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Sustainable development between sports facilities and ecological environment based on the dual carbon background

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The sustainable development of sports facilities and their integration with the ecological environment are crucial in addressing global environmental challenges. This study examines the coupling coordination between sports facilities and the ecological environment in nine prefecture-level cities in Fujian Province, China, from 2013 to 2020, within the framework of China's "Dual Carbon" strategy. Using a multidisciplinary approach that integrates economics, sociology, and geography, the study employs the entropy method and coupling coordination models to analyze the temporal evolution and spatial distribution of the coupling coordination between sports facilities and the ecological environment. The findings reveal that the overall trend of coupling coordination is positive, with the degree of coordination improving over time from severe imbalance in 2013 to high-quality coordination by 2020. Economic factors, such as per capita GDP, positively influence the coupling coordination, while factors like population density and regional GDP have a negative impact. Coastal cities, such as Xiamen and Zhangzhou, demonstrate stronger regional correlations and play a critical role in improving the overall coupling level of the province. This research provides several recommendations for promoting orderly and optimal development, considering the distinct characteristics of sports facilities and the ecological environment.

Keywords Sports facilities, Ecological environment, Sustainable development

The interplay between sports facilities and the ecological environment is a critical area of study, especially in the context of sustainable development and environmental conservation. The World Health Organization's Global Action Plan on Physical Activity 2018–2030 has catalyzed a global surge in sports facility construction, raising significant questions about their environmental impact[1]. This study aims to explore the coupling coordination between sports facilities and the ecological environment in Fujian Province, China, under the "Dual Carbon" strategy.

The construction of sports facilities often involves the use of synthetic materials and practices that can lead to environmental degradation. For instance, plastic surfaces and artificial turfs contribute to pollution, and the design and planning processes frequently overlook ecological considerations[2]. Addressing these issues requires a comprehensive evaluation system that integrates economic, sociological, and geographical perspectives[3].

China's commitment to achieving carbon peaking by 2030 and carbon neutrality by 2060 underscores the importance of developing low-carbon, sustainable sports facilities. The "Dual Carbon" strategy provides a framework for examining how sports facilities can align with ecological goals, promoting green industrial transformation and high-quality development[4–6].

This study introduces a coupling degree model and a coupling coordination degree model to empirically measure the relationship between sports facilities and the ecological environment in nine prefecture-level cities in Fujian Province. By analyzing the temporal evolution and internal logic of this relationship, the study aims to provide insights into the sustainable development of sports facilities and their ecological impact.

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The research questions guiding this study are:

(1) How can a coupling coordination evaluation index system for sports facilities and the ecological environment be constructed?
(2) How can the coupling degree and coupling coordination degree models be applied to evaluate this relationship in Fujian Province?
(3) What is the current state of coupling coordination between sports facilities and ecological environment development in the region?
(4) What are the future pathways for the green development of sports facilities in Fujian Province, considering their ecological impact?

By addressing these questions, this study seeks to contribute to the theoretical and practical understanding of sustainable sports development, providing a reference for policy makers and stakeholders involved in the planning and management of sports facilities.This study also delves into the theoretical frameworks underpin the relationship between sports facilities and the ecological environment. The theoretical analysis includes Systems Theory, Sustainable Development Theory which collectively explain the existence and importance of the coupled relationship between sports facilities and the ecological environment.

Literature review

The sustainable development of sports facilities and their integration with the ecological environment is crucial in addressing global environmental challenges. Sustainable sports development requires an understanding of how sports facilities can be designed and managed to minimize environmental impact while promoting social and economic benefits. The construction and operation of sports facilities often involve the use of synthetic materials and practices that can lead to environmental degradation. For instance, plastic surfaces and artificial turfs contribute to pollution, and the design and planning processes frequently overlook ecological considerations. Addressing these issues requires a comprehensive evaluation system that integrates economic, sociological, and geographical perspectives. He, Yeerkenbieke, and Baninla (2020) discuss the environmental sustainability of the 2022 Winter Olympics, highlighting the importance of public participation and information disclosure[2]. Button et al. (2020) introduce an ecological dynamics approach to skill acquisition, which can be applied to understand the interaction between sports activities and environmental factors[3].

The inclusion of environmental considerations in international policies and charters underscores the global recognition of the need for sustainable sports development. The United Nations' establishment of the Intergovernmental Panel on Climate Change (IPCC) in 1988 and the Olympic Charter's amendments in 1991 to address environmental issues highlight this commitment. Agrawala (1998) provides a historical context of the IPCC and its role in climate change discussions. Farmer et al. (2013) discuss the importance of contextual interventions to promote student engagement, which parallels the need for targeted strategies in sports facility management[7-8].

China's commitment to achieving carbon peaking by 2030 and carbon neutrality by 2060 underscores the importance of developing low-carbon sustainable sports facilities. The "Dual Carbon" strategy provides a framework for examining how sports facilities can align with ecological goals, promoting green industrial transformation and high-quality development. Liu, Zhang, and Chen (2022) discuss the role of China's "Dual Carbon" strategy in sustainable development, emphasizing the need for low-carbon practices in various industries, including sports. Zhang et al. (2021) explore the coupling coordination relationship between urbanization and ecosystem service value, providing insights into how urban sports facilities can be integrated with ecological considerations[4–6].

Despite the growing body of research, there are few quantitative empirical studies on the coupling coordination between sports facilities and the ecological environment in China. Most existing studies have focused on isolated aspects, lacking comprehensive indicator systems or mathematical models based on macro-level data. Li et al. (2012) emphasize the need for research on complex systems' coupling coordination, advocating for a multidisciplinary approach to capture the multifaceted interactions between sports facilities and the ecological environment[9]. Tang (2015) uses an integrated approach to evaluate the coupling coordination between tourism and the environment, providing a methodological framework that can be adapted to sports facilities research[10,11]. Feng et al. (2020) highlight the importance of landscape patterns and urban planning in enhancing ecological sustainability, which is crucial for developing sports facilities that harmonize with their surrounding environments[12].

Case studies of sustainable sports facilities provide valuable lessons on integrating sustainability into sports facility management. These studies underscore the importance of harmonizing public interests, including natural environmental benefits, economic viability, and social equity. Bunds et al. (2019) examine the sustainability of stadiums, specifically the case study of SC Freiburg, highlighting the need for integrating sustainability into sports facility management[13]. Kellison and Hong (2015) apply Rogers' diffusion-of-innovations framework to the conceptualization of environmental sustainability in sports, emphasizing critical factors and measures conducive to environment-friendly sports facilities[14].

In conclusion, while significant progress has been made in understanding the relationship between sports facilities and the ecological environment, there remains a need for more comprehensive and empirical research. Integrating multidisciplinary approaches, developing robust evaluation systems, and adapting innovative methodologies from related fields can provide deeper insights and practical solutions for achieving sustainable development in sports facilities. This study aims to fill these gaps by introducing a coupling degree model and a coupling coordination degree model to empirically measure the interaction between sports facilities and the ecological environment in Fujian Province, China, within the framework of the "Dual Carbon" strategy.

Study region

Fujian Province, which is situated on the southeastern coast of China, shares a border with Zhejiang Province to the northeast, and is bordered by Jiangxi Province to the west and northwest, as well as Guangdong Province to the southwest. Additionally, Fujian Province faces Taiwan Province across the Taiwan Strait to the east. The province is presently responsible for governing nine cities, namely Fuzhou, Xiamen, Putian, Quanzhou, Zhangzhou, Longyan, Sanming, Nanping, and Ningde, as well as the Pingtan Comprehensive Experimental Zone (Pingtan County) as shown in Fig. 1.

With a forest coverage rate of 65.95%, Fujian ranks first in the country. It has a forest area of 115 million and absorbs over half of the province's total annual carbon dioxide emissions, making it one of the six major forest areas in China. Fujian Province is now entering a new period of development, faced with the critical period of rapid development of the Haixi Economic Zone, as well as its special status and unique role in China's "Belt and Road"[15].

Methods

Entropy method

The entropy technique is a neutral method for assigning weights, which involves calculating the significance of each indicator based on the extent of information contributed by each observation[16].This involves three main steps: data normalization, entropy calculation, and weight determination.

Step 1: Different data units can affect analysis results, so data should be normalized to ensure consistency[17]. For positive indicators, the normalization formula is $x_{ij}=\frac{x_{ij}-\min x_{ij}}{\max x_{ij}-\min x_{ij}}$. The negative indicator's normalization formula is $x_{ij}=\frac{\max x_{ij}-x_{ij}}{\max x_{ij}-\min x_{ij}}$. In the formula, x_{ij} represents the actual value of the j index of the i year, $\max x_{ij}$ and $\min x_{ij}$represent the maximum and minimum values of the index j, x_{ij}represents the standardized data of the j index of the i year. After standardization, After normalization, all values are between 0 and 1. To avoid losing original data, a small constant ($\alpha=0.001$) is added to the normalized data: $x_{ij}=x_{ij}+\alpha$.

