frontiers | Frontiers in Environmental Science

ORIGINAL RESEARCH
published: 13 July 2022
doi: 10.3389/fenvs.2022.946993

The Green and Low-Carbon Development Effect of Comprehensive Sports Events: A Quasi-Natural Experiment From China

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Large-scale sports events can improve public environmental awareness, strengthen urban governance, and push green innovation. However, it may also increase the burden on infrastructure, cause energy consumption, and lead to some pollution. Using the panel data of 278 cities in China from 2006 to 2019, this study systematically discusses how comprehensive sports events affect the green and low-carbon development of Chinese cities. First, the green total factor productivity and carbon emission efficiency calculated by the SBM-DEA model are taken as proxy variables of green and low-carbon development. And then, the spatial difference-in-differences (SDID) model is used to undertake empirical analysis and further test the impact mechanism and heterogeneity. Four main results are derived from this study: 1) the hosting of comprehensive sports events can significantly enhance the green and low-carbon development of cities. This result is still valid after a whole string of robustness tests; 2) comprehensive sports events have a significant positive spatial spillover effect on the green and low-carbon development of adjacent cities; 3) the mechanism analysis shows that comprehensive sports events can encourage green development of cities through technological innovation, sports industry development, and foreign investment, but through foreign investment, sports events cannot significantly affect the green total factor productivity and carbon emission efficiency of host cities; and 4) heterogeneity exists between the city rank and the event level. The promotional effect of comprehensive sports events on cities' green and low-carbon development is more significant in first-tier cities and for international events.

Keywords: comprehensive sports events, green and low-carbon development, SBM-DEA model, spatial difference-in-differences model, spatial spillover effect

Edited by:
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Specialty section:
This article was submitted to Environmental Economics and Management, a section of the journal Frontiers in Environmental Science.

Received: *18 May 2022*
Accepted: *07 June 2022*
Published: *13 July 2022*

Citation:
Zhang X and Wu Y (2022) The Green and Low-Carbon Development Effect of Comprehensive Sports Events: A Quasi-Natural Experiment From China. Front. Environ. Sci. 10:946993. doi: 10.3389/fenvs.2022.946993

1 INTRODUCTION

Centering on "green economy" and "sustainable development," the 2012 United Nations Conference on sustainable development emphasized that countries give higher priority to issues such as environment and energy. *Transforming our World: The 2030 Agenda for Sustainable Development* of the United Nations also further emphasizes the vision of promoting sustainable human development. China has always made much account of the construction of ecological civilization. *2050 China Energy and CO_2 Emissions Report* has already paid attention to the issue of global climate change and put forward suggestions for promoting sustainable development and reducing greenhouse gas emissions. In recent years, "green and low carbon," as a momentous concept of the 14th Five-Year Plan, has run through all fields and links of the economy and society. *The Outline of the 14th Five-Year Plan for Economic and Social Development and Long-range Objectives through the Year 2035 of the People's Republic of China* put forward the strategic goal of "double carbon," that is, to perform all one can to achieve a carbon peak by 2030 and carbon neutralization by 2060.

Meanwhile, for the sake of accelerating the construction of a powerful sports country, the State Council promulgated the *National Fitness Program (2021–2025)*, which requires extensive fitness events and increases the supply of fitness venues and facilities. In addition, the scale and frequency of global sports events have increased significantly over recent years. With the amelioration of comprehensive national strength, China has also become a gathering place for comprehensive sports events. For instance, in 2022, China hosted the Olympic and Paralympic Winter Games Beijing 2022 and is about to host the Chengdu 2021 FISU World University Games and the 19th Asian Games Hangzhou 2022, and the other comprehensive sports events. Particularly in the context of the prevalence of COVID-19, according to the report of the World Bank, blockade and other measures taken by countries will affect the pace of progress toward the Sustainable Development Goal (SDG 7), including renewable energy and energy efficiency. However, these human activities may lead to energy consumption and severely affect the ecosystem (Yu et al., 2022b; Ke et al., 2022), thus hindering sustainable economic development (Huo et al., 2022). So, the current environmental problems have become an urgent and important topic.

