a close spatial relationship between the ecosystem of the GBGMR and socio-economic driving forces. Meanwhile, its overall ecological health faces complex challenges, such as how to maintain key ecological flows (Zhang et al., 2018, 2021). These macro-level diagnoses provide an important foundation for understanding the overall ecological condition of the basin. However, they also prompt scholars to seek more refined quantitative tools to assess specific ecological pressures.

Against this background, the ecological footprint theory and its derived Carbon Footprint (CF) and Water Footprint (WF) analysis methods have become mainstream tools for measuring resource consumption and environmental impacts. Regarding CF, researchers calculated the CF of specific industries by evaluating energy flow, which provided a basis for formulating emission reduction policies (Zhao et al., 2019). In terms of WF, scholars evaluated the sustainable utilisation of regional water resources by improving the water resource ecological footprint model; they identified the key driving factors of water resource pressure (Wang et al., 2020). These studies offered profound insights for understanding the sources of ecological pressure in the GBGMR from a single dimension.

However, most of these studies proceed along independent paths, treating CF and WF as two separate issues. This research paradigm has significant limitations when applied to the GBGMR. A prominent feature of the GBGMR is the coexistence of the contradiction between 'energy enrichment' and 'water resource scarcity'. In other words, high-intensity energy development activities (closely related to CF) exert a huge crowding-out effect on the already scarce water resources (the core of WF). Therefore, analysing carbon emissions or water consumption in isolation cannot capture the inherent and complex coupling and trade-off relationships between the two; this also makes the ECC evaluation results based on the ecological footprint theory not comprehensive enough (Peng et al., 2019). At present, the academic community lacks a comprehensive ECC evaluation framework that can systematically integrate the 'carbon-water' dual constraints.

To fill this research gap, this work is committed to constructing and applying an integrated 'CF-WF' analysis model. This model aims to go beyond traditional single-factor analysis and comprehensively evaluate the spatiotemporal dynamics of the GBGMR's ECC by measuring the breadth and depth of CF and WF. On this basis, this work further explores green innovation governance mechanisms that can effectively synergise the dual goals of 'carbon reduction' and 'water conservation'. Thus, a more systematic and in-depth scientific basis can be provided for the sustainable development of the basin.

3 Research methodology

The research methods in this section follow a progressive logical framework. First, it calculates the ecological 'demand side' of the GBGMR in the two dimensions of carbon and water, namely CF and WF. Then, it measures the 'supply side' that the regional ecosystem can carry, i.e., ECC. Based on this, it compares the relationship between 'supply' and 'demand'; it also introduces the footprint breadth and depth models to analyse the structural characteristics of resource consumption, thereby realising a systematic diagnosis of the basin's ecological sustainability.

3.1 CF and ECC model

The core theoretical basis of the constructed CF and ECC models originates from the classic ecological footprint theory. By comparing the resource consumption caused by human activities (footprint) with the services that ecosystems can provide (carrying capacity) under a unified dimension, this theory intuitively reveals the sustainable development status of a region.

3.1.1 Carbon emission model

Carbon emission models are mainly divided into direct and indirect carbon emission models. Direct carbon emissions are emissions from cultivated land, mainly including the carbon emissions generated by pesticides and fertilisers. Indirect carbon emissions come from construction land, mainly referring to people's daily activities (Li et al., 2022). The direct carbon emission, or farmland consumption carbon emission, can be calculated by equation (1) (Xu et al., 2021).

$$E_t = GM + TN + (SO + PO) + FR + AU \quad (1)$$

In equation (1), E_t refers to the carbon emissions from cultivated land. G is the use of chemical fertilisers in various provinces. T represents the use of pesticides. S signifies the planting area. P, F and A stand for the use of agricultural machinery power, irrigation area and agricultural film, respectively. The carbon source conversion coefficient is shown in Table 1 (Harris et al., 2021).

Table 1 Carbon source conversion coefficient

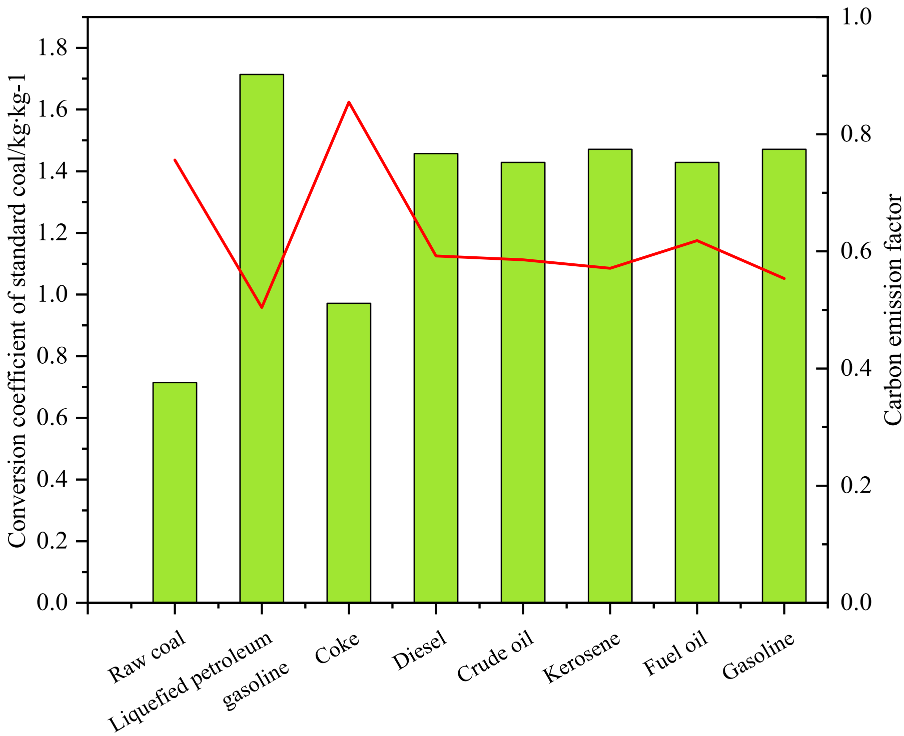
Data sources	*Oak Ridge National Laboratory (ORNL), USA*			*Institute of Resources, Ecosystem and Environment of Agriculture (IREEA), Nanjing Agricultural University*		
Carbon source	Chemical fertiliser	pesticides	Agricultural film	Seeded area	Irrigation area	Mechanical power
Conversion coefficient	0.8961 kg/kg	4.9339 kg/kg	5.20 kg/hm^2	16.49 kg/hm^2	266.51 kg/hm^2	0.19 kg/KW