Step 2: The entropy method was utilized for the purpose of computing the weights of the various indicators that were used in the assessment of the ecological environment and the sports facilities. The calculation formula is as follows: $p_{ij}=\frac{x_{ij}}{\sum_{ij}^{n} x_{ij}}$, p_{ij} indicates the weight of indicator j in year i. $E_j=-k\sum_{i=1}^{n} p_{ij}\ln p_{ij}$, E_j indicates the entropy value of the j indicator. Where $k=\frac{1}{\ln n}$ and and n is the number of years. $D_j=1-E_j$, D_j Indicates indicator entropy redundancy.

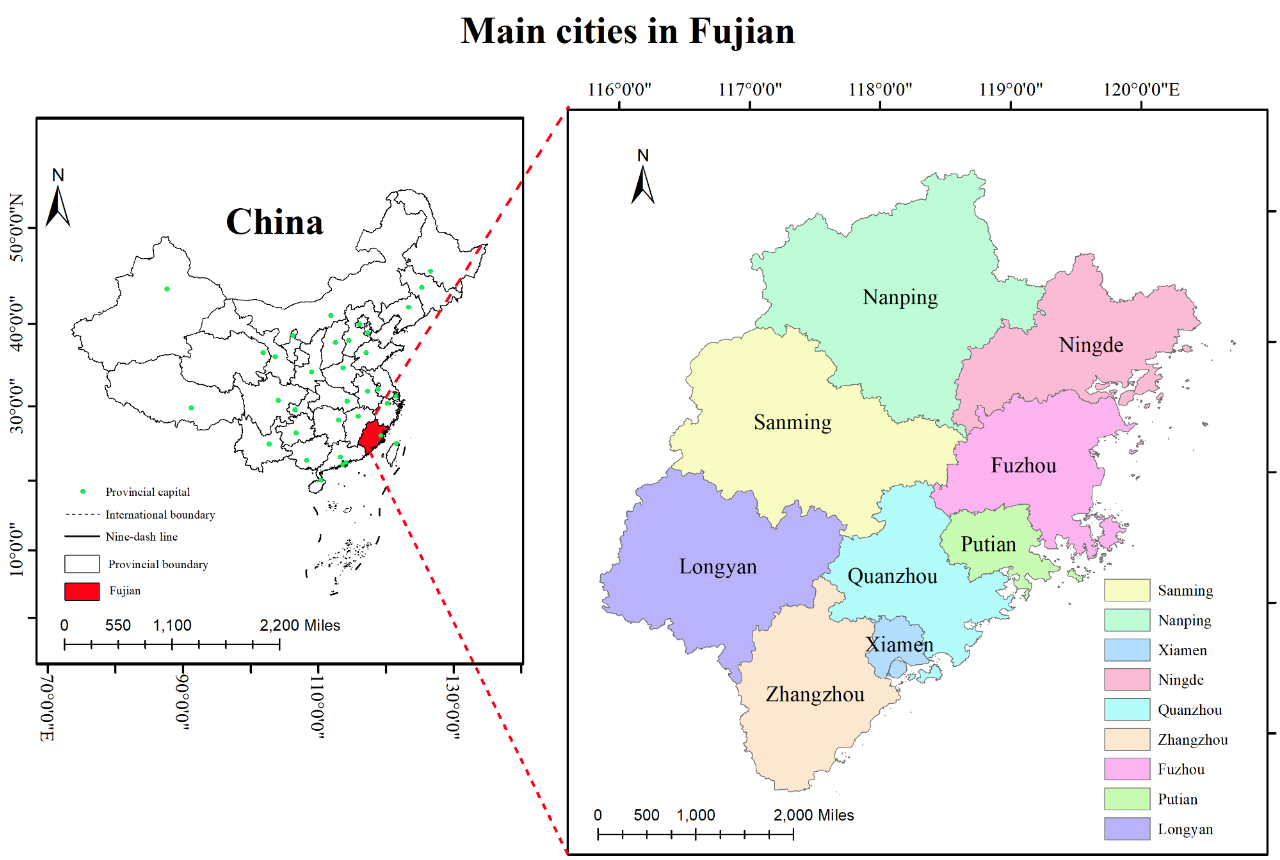

Fig. 1. Location of study area and distribution of main cities in Fujian Province.The map was generated using ArcGIS version 10.8 (https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview).

Step 3: The linear weighting method was utilized in order to achieve the comprehensive evaluation value of the of sports facilities and the ecological environment. The weight for each indicator is determined by normalizing the redundancy values: $w_j = \frac{D_j}{\sum_{j=1}^{m} D_j}$, where w_j indicates weights.The comprehensive evaluation value F is obtained by combining the normalized values and weights using a linear weighting method: $F=\sum_{i=1}^{n} x_{ij} \bullet \omega_i$. This method ensures an objective and thorough assessment of the ecological environment and sports facilities, considering the information provided by each indicator[10,16].

Coupling coordination model

This study employs the coupling degree model to empirically evaluate the relationship between sports facilities and ecological environment in Fujian Province in order to examine the mutual coordination between sports facilitiesdevelopment and ecological environment (Zhao et al., 2023). Three index values—the coupling degree C, the coordination index T, and the coupling coordination degree D—are calculated as part of the coupling coordination model. The coupling coordination degree D is calculated by adding the criteria for classifying the coordination level to the coupling coordination degree D. The ultimate coupling coordination degree of each item is calculated by adding the coupling coordination degree D value and the coordination level categorization criteria. The coupling coordination formula is $D = \sqrt{CT}, T = \beta F1 + \gamma F2$,where where D represents coupling coordination, C represents coupling, T represents coordination, F represents overall evaluation value, β and γ is the correlation coefficient[11].

In order to intuitively reflect the coordination of the sports facilities and ecological environment, refer to Zhang et al. for a study on the classification of the degree of coupling coordination of the 3 major categories and 10 sub-categories which shows in Table 1[6].

Index system construction

The interaction between sports facilities and ecological environment is relatively complex and is not one-to-one linear relationship. Scholars believe that research on complex systems' coupling coordination and interactions should be based on a comprehensive evaluation of the two systems and multiple indicators[9]. In order to better correspond to the "Dual Carbon" objective, the indicators selected in this paper are derived from the indicators mentioned in the literature related to the study of ecological and environmental coupling and sports facilities since 2015, taking into account factors such as the selection of indicators to ensure the accessibility of data as far as possible for screening and summarizing. In order to better reflect the correlation between the two, the selection of indicators in this paper upholds the principles of scientific, accessibility and comprehensiveness without one, and the evaluation index system of sports facilities and ecological environment is screened, as shown in Fig. 2[12,18]. Figure 2 presents the complex interactions and dependencies between these two systems. The framework is structured to assess the degree of coordination and identify areas for improvement, facilitating sustainable development.

In this paper, indicators were selected in detail based on previously selected and used indicators were summarized, taking into account indicators that were used more frequently and for which data were available. Finally, this pater constructed a coupling coordination evaluation index system of sports facilities construction and ecological environment, which includes 1 first-level index and 12 s-level indexes (Table 2).

This paper draws its information from the Fujian Statistical Yearbook of China (2013–2021), the Fujian Provincial Sports facilitiesStatistical Database (2013–2020), the National Economic and Social Development Statistical Bulletin of nine prefectures in Fujian Province (2013–2021), the Environmental Quality Bulletin, the annual government work reports, and other relevant statistical data and documents. This paper collects and analyzes relevant information from Fujian Province and its nine prefectures to obtain raw data for each evaluation index system from 2013 to 2021 based on the evaluation index system for the coupling coordination of sports facilities and the ecological environment[19–27].

Coupling Coordination Level	Coupling Coordination Degree (D)	Classification Level
Coordination Development	0.90–1.00	Quality coordination
	0.80–0.89	Good coordination
	0.70–0.79	Intermediate coordination
	0.60–0.69	Primary coordination
Excessive Development	0.50–0.59	Grudging coordination
	0.40–0.49	Borderline disorder
	0.30–0.39	Mild disorder
Dysfunctional Decline Development	0.20–0.29	Moderate disorder
	0.10–0.19	Serious disorder
	0.00–0.19	Extreme maladjustment

Table 1. The degree of coupling coordination and level classification.