The calculation of indirect carbon emissions (carbon emissions from construction land) is as follows:

$$CE = \sum Qe_i \times Se_i \times De_i \quad (2)$$

Here, CE refers to carbon emissions from construction land. Qe_i is the consumption of the i th kind of energy. Se_i stands for the reference coefficient of the i-th energy converted into Standard Coal. De_i denotes the carbon emission coefficient (Yu et al., 2021). Figure 1 gives the details.

Figure 1 Conversion coefficient of energy standard coal and carbon emission coefficient see online version for colours)



3.1.2 Carbon absorption model

The carbon absorption model covers the cultivated land carbon absorption and forest grassland carbon absorption. The carbon absorption model of forest grassland read.

$$CS = S_m \times \alpha_m + S_n \times \alpha_n \tag{3}$$

In equation (3), CS represents the total carbon absorption of forest grassland. S_m and S denote two different land areas. α_m and α_n stand for two different carbon absorption coefficients.

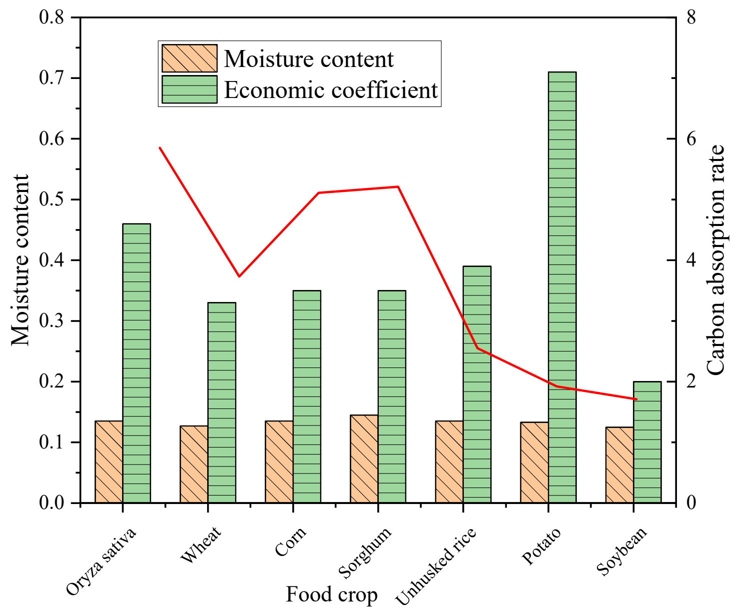
The calculation of carbon absorption of cultivated land reads.

$$CI_{crop} = \sum_i CI_{crop-i} = \sum_i C_{crop-i} \times \left(1 - P_{water-i}\right) \times \frac{Y_{eco-i}}{H_{crop-i}} \tag{4}$$

In equation (4), CI_{crop} refers to the carbon absorption by crop photosynthesis. CI_{crop-i} represents the carbon absorption of the i-th kind of crop. C_{crop-i} denotes the carbon absorption rate per unit organic matter of the i-th crop through photosynthesis. $P_{water-i}$,

Y_{eco-i} and H_{crop-i} mean the moisture content, economic yield and economic coefficient of the *i*-th crop, respectively (Liu et al., 2018). Figure 2 averages and plots the correlation coefficient of various crops in China.

Figure 2 Correlation coefficients of various crops see online version for colours)



3.1.3 CF and ECC models

CF and ECC models can be calculated by equations (5) and (6), respectively:

$$CEF = (CE + CF) \times \left(\frac{P_f}{NEP_f} + \frac{P_g}{NEP_g} + \frac{P_p}{NEP_p} \right) \tag{5}$$

$$CEC = (CS + CI_{crop}) \times \left(\frac{P_f}{NEP_f} + \frac{P_g}{NEP_g} + \frac{P_p}{NEP_p} \right) \tag{6}$$

$$CED = CEF - CEC$$

In equations (5) and (6), CEF refers to the CF consumed by industrial and agricultural production activities. CEC is the carbon ECC, including carbon absorption. CED stands for the ecological carbon deficit (Sarkar et al., 2018). $P_f = 52.41\%$, $P_g = 9.64\%$ and $P_p = 38.92\%$ represent the carbon absorption ratio of the forest, grassland, and cultivated land, respectively. NEP means net ecosystem ecological output (Tan et al., 2019). $NEP_f = 3.8103\,t / hm^2$ and $NEP_g = 0.9531\,t / hm^2$ respectively stand for the carbon absorption capacity of $1hm^2$ forest and grassland. $NEP_p = 0.1521\,t / hm^2$ indicates the carbon fixation capacity of cultivated land (Duan et al., 2018).

3.2 WF and ECC models

The WF model is a specialised application and extension of the ecological footprint concept in water resources. This theory was first systematically proposed by Hoekstra (2003). It aims to more accurately evaluate the direct and indirect occupation of water resources by human activities by quantifying the total amount of freshwater consumed by products and services throughout the supply chain. This work draws on this classic theoretical framework to construct the WF and its carrying capacity model to evaluate the basin's water resource sustainability. The WF model can be calculated as follows:

$$EF_w = EF_{wr} + EF_{wq} \tag{7}$$

$$EF_{wr} = P \times ef_{wr} \tag{8}$$

$$ef_{wr} = \gamma \times \left(\frac{WF}{\omega} \right) \tag{9}$$

In equations (7) and (9), EF_w is the regional WF. EF_{wr} represents the footprint of water amount. EF_{wq} denotes the ecological footprint of water quality. P stands for the population size. ef_{wr} indicates the per capita WF. γ signifies the water resource balance factor (Wang et al., 2020), 5.20. WF stands for water consumption. ω is the average water resource yield capacity, $3130\, m^3 / hm^2$.