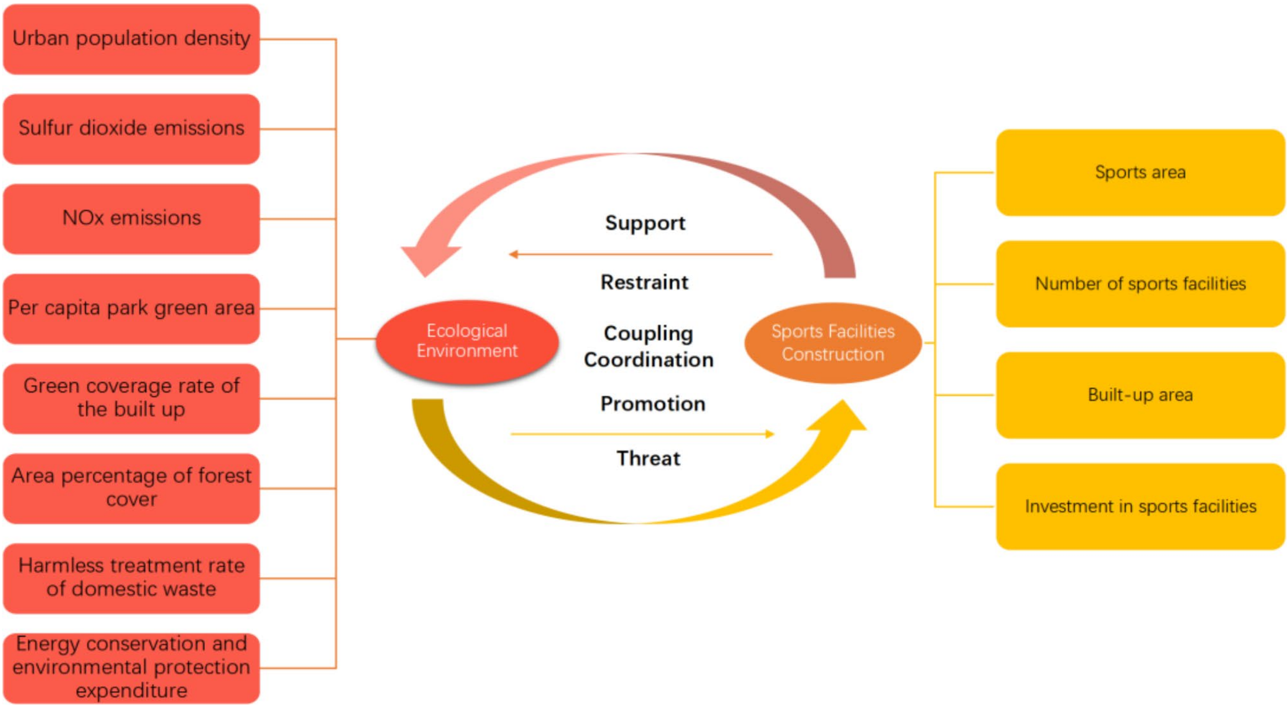

Fig. 2. Framework of coupling coordination between sports facilities construction and ecological environment.

System Layer	Indicator Layer	Nature of Indicator	Weights
Sports facilities construction	Sports area	+	0.2403
	Number of sports facilities	+	0.2491
	Built-up area	+	0.2533
	Investment in sports facilities	+	0.2574
Ecological Environment	Urban population density	–	0.1029
	Sulfur dioxide emissions	–	0.1280
	NOx emissions	–	0.0816
	Per capita park green area	+	0.1252
	Green coverage rate of the built up	+	0.0521
	Area percentage of forest cover	+	0.3160
	Harmless treatment rate of domestic waste	+	0.0906
	Energy conservation and environmental protection expenditure	+	0.1036

Table 2. Evaluation index system for the coupling coordination of the sports facilities construction and ecological environment.

Results

Analysis of coupling coordination results

According to Fig. 3, the coupling coordination results of various cities in Fujian Province from 2013 to 2020 range from 0.1002 to 0.9689. Based on the evaluation criteria for the coupling coordination development types of sports facilities and ecological environment shown in Fig. 4, it can be visually observed that all cities in Fujian Province reflect development characteristics such as imbalance and coordinated development, spanning 9 levels from severe imbalance to high-quality coordination. The coupling coordination status between sports facilities and ecological environment is gradually improving, growing from severe imbalance in 2013 to high-quality coordination in 2020.

The highly coupling coordination between sports facilities and ecological environment in the later period indicates that the technology level of sports facilities has been improving year by year, and the ecological benefits have been increasing year by year, as shown in Fig. 5. It means that the law of change has a periodicity in time. From 2013 to 2014, it was in a state of imbalance, with a coupling coordination degree of less than 5. During this stage, the of sports facilitieswas excessively developed, occupying an absolute dominant position, which resulted in increased pressure on the ecological environment and highlighted the ecological problems caused

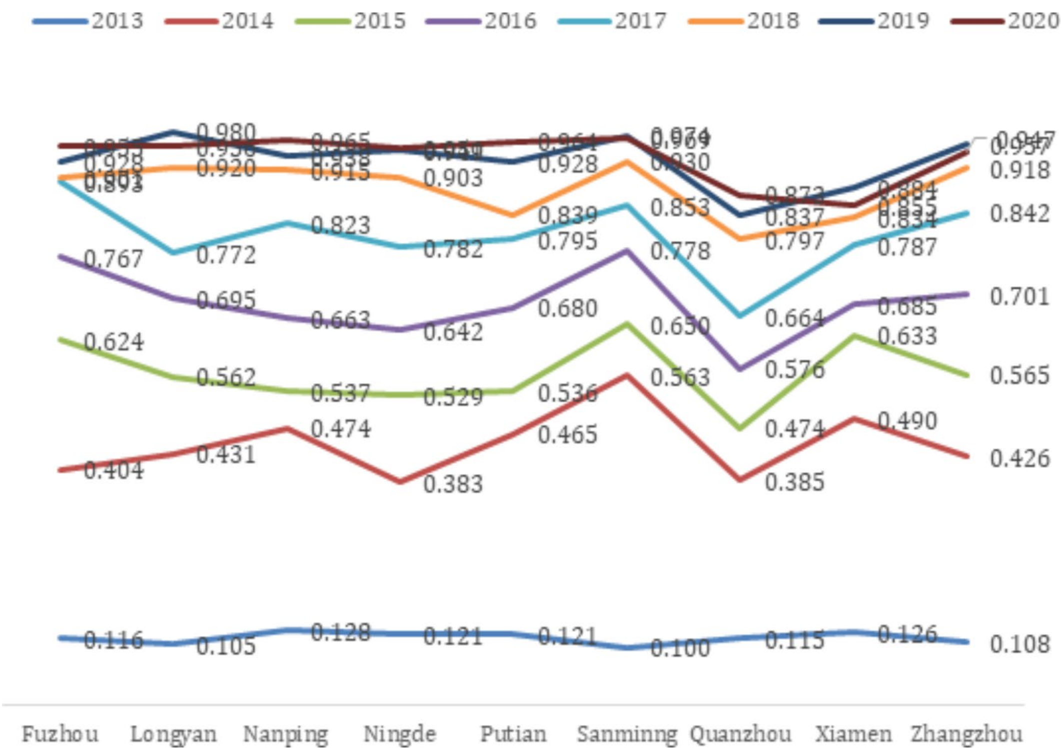

Fig. 3. Result of coupling coordination degree in Fujian Province.

by pollution. From 2015 to 2017, except for Quanzhou, the D value interval was basically between 0.5 and 0.8, which was in the transitional stage from barely coordinated to good coordination.

During this stage, the development speed of sports facilities slowed down, and attention was paid to the ecological problems brought about by sports facilities and repair was carried out. From 2018 to 2020, except for Quanzhou in the intermediate stage, the coupling coordination degree of other cities was basically between 0.8 and 1.0, which was in the stage of good coordination. During this stage, some progress was made in ecological, and the of sports facilitiesand the ecological environment promoted each other, which can meet the needs of different interest groups and achieve orderly development.

Expanding the area of sports facilitieswill inevitably have a certain impact on the ecological environment[28]. As shown in Fig. 6, from 2013 to 2018, the overall area of sports facilitiesin various cities in Fujian Province grew rapidly, which brought pressure on the ecological environment and to some extent constrained the coordinated development of sports facilities and the ecological environment. The growth rate of sports facilitiesarea sharply decreased from 2019 to 2020, which had a positive impact on the ecological environment to some extent. This also explains the reason why the overall high-quality coordination between sports facilities and the ecological environment in Fujian Province from 2019 to 2020 is shown in Fig. 5. Xiamen entered the primary coordination stage as early as 2015, and was one of the earliest cities in the nine prefecture-level cities in Fujian Province to do so. However, its growth rate of sports facilitiesarea is the slowest among the nine prefecture-level cities. In 2015, its growth rate of sports facilitiesarea was 10% points lower than that of the highest-ranking Longyan, which only entered the primary coordination stage in 2016.