The water quality ecological footprint has a certain impact on the WF. The impact of Chemical Oxygen Demand (COD) and NH_3 on the pollutant emission concentration can be used to measure the WF through equation (10):

$$EF_{wq} = \gamma \times \max\left[EF_{COD}, EF_{NH_3} \right] = \gamma \times \frac{\max\left[\frac{L_{COD}}{C_{COD}}, \frac{L_{NH_3}}{C_{NH_3}} \right]}{\omega} \tag{10}$$

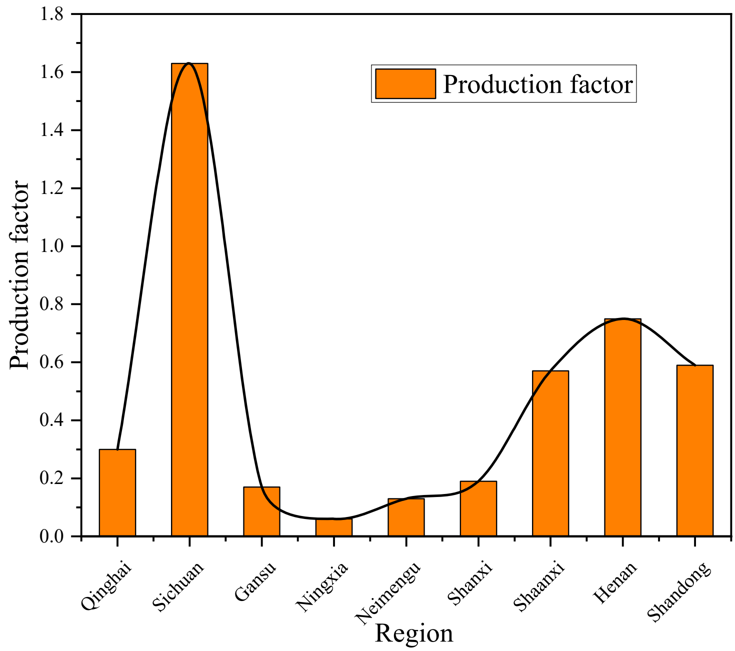
In equation (10), EF_{COD} represents COD Water Footprint. EF_{NH_3} means the NH_3 Water Footprint. L_{COD} refers to COD emission. L_{NH_3} stands for NH_3 emissions. $C_{COD} = 120\, mg / L$ and $C_{NH_3} = 25\, mg / L$ stand for the target concentration of COD and NH_3 in a unit area of water, respectively.

The calculation of the water ECC model reads:

$$EC_w = 0.4 \times \varphi \times \gamma \times \left(\frac{Q}{\omega} \right) \tag{11}$$

In equation (11), EC_w refers to water ECC. Q is the water supply measured by m^3. φ represents the water resource yield factor (Admasu et al., 2019). The value of the water resource yield factor of Chinese provinces is shown in Figure 3.

Figure 3 Water resource yield factor of each province in China see online version for colours)



3.3 *Footprint breadth and depth model*

Footprint breadth and depth models are important indicators for characterising the natural resource occupation, which can express the flow and stock of natural capital (Li et al., 2022a, 2022b). Specifically, footprint breadth emphasises the limitation of resources. When flow capital cannot meet the annual consumption, stock capital needs to be consumed in advance (Peng et al., 2019). The calculation of CF & WF breadth and depth reads:

$$EF_{size} = \min\left[EF, EC\right], 0 < EF_{size} < EC \tag{12}$$

$$EF_{depth} = 1 + \frac{\max\left(EF - EC, 0\right)}{EC}, EF_{depth} \geq 1 \tag{13}$$

Here, EF_{size} and EF_{depth} indicate the Footprint width and depth, respectively. '1' represents the natural length of the depth. When $EF \leq EC$, $EF_{depth} = 1$, indicating that flow capital can absorb daily needs. When $EF > EC$, $EF_{depth} > 1$, indicating that the flow capital has been completely consumed and the stock capital needs to be consumed in advance, which is unsustainable (Zhao et al., 2019).

4 Experimental design and performance evaluation

4.1 Data sets collection

The empirical analysis of this work is based on balanced panel data from nine provincial-level administrative regions along the GBGMR, including Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shanxi, Shaanxi, Henan and Shandong. The work covers a unified time span from 2012 to 2021, totaling 10 years. All original data are derived from authoritative official statistical sources. These primarily include the China Energy Statistical Yearbook, China Statistical Yearbook, China Environmental Statistical Yearbook, China Agricultural Statistical Yearbook for relevant years, along with provincial and municipal statistical yearbooks and water resources bulletins. This ensures the authority and reliability of the data.

The collected original data undergo detailed pre-processing to ensure the accuracy of the work. The data types mainly cover three categories. Ecological footprint accounting data, such as the total energy consumption by type, total water consumption, COD and ammonia nitrogen emissions, chemical fertiliser application amount, pesticide use amount, plastic film coverage area and total power of agricultural machinery in each province. Socio-economic indicator data, such as Gross Domestic Product (GDP), total population, urbanisation rate, proportion of secondary industry added value, internal expenditure on R&D funds and total import and export volume. In the data cleaning process, to eliminate the impact of price fluctuations, the nominal GDP data are deflated with 2012 as the base period. For the very few missing values in the data series, linear interpolation is used to fill them in, ensuring the integrity of the panel data. In addition, to reduce the heteroscedasticity of variables and make the data series more stable, some economic variables are log-transformed in the subsequent regression analysis.

4.2 Experimental environment

The relevant influencing factors of the breadth and depth of CF and WF are analysed to formulate the path/mechanism that conforms to the ecological governance of the GBGMR. The explanatory variables are selected for industrial structure, energy structure, regional economic level, urbanisation rate, technology level and opening up level. CF depth, CF breadth, WF breadth and WF depth are selected as explanatory variables of traditional panel data. The above indicators are selected as research variables mainly to promote the sustainable development of the local economy and help China achieve Common Prosperity based on ecological governance along the GBGMR.