This improvement can be attributed to the implementation of environmental protection policies and the "Dual Carbon" strategy, which encourage the development of eco-friendly sports facilities and promote sustainable practices. Additionally, economic factors such as per capita GDP have positively influenced coupling coordination, as economic growth provides the necessary resources for investing in sustainable sports facilities and improving the ecological environment. Improved urban planning and increased awareness of environmental sustainability have led to better integration of sports facilities within the ecological framework. Cities like Xiamen and Zhangzhou, which have stronger regional correlations, have effectively leveraged their coastal advantages to enhance overall coupling coordination. Furthermore, advancements in technology have enabled the development of more sustainable sports facilities, reducing their environmental impact and improving their integration with the ecological environment. Increased public awareness and participation in environmental sustainability initiatives have also played a role in improving the coupling coordination between sports facilities and the ecological environment.

Spatial correlation

From the results of degree of coupling coordination, it can be seen that there is a certain difference in the level of coordinated development between sports facilities and ecological environment in Fujian Province. To further explore the spatial distribution pattern of coupling coordination, the gravity model was selected to

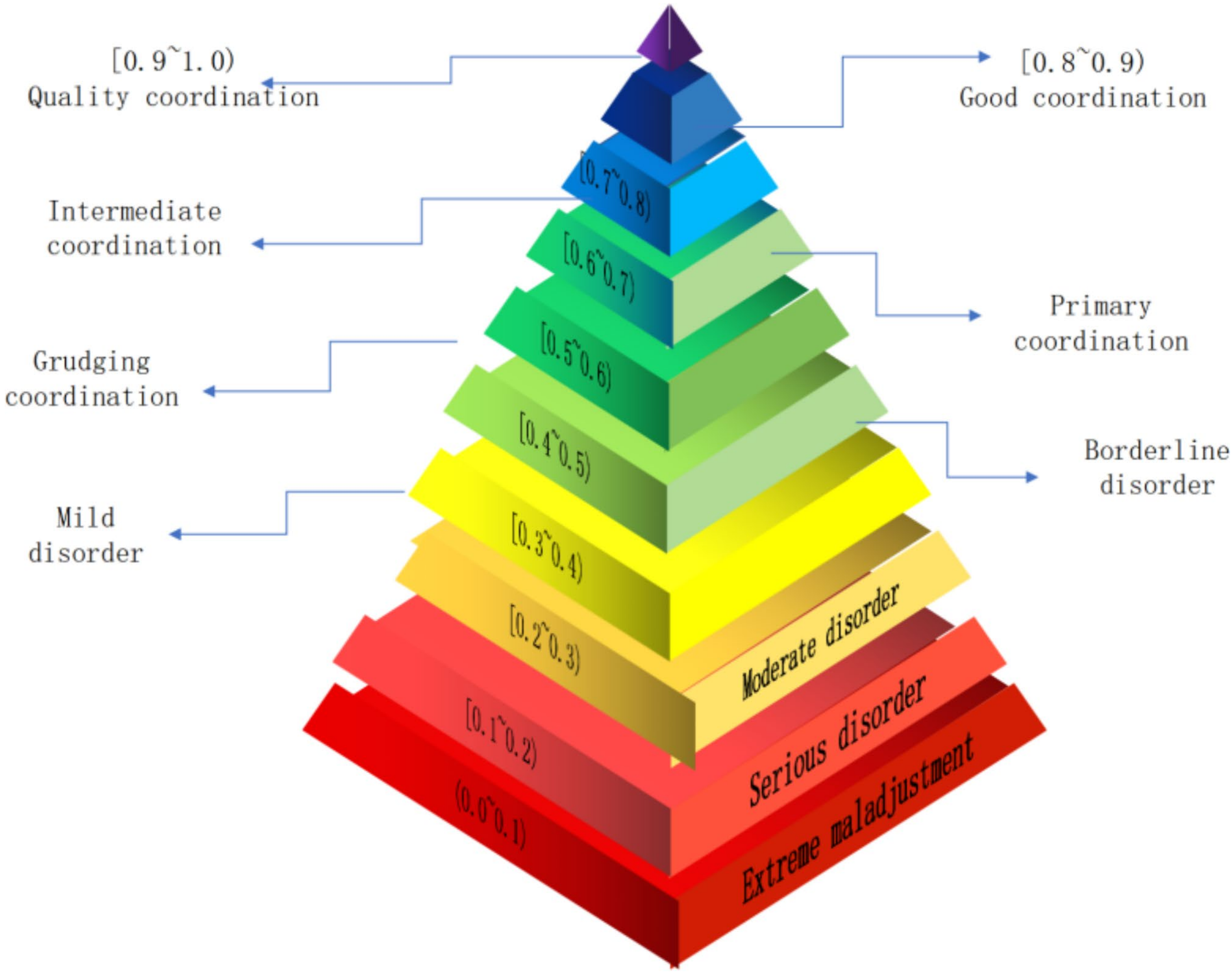

Fig. 4. Classification standard of coupling coordination degree.

measure the mutual interaction of coupling coordination among the 9 cities in Fujian Province. The formula for calculating the gravity model is: $R_{mn} = K\frac{D_m D_n}{T_{mn}^2}$,where R_{mn} represent the spatial correlation strength of coupling coordination between cities m and n, D_m and $D_n$represent the coupling coordination respectively. represents the actual distance between cities m and n, T_{mn} expressed in kilometers between provincial capital cities. K is the gravitational constant, which is usually taken as 1. The spatial correlation strength of coupling coordination between sports facilities and ecological environment from 2013 to 2020 in Fujian Province was calculated, and a gravity map was drawn using ArcGIS 10.8, as shown in Fig. 7. The legend is divided into five levels according to the natural break classification method provided by the software. The wider the connecting line, the greater the spatial contact strength, which can intuitively examine the mutual interaction of coupling coordination between cities in the spatial dimension.

From Fig. 7, it can be seen that the spatial correlation of coupling coordination among the nine cities in Fujian Province show a relatively similar distribution pattern. The high-intensity relationships are reflected in the cities of Xiamen and Zhangzhou. The coupling coordination between sports facilities and ecological environment have a strong regional correlation. By comparing the strength values of spatial correlation, it is found that coastal cities have more significant influence, and they play a positive role in improving the overall coupling level of Fujian Province through their advantages in sports facilitiesand high-level integration with the ecological environment. In addition, due to their proximity, it is conducive to forming a cross-provincial joint development model, which promotes the cross-regional coupling development of sports facilities and ecological environment in the entire region[29]. Furthermore, the spatial correlation strength of coupling coordination between Sanming and Nanping is also at a relatively high level. As the "green treasure house" of our province, the ecological environment has a high degree of synergy, which indirectly leads to the high spatial correlation strength of sports facilities and ecological environment coupling coordination in Sanming and Nanping. In addition, other regions do not show high spatial correlation features of coupling coordination. The results shows that coastal cities like Xiamen and Zhangzhou benefit from better access to resources and more opportunities for economic development, which contributes to their stronger coupling coordination. Their geographical location allows