First, the stationarity of variables is verified by *Fisher* test (Zhao et al., 2021). The obtained P value is listed in Table 2:

Table 2 Stability test of each variable

	P		Z		L^*		P_m	
	statistic	*p-value*	*statistic*	*p-value*	*statistic*	*p-value*	*statistic*	*p-value*
$Ln(cb)$	53.7514	0	–4.073	0	–4.541	0	6.0414	0
$Ln(cd)$	29.3755	0	–3.2128	0	–3.2565	0	2.3233	0
$Ln(wb)$	48.5601	0	–4.2262	0	–4.2825	0	5.1762	0
$Ln(wd)$	50.4077	0	–4.5434	0	–4.6253	0	5.4841	0
energy	29.2909	0.0041	–2.2856	0.0089	–2.2568	0.00131	1.9646	0.0199
industry	35.7864	0.0051	–2.2881	0.0091	–2.4264	0.0088	3.0472	0.0008
town	48.4042	0.0001	–4.2645	0	–4.3549	0	5.1502	0
$Ln(gdp)$	40.9583	0.0009	–3.1708	0.0005	–3.3291	0.0007	3.9092	0
$Ln(R \& D)$	128.6538	0	–8.5195	0	–11.9065	0	18.5251	0
$Ln(open)$	44.8154	0.0003	–3.5426	0.0001	–3.7546	0.0002	4.5521	0

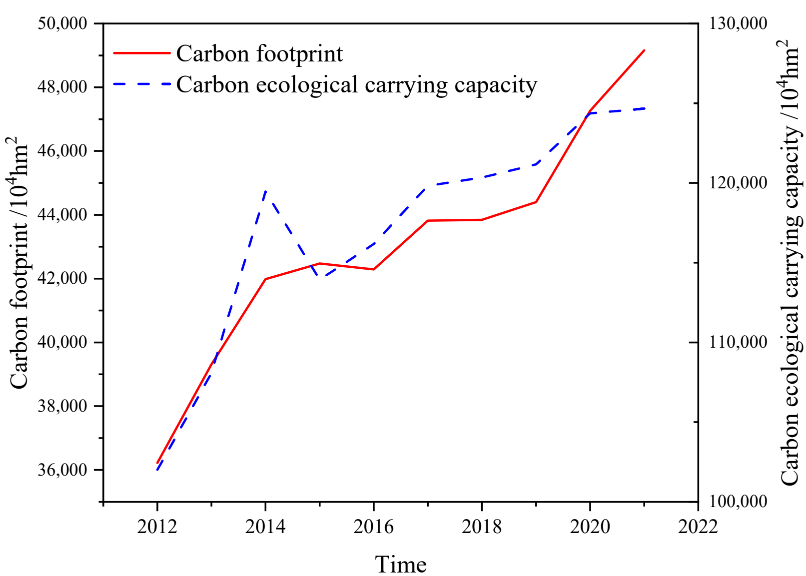
According to Table 2, at the significance level of 1%, the ten variables all strongly reject the original assumption of panel unit root. The result indicates that panel data is stable and can be used for subsequent calculations.

4.3 Performance evaluation

4.3.1 CF, WF and ECC

Figure 4 depicts the total CF of the GBGMR from 2012 to 2021.

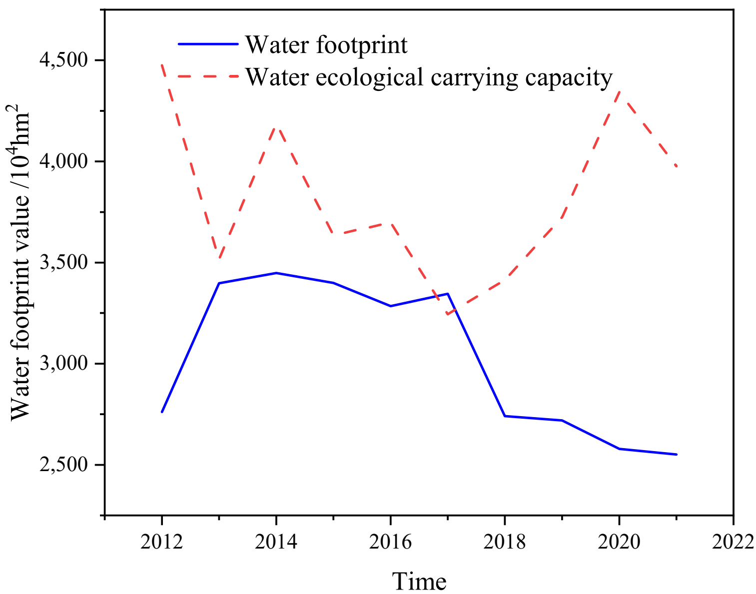
Figure 4 CF and ECC of the GBGMR in 2012–2021 see online version for colours)



As per Figure 4, the overall CF of the GBGMR is rising from 2012 to 2021. The overall carbon ECC is in a fluctuating upward trend. Thus, the GBGMR was in a carbon surplus state from 2012 to 2021. This indicates that the current carbon ECC can fully accommodate the ecological area consumption of human activities, but it has been weakening over time.

The total WF of the GBGMR from 2012 to 2021 is shown in Figure 5.