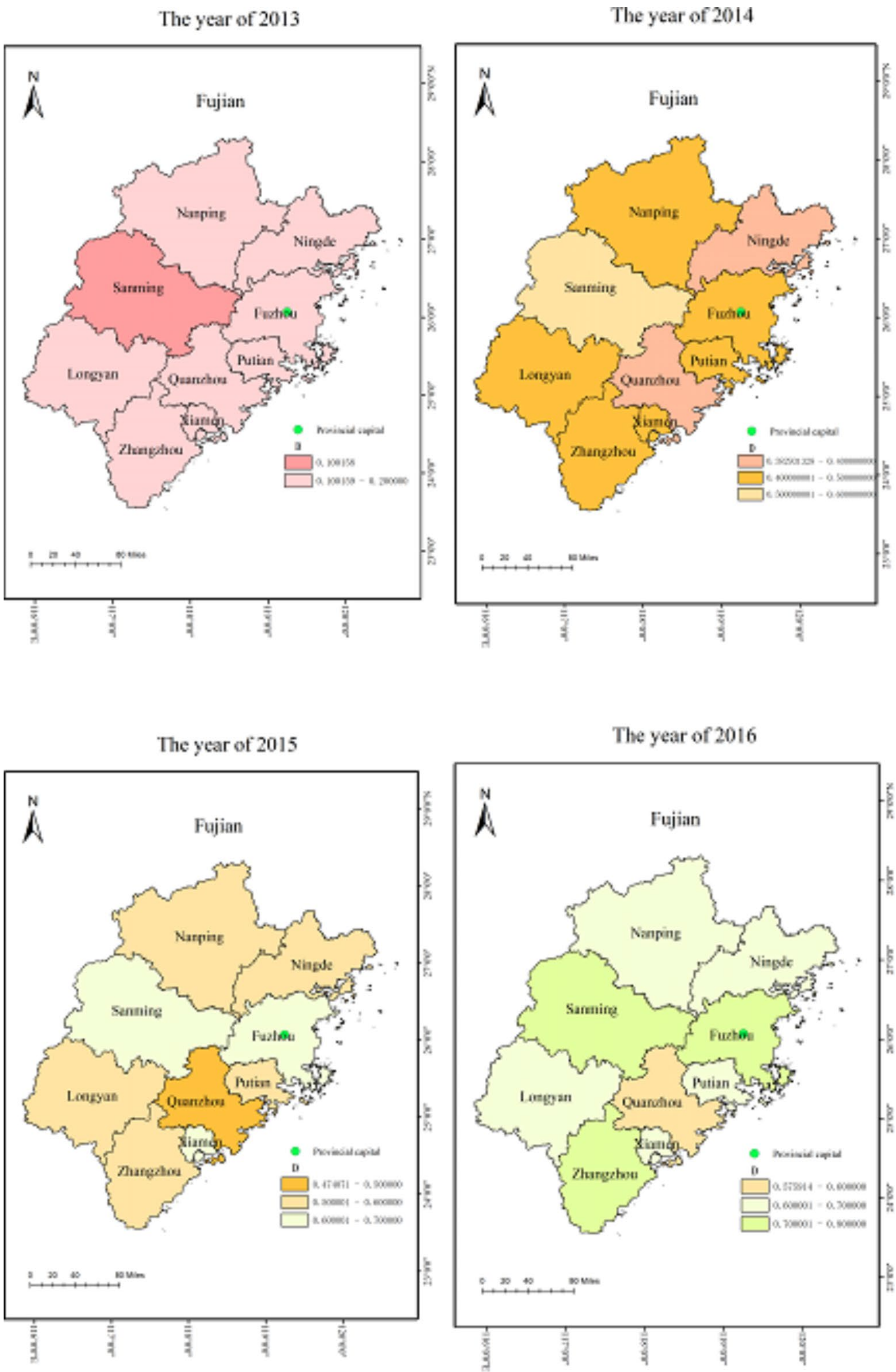

Fig. 5. Spatial distribution of the coupling coordination between sports facilities construction and ecological environment in 9 cities of Fujian Province from 2013 to 2020.The map was generated using ArcGIS version 10.8 (https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview).

for more effective implementation of sustainable practices. Proximity and regional collaboration among these coastal cities facilitate the sharing of best practices and resources, enhancing the overall coupling coordination. These cities can form cross-regional joint development models that promote sustainable development across the entire region. The implementation of stringent environmental policies in these regions has resulted in better ecological management and improved integration of sports facilities with the environment. Coastal cities often

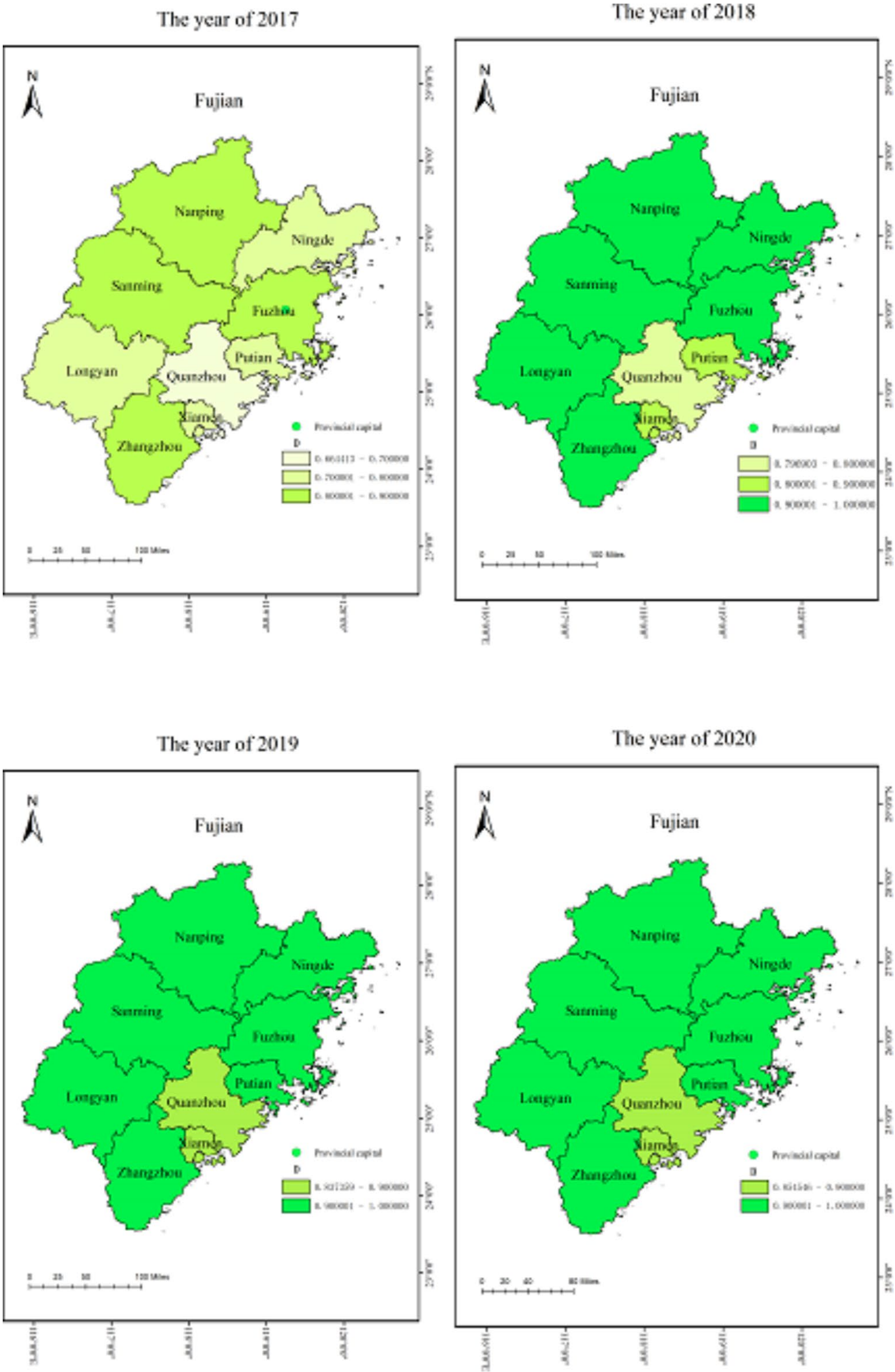

Figure 5. (continued)

have more robust policies due to their vulnerability to environmental changes. The concentration of economic activities in coastal cities provides the financial means to invest in sustainable infrastructure, allowing these cities to implement and maintain higher standards of environmental sustainability in their sports facilities. Higher levels of public awareness and governmental support in coastal cities lead to more effective execution of sustainable development projects, benefiting from both top-down policy implementation and bottom-up public participation.

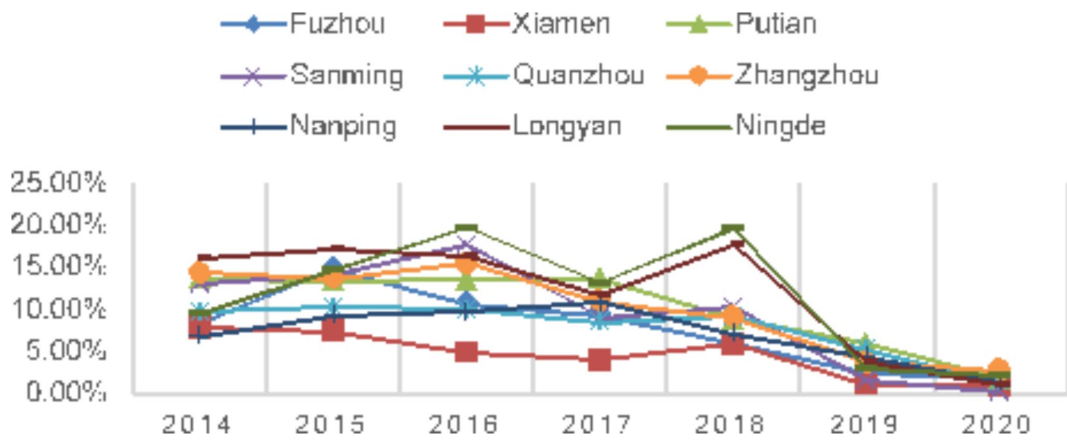

Fig. 6. The growth rate of sports facilities area in 9 cities of Fujian Province (2014–2020).

Stationarity test and panel model analysis

The coupling coordination of the sports facilities andecological environment is a systematic project, and the factors affecting its coupling coordination are many and complex[30]. When constructing the influencing factors for testing, this paper considers the impact of both population and economy on the degree of coupling coordination[31,32].This paper selects the degree of coupling coordination as the explanatory variable, and uses GDP per capita, resident population, gross regional product and sports lottery public welfare expenditures: sports facilities as explanatory variables as explanatory variables for quantitative analysis, which are shown in Table 3.

Stability test of variables

Before analyzing the impact factor, it is necessary to test the stationary of the data. If the data is non-stationary, there may not be a long-term equilibrium relationship between the variables, and to avoid the phenomenon of spurious regression in the empirical process, it is necessary to test the stationary of each variable This paper uses the unit root (ADF) test. If $p = 1$, the series is a first-order single integrated non-stationary series. If the absolute value of p is greater than 1, the series diverges. Therefore, to determine whether a series is stationary, it can be achieved by testing whether p is strictly less than 1. The test results are shown in the following Table 3.

This is a description of a statistical analysis that uses panel data to investigate the relationship between several explanatory variables (per capita GDP, resident population, regional GDP, and sports lottery public welfare expenditure: sports facilities) and a dependent variable (D value). The variables selected for this study—namely GDP per capita, resident population, gross regional product, and sports lottery public welfare expenditures—were chosen due to their significant influence on the coupling coordination between sports facilities and the ecological environment. GDP per capita and gross regional product offer insights into the economic capabilities and development levels of the regions, which are crucial for understanding the resources available for infrastructure development and environmental protection. The resident population serves as a key determinant of the demand for sports facilities and the potential stress on the ecological environment. Lastly, sports lottery public welfare expenditures represent targeted financial investments in sports facilities, which, while enhancing public health and community engagement, may also introduce environmental challenges if not managed sustainably.

Each variable is sourced from the National Statistical Yearbook, ensuring the authenticity and reliability of the data used in this analysis. The integration of these variables into the study provides a comprehensive understanding of the factors driving the coupling coordination between sports facilities and the ecological environment. The analysis uses robust standard error methods and involves constructing three models: a mixed POOL model, a fixed-effects (FE) model, and a random-effects (RE) model as shown in Table 4[33].

The models are tested to determine the best fit, and the results show that the FE model is superior to the POOL model based on an F-test with a significance level of 5% ($F(8,59) = 7.091, p = 0.000 < 0.05$). Additionally, the RE model is superior to the POOL model based on a BP test with a significance level of 5% ($chi(1) = 13.486, p = 0.000 < 0.05$). However, a Hausman test does not show significant results ($chi(4) = -198.608, p = 1.000 > 0.05$), indicating that the RE model is more appropriate than the FE model. At the same time, the results of the Hausman test are not significant, so a random effect model is selected for analysis.

In the regression results of random effects which shown in Table 5, it can be seen that in terms of per capita GDP, it exhibits significant level at the 0.01 level ($t = 9.647$, $p = 0.000 < 0.01$), and the regression coefficient value is $0.000 > 0$, indicating that per capita GDP has a significant positive impact on the coupling coordination degree (D) value, and the improvement of per capita GDP promotes the coordinated development of sports facilities and ecological environment.

However, for the permanent population and regional GDP, it also exhibits significant level at the 0.01 level, and the regression coefficient value is $-0.000 < 0$, indicating a significant negative impact on the coupling coordination degree (D) value. According to the national sports facilitiespolicy (such as the opinions on promoting nationwide fitness and sports consumption to promote the high-quality development of the sports

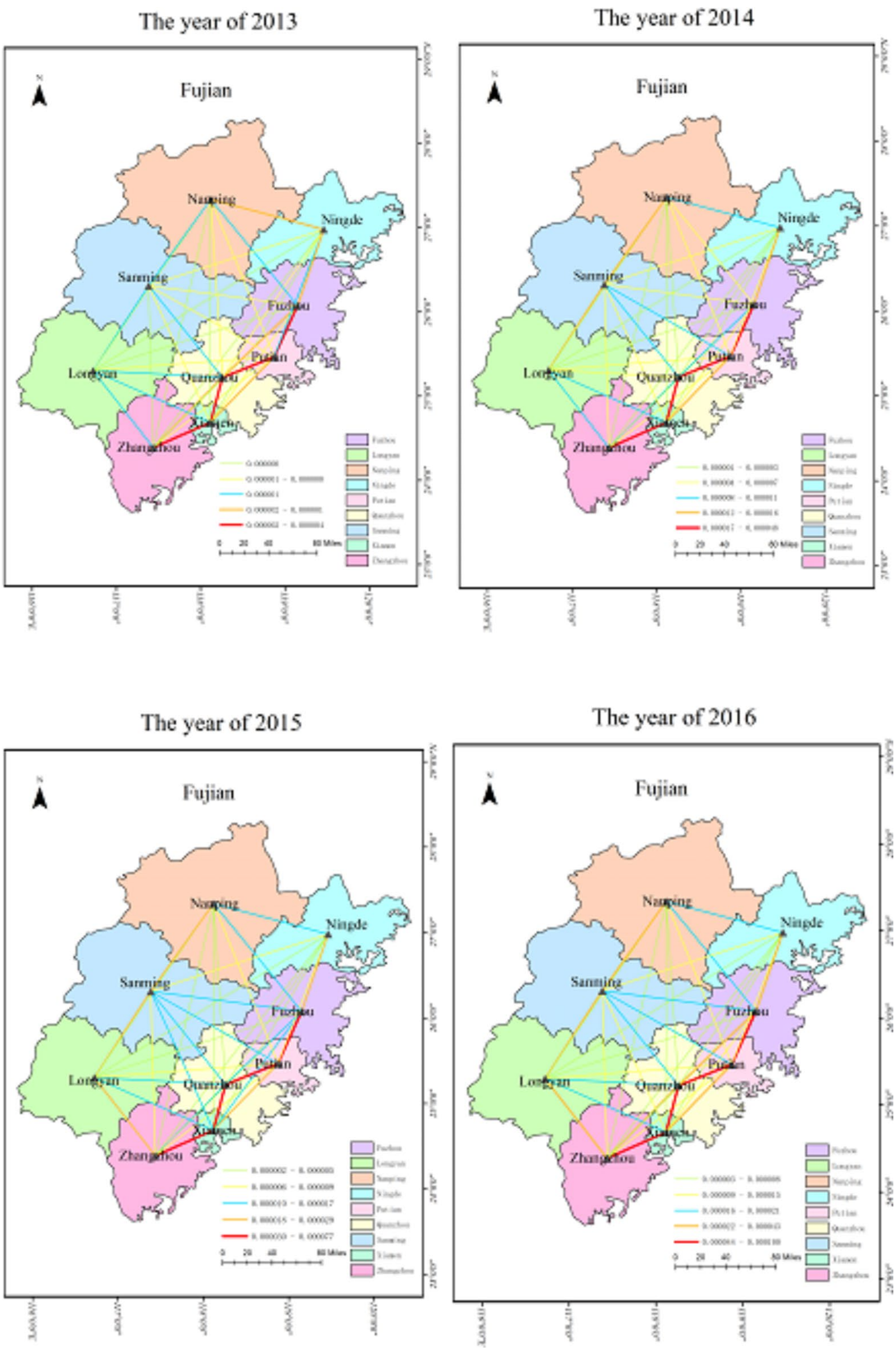

Fig. 7. The spatial coupling intensity between the construction of sports facilities and ecological environment in 9 cities of Fujian Province (2013–2020).The map was generated using ArcGIS version 10.8 (https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview).

industry), the government has increased investment in sports facilities funds and included investment in facilities funds in the city's financial budget[34].

The of sports facilities should be based on the city's economic development level, population size, and other actual conditions, gradually establish sports facilities that are in line with the national conditions and suitable for each city, and meet the demand for sports facilitiesof different populations in different cities. The government