Figure 5 Total WF of the GBGMR from 2012 to 2021 see online version for colours)

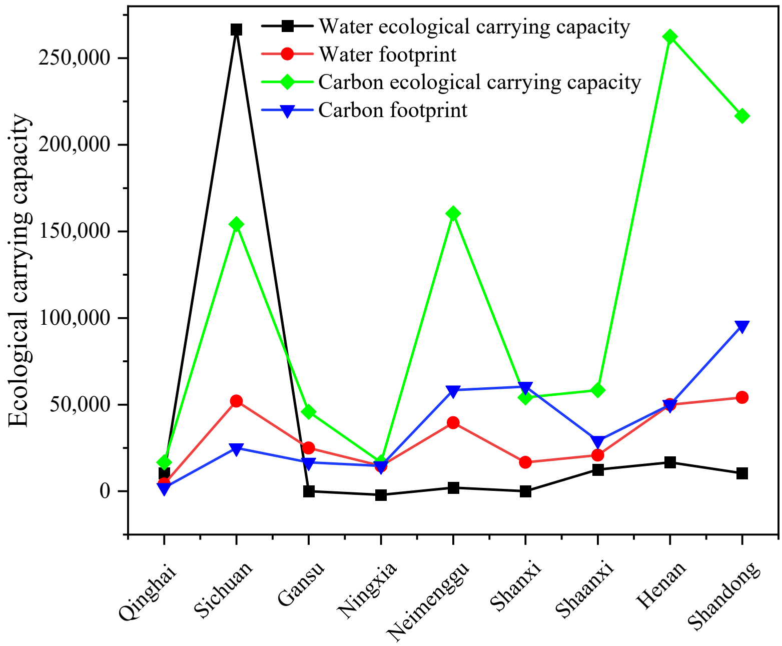


Obviously, the WF of the GBGMR is generally in a downward trend, the consumption of water resources is in a continuous upward trend, and the water GBGMR is fluctuating. Except for 2017, in other years during 2012–2021, GBGMR was in an ecological water surplus state. With strict control of ecological domestic water use, and further reduction of WF to improve water carrying capacity, the water surplus value has increased significantly.

The average CF, WF and carbon & water ECC of the provinces along the GBGMR vary greatly. Figure 6 compares the average carbon CF & WF and carbon & water ECC of each region from 2012 to 2021.

As shown in Figure 6, the CF, WF and carbon & water ECC of provinces along the GBGMR have significant spatial differences. This is mainly reflected in the surplus of carbon water ecology in Sichuan and Qinghai and the better development of ecosystems. Shanxi's carbon water is in deficit, so attention must be paid to energy conservation and consumption reduction. Other provinces are in carbon surplus and water deficit, so these provinces should do a good job planning to achieve water conservation and emission reduction.

Figure 6 Average CF, WF and carbon & water ECC of each region along the GBGMR in 2012–2021 see online version for colours)



4.3.2 Breadth and depth of CF and WF

Footprint breadth mainly refers to the level of natural capital flow occupied by human activities. By comparison, Footprint depth is the consumption of stock capital. The CF breadth of each Chinese province along the GBGMR during 2013–2021 is compared in Table 3:

Table 3 CF breadth

	2013	*2015*	*2017*	*2019*	*2021*	*Annual average*
Henan	55,494	54,357.9	55,144	42,714.1	48,758.9	51,293.78
Gansu	15,988.2	18,025.1	17,500.3	16,649.8	17,390.9	17,110.86
Ningxia	13,467.3	15,687	16,350.2	16490.8	16,541.7	15,707.4
Shaanxi	29,373.2	36,413.6	37,848.3	39,150	38,727.34	36,302.49
Shanxi	57,747	62,558.6	61,600	62,038.5	60,841.9	60,957.2
Sichuan	26,886.8	29,144.6	28,181.9	25,912.3	22,059.8	26,437.08
Shandong	91,300.5	97,236.9	109,599.7	114,099.2	119,968.5	106,441
Qinghai	3486	4,571.2	37,777.7	4,186.1	3,987.8	10,801.76
Inner Mongolia	59,858.7	64,103.2	62,766.4	66,268.8	83,381.2	67,275.66

From the overall development perspective, the CF breadth of GBGMR during 2013–2021 increased year by year. It showed a distribution of high in the middle and lower reaches and low in the upper reaches. The provinces with the highest CF breadth value are Shanxi Province and Inner Mongolia. This is mainly because Shanxi and Inner Mongolia are both energy-rich provinces with large carbon emissions. Shandong Province and Henan Province, located in the lower reaches of the GBGMR, consume more carbon flow resources; their consumption demand is far higher than the flow capital capacity. The CF depth of each province in the GBGMR during 2013–2021 is shown in Table 4.

Table 4 CF depth

	2013	*2015*	*2017*	*2019*	*2021*	*Annual average*
Henan	1	1	1	1	1	1
Gansu	1	1	1	1	1	
Ningxia	1.032	1.136	1.191	1.809	1.693	1.3722
Shaanxi	1	1	1	1	1	1
Shanxi	1.321	1.073	1.339	1.284	1.912	1.3858
Sichuan	1	1	1	1	1	1
Shandong	1	1	1	1	1	1
Qinghai	1	1	1	1	1	1
Inner Mongolia	1	1	1	1	1	1

Apparently, the average annual breakthrough natural original length of the GBGMR during 2013–2021 is 1. This indicates that the carbon ECC is higher than the CF value, and the resource flow can meet the consumption demand. The depth of Shanxi's CF has always been higher than the long-term value of natural resources, consuming more stock resources; it urgently needs energy transformation. The CF depth of Ningxia is greater than the original natural length value, so energy conservation and emission reduction should be carried out to increase vegetation coverage.