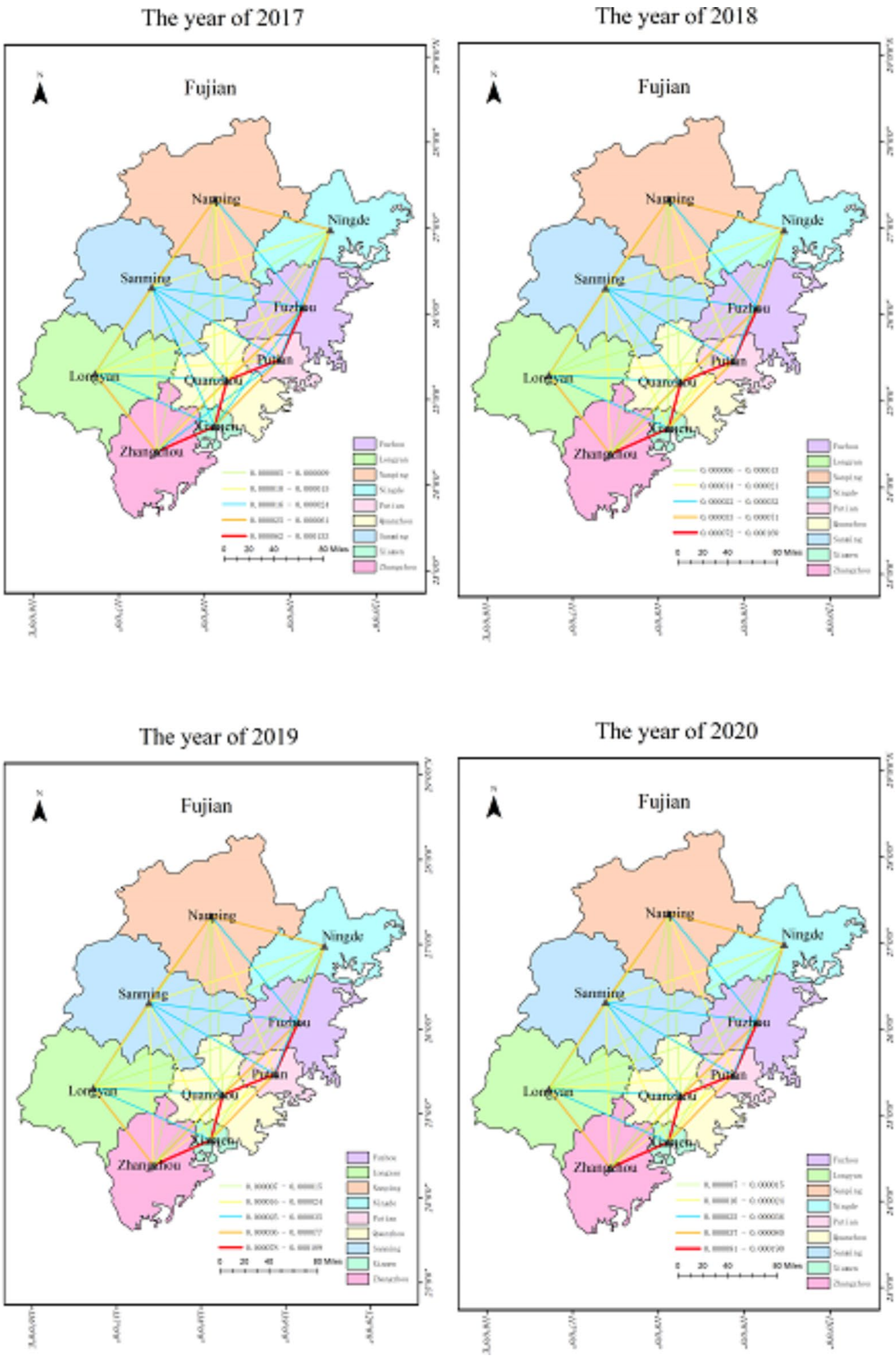

Figure 7. (continued)

and relevant departments should improve the existing sports facilities and scientific management work, increase the number of facilitieswhile strengthening the utilization rate of the facilities, and alleviate the unreasonable use of facilitiesand the excessive pressure on the ecological environment caused by the large population[35].

The lottery public welfare fund is a fund extracted from the facilitiesof lottery sales according to the prescribed proportion, which is specifically used for social welfare, sports and other public welfare undertakings. Research has found that the use of lottery funds for sports facilitiesshows a significant negative impact on the coupling coordination degree D, with a regression coefficient value of −0.000 < 0 and significance level of 0.01 (t = −3.977,

Variable	t	p	Critical value			Order of difference	Sequence stationary
			1%	5%	10%		
GDP per capita	−10.912	0.000	−6.045	−3.929	−2.987	1	Stationary
Total resident population	−1.682	0.088	−3.039	−1.935	−1.531	1	Stationary
Gross regional product	−20.334	0.000	−6.045	−3.929	−2.987	1	Stationary
Lottery public welfare fund expenditure: sports facilities	−5.402	0.000	−6.045	−3.929	−2.987	1	Stationary

Table 3. The results of the unit root test of the variables.

Inspection type	Inspection purpose	Inspection value	Inspection conclusion
F test	Comparison and selection of FE model and POOL model	$F(8,59)=7.091, p=0.000$	FE model
BP test	Comparison and selection of RE model and POOL model	$\chi2(1)=13.486, p=0.000$	RE model
Hausman test	Comparison and selection of FE model and RE model	$\chi2(4)=-198.608, p=1.000$	RE model

Table 4. Results of model test.

Variable Name	POOL model	FE model	RE model
Intercept	−0.058 (−0.781)	0.447 (0.696)	−0.058 (−0.781)
GDP per capita	0.000** (9.647)	0.000** (10.204)	0.000** (9.647)
Permanent population	−0.000** (−3.011)	−0.002 (−1.367)	−0.000** (−3.011)
Gross regional product	−0.000** (−14.033)	−0.000** (−7.648)	−0.000** (−14.033)
Lottery public welfare fund expenditure: sports facilities	−0.000** (−3.977)	−0.000** (−3.924)	−0.000** (−3.977)
R^2	0.644	−1.566	0.644
R^2(within)	0.757	0.815	0.757
Sample size	72	72	72
test	$F(4,67)=2397.383, p=0$	$F(4,59)=134.876, p=0$	$\chi2(4)=9589.531, p=0$

Table 5. The the regression results of the coupling coordination and driving factors. Dependent variable: coordination degree (D). Note: ** denote a significance of 1% and 5%, respectively, T values are shown in parentheses.

$p=0.000<0.01$). It can be seen that, on the one hand, the support of the lottery public welfare fund has greatly promoted the development of sports in Fujian Province. Sports facilities supported by the public welfare fund are spread throughout the province, and many fitness paths, fitness centers, sports facilitiesand various mass fitness activities have been built. On the other hand, due to the of various sports facilities, the protection of the environment has been ignored, leading to a decrease in the quality of the ecological environment, which shows a negative impact on the coupling coordination degree.

Discussion

This study provides an in-depth analysis of the coupling coordination between sports facilities and the ecological environment in Fujian Province, China, within the context of the "Dual Carbon" strategy. The findings demonstrate that over time, the coordination between these two systems has evolved from a state of imbalance to one of high coordination and quality. This evolution is primarily attributed to the implementation of the "Dual Carbon" strategy, the influence of economic and social factors, and the support from policies and finances.

Firstly, the "Dual Carbon" strategy emphasizes reducing carbon emissions and promoting sustainable development, leading to policy changes and increased investments in eco-friendly infrastructure and technologies. Aligning the development of sports facilities with environmental goals has been crucial in driving this positive trend. This finding is consistent with Zhao et al. (2023), who highlighted the necessity of integrating green and low-carbon materials and cultivating carbon emission management experts in the sports field. The strategic goals outlined by the "Dual Carbon" policy align with the need for sustainable practices in sports facilities development, which has been underscored by the increased focus on ecological adaptation of sports spaces discussed in the introduction[36].

Secondly, economic factors, such as per capita GDP, significantly positively impact the coupling coordination degree, as economic growth provides necessary resources for investing in sustainable sports facilities and environmental protection measures. However, the negative impact of the permanent population and regional

GDP indicates that densely populated and economically active areas face greater challenges in balancing development and environmental preservation, underscoring the complexity of the relationship between economic activities and environmental sustainability. This complexity reflects the broader trends of urbanization and economic development impacting environmental sustainability, as highlighted by Agrawala (1998) and Farmer et al. (2013).

Furthermore, government policies and financial mechanisms, such as the national sports facilities policy and lottery public welfare funds, have been instrumental in promoting the coordinated development of sports facilities and the ecological environment. However, the research indicates that the focus on rapid development sometimes leads to environmental neglect, necessitating stricter regulations and better planning to ensure long-term sustainability. This dual impact of policy support on both development and environmental protection is highlighted in the research by Kanellos and Frame (2016), emphasizing the need for policies that balance these two aspects to achieve sustainable outcomes[37].

A key contribution of this study is the construction of a comprehensive evaluation index system for sports facilities and the ecological environment, based on multidisciplinary and interdisciplinary approaches, providing a robust framework for assessing the sustainability of sports facilities. The application of the entropy method and coupling coordination models offers a nuanced understanding of the interactions between these systems, significantly advancing traditional correlation analyses. This approach fills the gap identified in the introduction regarding the lack of quantitative empirical studies and indicator systems based on macro-level data for analyzing the coordination between sports facilities and the ecological environment.

Additionally, the innovative use of spatial correlation and gravity model analysis to examine regional interactions and dependencies between cities in Fujian Province highlights regional disparities and interactions, providing valuable insights into the spatial dynamics of sustainable development. The findings suggest that coastal cities play a critical role in improving overall coupling coordination through their advanced integration of sports facilities and the ecological environment, which is a vital consideration for policymakers. By focusing on Fujian Province, this study provides a detailed case study that can serve as a model for other regions with similar developmental contexts. The findings emphasize the importance of localized strategies and the need to tailor policies to specific regional conditions, a perspective often generalized in broader studies. The detailed examination of spatial correlations and interactions offers practical implications for policymakers aiming to promote balanced and coordinated development across different regions, highlighting the importance of localized strategies to achieve sustainable development goals.

All in all, this study aligns with the global action plan on physical activity outlined by the World Health Organization (WHO) and the increasing interest in the ecological adaptation of sports spaces. By providing empirical evidence and innovative methodologies, this research contributes to the broader discourse on sustainable development and the integration of sports facilities with ecological and environmental considerations. The insights gained from this study offer valuable guidance for policymakers and stakeholders involved in the planning and management of sports facilities and environmental sustainability, emphasizing the need for coordinated and context-specific approaches to achieve long-term sustainability goals.

This improvement can be attributed to the implementation of environmental protection policies and the "Dual Carbon" strategy, which encourage the development of eco-friendly sports facilities and promote sustainable practices. Additionally, economic factors such as per capita GDP have positively influenced coupling coordination, as economic growth provides the necessary resources for investing in sustainable sports facilities and improving the ecological environment. Improved urban planning and increased awareness of environmental sustainability have led to better integration of sports facilities within the ecological framework. Cities like Xiamen and Zhangzhou, which have stronger regional correlations, have effectively leveraged their coastal advantages to enhance overall coupling coordination. Furthermore, advancements in technology have enabled the development of more sustainable sports facilities, reducing their environmental impact and improving their integration with the ecological environment.

The findings of this study corroborate the theoretical frameworks discussed earlier. The positive trend in coupling coordination between sports facilities and the ecological environment supports the Systems Theory, which emphasizes the interdependence of different system components. The improvement in coordination over time aligns with the principles of Sustainable Development Theory, highlighting the need for balanced economic, social, and environmental development.

The empirical verification of the theoretical relationship between sports facilities and the ecological environment provides valuable insights for policymakers and stakeholders. The results underscore the importance of incorporating sustainability practices in the planning and management of sports facilities. Coastal cities like Xiamen and Zhangzhou, which demonstrated higher levels of coupling coordination, can serve as models for other regions. The study also highlights the need for targeted policies to address the challenges posed by high population density and regional economic activities.

Conclusions

This paper utilizes Fujian Province as a case study to establish a comprehensive evaluation index system for constructing sports facilitiesand improving the ecological environment. The entropy method and comprehensive evaluation function are employed to calculate the comprehensive evaluation values of sports facilitiesand ecological environment in nine prefecture-level cities within Fujian Province. The coupling degree model and coupling coordination degree model are also utilized to analyze the degree of coupling coordination between the of sports facilitiesand ecological environment in each prefecture-level city. The findings of the study are as follows:

(1) The overall trend of coupling coordination between sports facilities and the ecological environment is positive, with the type of coordinated development continuously improving. Between 2013 and 2020, the comprehensive level of sports facilities and ecological environment in each city has significantly increased. The coupling level of most prefecture-level cities in Fujian Province is developed, with the exception of Quanzhou and Xiamen, which remain in the stage of good coordination. However, all nine cities have entered the stage of high-quality coupling.
(2) The changes in coupling coordination exhibit distinct characteristics over time. Between 2013 and 2014, an imbalanced state was observed, and sports facilities and ecological environment began to compete with one another. Except for Sanming, the coupling coordination degree of other cities was below 0.5. Between 2015 and 2017, except for Quanzhou, the coupling coordination degree was mostly between 0.5 and 0.8, with the interaction between the two systems gradually strengthening and showing a benign coupling feature of mutual restraint and coordination. Between 2018 and 2020, the benign coupling between sports facilities and the ecological environment in various cities became stronger and gradually developed in an orderly direction. Except for Quanzhou, which was in the intermediate stage, the coupling coordination degree of other cities was mostly between 0.8 and 1.0, and they were in the stage of high-quality coordination.
(3) The coupling coordination degree between cities exhibits regional development imbalances. Only Xiamen and Sanming reached the primary coordination development type in 2015, while cities such as Putian, Quanzhou, and Xiamen lagged behind other cities in reaching the high-quality coordination level. The focus of each city's development differs due to factors such as policy, economy, geographical environment, and natural resources, which inevitably leads to differences in the basic development of sports facilitiesand ecological environment in different cities. While promoting high-quality sports facilities, attention should also be paid to sustainable development.
(4) The stationarity of the data was tested using the unit root (ADF) test to ensure the reliability of the results. The test results showed that the variables, including GDP per capita, total resident population, gross regional product, and lottery public welfare fund expenditure on sports facilities, were all stationary after taking the first difference. This indicates that the data used in the analysis are stable and suitable for the empirical investigation of the coupling coordination between sports facilities and the ecological environment[38].
(5) The panel model analysis revealed that per capita GDP positively impacts the coupling coordination degree, promoting the coordinated development of sports facilities and the ecological environment. Conversely, the total resident population and gross regional product negatively impact the coupling coordination degree, indicating challenges in balancing development and environmental preservation in densely populated and economically active areas. Additionally, the use of lottery public welfare funds for sports facilities, while promoting the development of sports, has shown a negative impact on the coupling coordination degree due to environmental neglect[39].

In conclusion, this study provides a comprehensive analysis of the dynamic relationship between sports facilities and the ecological environment in Fujian Province, advancing our understanding of sustainable development under the "Dual Carbon" strategy. Our findings indicate a positive trend in coupling coordination, enhanced by economic growth and supported by targeted policies.

Our study uniquely contributes to the understanding of sustainable development in sports facilities through its comprehensive evaluation of coupling coordination between sports infrastructure and the ecological environment in Fujian Province. Employing innovative models, our research not only advances methodological approaches but also provides robust empirical data supporting the positive influence of economic factors on ecological and sports facility integration. These insights are crucial for policymakers aiming to enhance regional development while maintaining ecological balance. Furthermore, our findings are applicable to other regions with similar coastal dynamics, offering a valuable model for integrating environmental considerations in sports facility planning. We also suggest areas for future research, particularly in adapting our models to different cultural and economic contexts, to further validate and refine the findings presented.

By providing empirical evidence and innovative methodologies, this research contributes significantly to the broader discourse on sustainable development and the integration of sports facilities with ecological and environmental considerations. The insights gained offer valuable guidance for policymakers and stakeholders involved in the planning and management of sports facilities, emphasizing the need for coordinated and context-specific approaches to achieve long-term sustainability goals.

Limitations

There are several limitations to research on the coupling coordination between sports facilities and ecological environment in Fujian Province under the "Dual Carbon" background. Some of these limitations include:

Firstly, the research may be limited by the availability of data on sports facilities and ecological environment in Fujian Province. The data may be incomplete or insufficient, making it challenging to draw accurate conclusions. Secondly, the research may focus only on Fujian Province, which may limit the generalization of the findings to other regions or countries. Thirdly, the research may be limited by methodological issues such as sample size, survey design, and statistical analysis. Lastly, the research may focus only on the coupling coordination between sports facilities and ecological environment, while ignoring other factors that may influence the relationship. These factors may include economic, social, and cultural factors.

Data availability

The data presented in this study are openly available in 2013 Fujian Statistical Yearbook. https://tjj.fujian.gov.cn/tongjinianjian/dz2013/index-cn.htm (accessed on 27 March 2023), 2014 Fujian Statistical Yearbook. https://tjj.fujian.gov.cn/tongjinianjian/dz2014/index-cn.htm (accessed on 27 March 2023), 2015 Fujian Statistical Yearbook. https://tjj.fujian.gov.cn/tongjinianjian/dz2015/index-cn.htm (accessed on 27 March 2023), 2016 Fujian Statistical Yearbook. https://tjj.fujian.gov.cn/tongjinianjian/dz2016/index-cn.htm (accessed on 27 March 2023), 2017 Fujian Statistical Yearbook. https://tjj.fujian.gov.cn/tongjinianjian/dz2017/index-cn.htm (accessed on 27 March 2023), 2018 Fujian Statistical Yearbook. http://tjj.fujian.gov.cn/tongjinianjian/dz2018/index-cn.htm (accessed on 27 March 2023), 2019 Fujian Statistical Yearbook. http://tjj.fujian.gov.cn/tongjinianjian/dz2019/index.htm (accessed on 27 March 2023), 2020 Fujian Statistical Yearbook. http://tjj.fujian.gov.cn/tongjinianjian/dz2020/index.htm (accessed on 27 March 2023), 2021Fujian Statistical Yearbook. http://tjj.fujian.gov.cn/tongjinianjian/dz2021/index.htm (accessed on 27 March 2023).

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Author contributions
Conceptualization, L.-H. and S.-T. ; data curation, L.-H. and S.-T.; formal analysis, L.-H., S.-T. and Y.-Y.; methodology, L.-H., S.-T.and X.-W. ; project administration, X.-W. and Y.Y.; resources, L.-H., S.-T.and Y.Y.; software, L.-H. and S.-T. ; visualization, L.-H. S.-T. and X.-W.; writing—original draft, L.-H. and S.-T.; writing—review & editing, L.-H., S.-T., X.-W.,Y.-Y., M.N. and N.E., All authors have read and agreed to the published version of the manuscript.

Declarations

Competing interests
The authors declare no competing interests.

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