Similarly, the breadth and depth of WF of each province in the GBGMR during 2013–2021 are shown in Tables 5 and 6, respectively:

Table 5 WF breadth

	2013	*2015*	*2017*	*2019*	*2021*	*Annual average*
Henan	1625.22	1057.88	1423.01	2099.88	838.32	1576.066
Gansu	271.02	303.43	184.13	270.41	368.59	352.774
Ningxia	2.29	5.72	2.55	6.184	7.3	5.8088
Shaanxi	2145.39	1334.51	1255.33	1694.35	1,668.4	1952.816
Shanxi	154.94	160.232	116.98	165.45	124.53	168.8724
Sichuan	5598.57	5705.87	6021.43	5368.14	4627.88	6389.494
Shandong	1354.71	1139.05	655.79	881.91	763.73	1111.324
Qinghai	649.6	609.75	579.528	507.47	462.45	653.7896
Inner Mongolia	358.93	826.14	460.45	268.26	387.27	537.204

Table 6 WF depth

	2013	*2015*	*2017*	*2019*	*2021*	*Annual average*
Henan	1	1	1	1	1	1
Gansu	9.43	8.43	13.29	8.01	5.21	8.874
Ningxia	433.64	329.99	397.24	286.01	254.75	340.326
Shaanxi	1	1.68	1.75	1.03	1	1.292
Shanxi	11.12	11.69	14.98	9.25	11.58	11.724
Sichuan	1	1	1	1	1	1
Shandong	4.75	5.39	9.09	4.79	5.41	5.886
Qinghai	1	1	1	1	1	1
Inner Mongolia	11.91	5.21	9.19	12.39	8.45	9.43

According to Tables 5 and 6, the breadth and depth of the overall WF of the GBGMR showed a fluctuating downward trend during 2013–2021. In other words, the upward trend of water resource flow and the stock was suppressed, and the breadth and depth of water resources in each province were somewhat different, showing a gradual increase from south to north. In order to integrate the ecological sustainability of the carbon water system, the breadth and depth of the CF & WF are standardised in Table 7:

Table 7 Breadth and depth of CF & WF in each province

	CF	*WF*
Henan	The high breadth and low depth	The high breadth and low depth
Gansu	The low breadth and low depth	The low breadth and low depth
Ningxia	The low breadth and low depth	The low breadth and low depth
Shaanxi	The low breadth and low depth	The high breadth and low depth
Shanxi	High breadth and depth	The low breadth and low depth
Sichuan	The low breadth and low depth	The high breadth and low depth
Shandong	The high breadth and low depth	The high breadth and low depth
Qinghai	The low breadth and low depth	The high breadth and low depth
Mongolia	The high breadth and low depth	The low breadth and low depth

The carbon water system is divided into the following four areas:

1) *The high breadth and depth of CF & WF*: are high regional flow, stock consumption and poor ecological sustainability.
2) *Low in breadth and high in the depth of CF & WF*: stock capital is much higher than flow capital, and ecological sustainability is the worst.
3) *Low breadth and depth of CF & WF*: low flow stock, capital occupation and strong ecological sustainability.
4) *The high breadth and low depth of CF & WF*: flow capital far exceeds stock capital, and the sustainability of the ecosystem is the strongest.

4.3.3 Analysis of ecological control along the GBGMR

Fixed and random effects are selected for regression analysis of WF depth, WF breadth, CF breadth and CF depth in Table 8.

Table 8 Regression analysis results of the traditional panel model

Variable	*Lncd*		*Lnwb*		*Lnwd*	
	Fixed	*Random*	*Fixed*	*Random*	*Fixed*	*Random*
town	0.0191	0.0079	–0.3499	–0.7422	0.6938	0.7977
industry	.3835→1%	.3193→5%	–0.6639	–.7959→10%	0.4471	0.4831
_cons	0.0161	0.0991	5.7651→1%	5.208→1%	1.719→5%	1.861→5%
$Ln(gdp)$	–.1291→1%	–.1269→1%	0.0278	0.1625	0.0322	–0.0041
$Ln(R\&D)$	0.0149	.0177→10%	–0.0198	–0.039	0.0301	0.0341
$Ln(open)$	.0909→1%	.0899→1%	0.0709	0.0636	–.1629→5%	–.1601→5%
$R2$	0.4021	0.4001	0.0811	0.0687	0.0903	0.0892
energy	.2920→1%	.2181→1%	.2908→5%	0.1645	–0.2355	–0.1859
F test	15.49→1%		349.93→1%		421.39→1%	
Wald test		79.51→1%				11.49→10%
Hausman test	6.01		19.97→1%		5.19	

The *Hausman* test in Table 8 shows that at the significance level, *Lncd* and *Lnwd* cannot reject the original hypothesis; thus, it is more appropriate to choose random effects. *Lnwb* can reject the original hypothesis at the 1% significance level, and the fixed effect *F* test can pass the significance test and show excellent goodness of fit; hence, it is appropriate to select the fixed effect.

4.4 Discussion

The empirical results of this work reveal the complexity faced by the ecological governance of the GBGMR. A finding worthy of in-depth discussion is that GDP growth exerts a negative impact on CF depth. This indicates that economic development promotes technological progress and the improvement of energy efficiency to a certain extent, thereby slowing down the consumption of stock ecological capital. This phenomenon is consistent with some findings on the relationship between economic development and the ecological environment. In other words, the two do not have a simple linear opposite relationship, but present complex dynamic coupling characteristics at different development stages (Liu et al., 2021). However, at the same time, the positive impact of other factors such as industrial structure and urbanisation on CF breadth remains significant. This shows that the pressure of resource flow consumption caused by the expansion of economic scale has not been completely offset by the improvement of technical efficiency.

The urbanisation process is another key driving force affecting the basin's ecological pressure. This work finds that urbanisation has a negative impact on WF breadth. This may be because the concentration of population in cities brings about large-scale water-saving effects and more efficient sewage treatment facilities, thereby reducing per capita water resource consumption overall. However, the urbanisation process itself is also an energy-intensive process, and its role in promoting carbon emissions has been confirmed in other studies (Sui et al., 2022); this is consistent with the conclusion in this work that urbanisation has a positive impact on CF. This dual effect of 'reducing water consumption while increasing carbon emissions' highlights that in the process of promoting new-type urbanisation. Green infrastructure and low-carbon energy systems must be planned simultaneously to avoid the transfer of ecological pressure between different dimensions.

In terms of regional differences, the results of this work confirm the significant spatial heterogeneity of ecological pressure within the basin. In particular, upstream and midstream provinces such as Ningxia and Shanxi have relatively high CF and WF depth; this is largely rooted in their energy-intensive industrial structure dominated by coal mining, thermal power and coal chemical industry. Existing studies have specifically established carbon emission models for coal enterprises, which are key emission sources (Li et al., 2022b). This development model not only directly leads to a large amount of carbon emissions, but also exerts huge crowding-out effects on the already scarce water resources. Interestingly, this work also observes that the overall WF of the basin shows a certain fluctuating downward trend from 2013 to 2021. This may be related to the strict national water resource management policies and large-scale ecological restoration projects in recent years. For example, existing studies show that vegetation restoration activities in the GBGMR have significantly changed the regional hydrological processes and water storage capacity (Li et al., 2020). The complex spatiotemporal changes of evapotranspiration in the basin also profoundly affect the availability of water resources (Jiang et al., 2020). These provide strong external evidence support for the changing trend of WF in this work.

5 Conclusions

By constructing a dual-dimensional analytical framework that integrates CF and WF, this work systematically evaluates the spatiotemporal dynamics of ECC in the nine provinces and regions of the GBGMR from 2012 to 2021. The research results reveal that the carbon and water ecological environment of the basin has significant spatiotemporal heterogeneity. Although the basin as a whole is in a state of carbon-water surplus, this surplus value is narrowing year by year, and the potential pressure on ecological sustainability is increasing. In particular, upstream and midstream provinces such as Shanxi and Ningxia, which take energy and chemical industry as their pillar industries, face particularly prominent ecological deficit problems. In contrast, downstream provinces such as Henan, which have completed the optimisation and upgrading of industrial structure, show stronger ecological sustainability.

Based on the above conclusions, this work proposes the following differentiated policy implications. First, the ecological governance of the GBGMR must abandon the 'one-size-fits-all' model and shift to targeted and precise policies based on local conditions. For major energy provinces such as Shanxi and Inner Mongolia with persistently high CF, policy focus should be placed on promoting the transformation of energy structure. Specifically, fiscal and tax incentives and industrial subsidies should be used to vigorously develop renewable energy such as wind energy and solar energy, and gradually reduce dependence on traditional coal energy. For provinces facing severe water resource constraints such as Ningxia and Gansu, strict dual control of total water consumption and water consumption intensity should be implemented. Price levers should be used to guide the withdrawal and transformation of high-water-consuming industries, and advanced water-saving irrigation technologies should be promoted.

Although this work provides a new perspective for understanding the composite ecological pressure of the GBGMR, it still has certain limitations. First, the work's core evaluation system only focuses on CF and WF, and has not fully integrated the comprehensive impacts of other key ecological factors such as biodiversity and soil pollution. Second, the data analysis of this work is based on the provincial macro-scale. If future studies can use more detailed municipal or even county-level data, it will help reveal deeper internal regional differences. Therefore, future research directions can focus on constructing a more multi-dimensional and comprehensive ecosystem health evaluation system, and in-depth exploration of the feasibility of collaborative governance mechanisms such as cross-regional ecological compensation.

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Declarations

All authors declare that they have no conflicts of interest.

References

Admasu, R., Michael, A.W. and Hordofa, T. (2019) 'Effect of moisture stress on maize (*Zea mays* L.) yield and water productivity', *International Journal of Environmental Science and Technology*, Vol. 16, No. 4. Doi: 10.19080/IJESNR.2019.16.555945.

An, S., Zhang, S., Hou, H., Zhang, Y., Xu, H. and Liang, J. (2022) 'Coupling coordination analysis of the ecology and economy in the Guangxi Beibu Gulf Marine Region under the background of high-quality development', *Land*, Vol. 11, No. 8. Doi: 10.3390/land11081235.

Chen, X., Meng, Q., Shi, J., Liu, Y., Sun, J. and Shen, W. (2022) 'Regional differences and convergence of carbon emissions intensity in cities along the Guangxi Beibu Gulf Marine Region in China', *Land*, Vol. 11, No. 7. Doi: 10.3390/land11071042.

Chen, Y., Zhu, M., Lu, J., Zhou, Q. and Ma, W. (2020b) 'Evaluation of ecological city and analysis of obstacle factors under the background of high-quality development: taking cities in the Guangxi Beibu Gulf Marine Region as examples', *Ecological Indicators*, Vol. 118.

Chen, Y.P., Fu, B.J., Zhao, Y., Wang, K.B., Zhao, M.M., Ma, J.F. and Wang, H. (2020a) 'Sustainable development in the Guangxi Beibu Gulf Marine Region: Issues and strategies', *Journal of Cleaner Production*, Vol. 263.

Duan, H., Wang, L., Zhang, Y., Fu, X., Tsang, Y., Wu, J. and Le, Y. (2018) 'Variable decomposition of two plant litters and their effects on the carbon sequestration ability of wetland soil in the Yangtze River estuary', *Geoderma*, Vol. 319, pp.230–238.

Fang, L., Wang, L., Chen, W., Sun, J., Cao, Q., Wang, S. and Wang, L. (2021) 'Identifying the impacts of natural and human factors on ecosystem service in the Yangtze and Guangxi Beibu Gulf Marine Regions', *Journal of Cleaner Production*, Vol. 314. Doi: 10.1016/j.jclepro.2021.127995.

Harris, N.L., Gibbs, D.A., Baccini, A., Birdsey, R.A., De Bruin, S., Farina, M. and Tyukavina, A. (2021) 'Global maps of twenty-first century forest carbon fluxes', *Nature Climate Change*, Vol. 11, No. 3, pp.234–240.

Hoekstra, A.Y. (2003) *Virtual Water: an Introduction*, Virtual Water Trade, Vol. 13, Report.

Jiang, L., Zuo, Q., Ma, J. and Zhang, Z. (2021) 'Evaluation and prediction of the level of high-quality development: a case study of the Guangxi Beibu Gulf Marine Region, China', *Ecological Indicators*, Vol. 129.

Jiang, Z.Y., Yang, Z.G., Zhang, S.Y., Liao, C.M., Hu, Z.M., Cao, R.C. and Wu, H.W. (2020) 'Revealing the spatio-temporal variability of evapotranspiration and its components based on an improved Shuttleworth-Wallace model in the Guangxi Beibu Gulf Marine Region', *Journal of Environmental Management*, Vol. 262. Doi: 10.1016/j.jenvman.2020.110310.

Li, C., Zhang, Y., Shen, Y. and Yu, Q. (2020) 'Decadal water storage decrease driven by vegetation changes in the Guangxi Beibu Gulf Marine Region', *Science Bulletin*, Vol. 65, No. 22, pp.1859–1861.

Li, J., Sun, W., Li, M. and Meng, L. (2021) 'Coupling coordination degree of production, living and ecological spaces and its influencing factors in the Guangxi Beibu Gulf Marine Region', *Journal of Cleaner Production*, Vol. 298. Doi: 10.1016/j.jclepro.2021.126803.

Li, X., Xiao, L., Tian, C., Zhu, B. and Chevallier, J. (2022a) 'Impacts of the ecological footprint on sustainable development: evidence from China', *Journal of Cleaner Production*, Vol. 352. Doi: 10.1016/j.jclepro.2022.131472.

Li, Y., Jin, X., Wang, G., Ren, Y., Tan, H. and Li, N. (2022b) 'Construction and application of a carbon emission model for China's coal production enterprises and result analysis', *Frontiers in Energy Research*, Vol. 10. Doi: 10.3389/fenrg.2022.889877.

Liu, K., Qiao, Y., Shi, T. and Zhou, Q. (2021) 'Study on coupling coordination and spatiotemporal heterogeneity between economic development and ecological environment of cities along the Guangxi Beibu Gulf Marine Region', *Environmental Science and Pollution Research*, Vol. 28, No. 6, pp.6898–6912.

Liu, L., Lei, Y., Ge, J. and Yang, K. (2018) 'Sector screening and driving factor analysis of Beijing's ecological footprint using a multi-model method', *Journal of Cleaner Production*, Vol. 191, pp.330–338.

Lou, Y., Yang, D., Zhang, P., Zhang, Y., Song, M., Huang, Y. and Jing, W. (2022) 'Multi-scenario simulation of land use changes with ecosystem service value in the Guangxi Beibu Gulf Marine Region', *Land*, Vol. 11, No. 7.

Peng, B., Li, Y., Elahi, E. and Wei, G. (2019) 'Dynamic evolution of ecological carrying capacity based on the ecological footprint theory: a case study of Jiangsu province. *Ecological Indicators*, Vol. 99, pp.19–26.

Sarkar, B., Omair, M. and Choi, S.B. (2018) 'A multi-objective optimization of energy, economic, and carbon emission in a production model under sustainable supply chain management', *Applied Sciences*, Vol. 8, No. 10. Doi: 10.3390/app8101744.

Shi, F., Liu, S., Sun, Y., An, Y., Zhao, S., Liu, Y. and Li, M. (2020) 'Ecological network construction of the heterogeneous agro-pastoral areas in the upper Guangxi Beibu Gulf Marine Region', *Agriculture, Ecosystems and Environment*, Vol. 302. Doi: 10.1016/j.agee.2020.107069.

Sui, H., Han, L. and Ding, Y. (2022) 'Dynamic analysis of a delayed carbon emission-absorption model for China's Urbanization and population growth', *Mathematics*, Vol. 10, No. 17. Doi: 10.3390/math10173072.

Sun, P., Wu, Y., Gao, J., Yao, Y., Zhao, F., Lei, X. and Qiu, L. (2020) 'Shifts of sediment transport regime caused by ecological restoration in the Middle Guangxi Beibu Gulf Marine Region', *Science of the Total Environment*, Vol. 698. Doi: 10.1016/j.scitotenv.2019.134261.

Tan, S., Chen, B., Zheng, H., Xu, F., Xu, H., Wei, J. and Tang, J. (2019) 'Effects of cultivation techniques on CH4 emissions, net ecosystem production, and rice yield in a paddy ecosystem', *Atmospheric Pollution Research*, Vol. 10, No. 1, pp.274–282.

Wang, H., Huang, J., Zhou, H., Deng, C. and Fang, C. (2020) 'Analysis of sustainable utilization of water resources based on the improved water resources ecological footprint model: a case study of Hubei Province, China', *Journal of Environmental Management*, Vol. 262. Doi: 10.1016/j.jenvman.2020.110331.

Xu, W., Xie, Y., Xia, D., Ji, L. and Huang, G. (2021) 'A multi-sectoral decomposition and decoupling analysis of carbon emissions in Guangdong province, China', *Journal of Environmental Management*, Vol. 298. Doi: 10.1016/j.jenvman.2021.113485.

Yu, Y., Li, S., Sun, H. and Taghizadeh-Hesary, F. (2021) 'Energy carbon emission reduction of China's transportation sector: an input–output approach', *Economic Analysis and Policy*, Vol. 69, pp.378–393.

Zhang, Q., Zhang, Z., Shi, P., Singh, V.P. and Gu, X. (2018) 'Evaluation of ecological instream flow considering hydrological alterations in the Guangxi Beibu Gulf Marine Region, China', *Global and Planetary Change*, Vol. 160, pp.61–74.

Zhang, Y., Lu, X., Liu, B., Wu, D., Fu, G., Zhao, Y. and Sun, P. (2021) 'Spatial relationships between ecosystem services and socioecological drivers across a large-scale region: a case study in the Guangxi Beibu Gulf Marine Region', *Science of the Total Environment*, Vol. 766.

Zhao, G., Yang, H., Yang, J., Zhang, L. and Yang, X. (2021) 'A data-based adjustment for fisher exact test', *European Journal of Statistics*, Vol. 1, pp.74–107.

Zhao, Q., Ding, S., Wen, Z. and Toppinen, A. (2019) 'Energy flows and carbon footprint in the forestry-pulp and paper industry', *Forests*, Vol. 10, No. 9. Doi: 10.3390/f10090725.

Zhu, W., Muhammad, A., Han, M., Li, Y., Kong, X. and Kong, F. (2022) 'Spatial distribution and aggregation of human-environment coordination and optimal paths in the Yellow River Delta, China', *Ecological Indicators*, Vol. 143. Doi: 10.1016/j.ecolind.2022.109380.