In the past, the holding of comprehensive sports events could be regarded as the opposite of environmental protection because such events can not only improve the status and image of the host city, increase employment opportunities (Mao et al., 2020), and promote economic development (Huang, 2011) but also have some negative effects on the city, including traffic congestion, noise pollution, and excessive energy consumption (Mei and Bao, 2018; Guo et al., 2021; Zhong et al., 2021), and even affect adjacent cities and other cities (Chen S et al., 2021). Hence, the International Olympic Committee, as a key player in the global sport's governance system, listed the environment as the third pillar after sports and culture in 1994. The purpose of this is to encourage countries to combine large-scale sports events with the environment to attain a win–win–win situation for sports competition, environmental protection, and even economic development. The Olympic 2020 Agenda adopted in 2014 directly introduced the concept of "sustainability." The city is an important carrier for the local economy. How it grasps the opportunity and realizes green and low-carbon development while holding large-scale sports events is particularly important.

Fortunately, in China, comprehensive sports events and environmental protection do not seem to be contradictory. BOCOG implements the concept of "green, shared, open, and honest" *sustainability—toward the future—sustainable development report of the Beijing Winter Olympic Games (before the games)* and also fully demonstrates the phased achievements of environmental sustainability and Green Olympics. In fact, as a means to enhance the image and status of the host city (Li and Zhao, 2009), the government usually takes environmental protection measures before and during large-scale sports events to better the urban ecological situation, R&D expenditure, and renewable energy, which can often make contributions to environmental quality (Khan et al., 2021d; Awosusi et al., 2022). Therefore, the holding of comprehensive sports events is often conducive to the green and low-carbon development of cities. Specifically, in terms of environmental regulation, Beijing fully noticed that air pollution was a problem of regional dynamic transmission in 2008. The "Beijing Blue" harvested during the Olympic Games verified the effectiveness of the regional linkage of six provinces and cities such as Beijing, Tianjin, and Hebei in air pollution prevention and control. After the practice test of the Beijing Summer Olympics, the State Council established the Beijing–Tianjin–Hebei joint prevention and control mechanism and the Yangtze River Delta joint prevention and control mechanism. This concept of joint prevention and control of air pollution and regional linkage has successful experiences of air quality assurance for other large-scale events to go by. For example, in 2014, the Yangtze River Delta also guaranteed the atmospheric environmental quality during the Nanjing Youth Olympic Games through joint prevention and control. With regard to urban traffic management, Beijing encourages residents to choose public transport by optimizing the public transport network and reducing bus fares. It also strengthened the pollution control of motor vehicles and allowed low-emission private cars to pass (Wu and Zhang, 2008). Shenzhen's bid to host the Summer Universiade in 2011 was successful, and the practice is also in line with it. For example, the construction of the greenway network in the Pearl River Delta has been implemented. The "demonstration operation scheme of new energy vehicles" has also been implemented, and residents are encouraged to "voluntarily stop driving." In addition, in terms of technological innovation, Shenzhen actively develops "green buildings," encourages green innovation, and promotes green industrial transformation. In 2022, the Winter Olympic Games held in Beijing adopted "green" as the primary concept, which fully demonstrated the correlation between sports events and urban green development. The original technology and core technology research and development of its ice and snow equipment industry also released multiple dividends for green and low-carbon development. After all, technological innovation is conducive to alleviating energy demand and promoting sustainable development (Yu et al., 2022a).

In view of the abovementioned analysis, if we only evaluate the economic benefits of comprehensive sports events, we tend to generalize and cannot accurately evaluate the internal value such as the ecological and environmental effects of the events. Therefore, this study raises the following three research questions: 1) Will the holding of comprehensive sports events bring positive external effects to the green and low-carbon development of the host city and other cities? 2) If so, through what mechanisms? 3) Which level of host city or event will bring a greater impact? To solve the abovementioned problems, this study used quasi-natural experiments to test.

2 LITERATURE REVIEW

At present, many studies have focused on sports events and urban development. These documents have been explored mainly from the perspectives of economy, society, and environment. Regarding economic impacts, some scholars believe that the holding of sports events will attract a lot of investment (Siegfried and Zimbalist, 2000) and improve urban infrastructure construction (Lindau et al., 2016), but the main source is government departments, which may crowd out private-sector investment to a certain extent. At the same time, the host city will also take a series of measures for urban renewal, such as the transformation of old urban areas and increase in groundwater levels (Wu and Zhang, 2008), which can provide a large number of jobs (Baumann et al., 2012) so as to accelerate the expansion of the tertiary industry, including sports industry and tourism. The Beijing Summer Olympics contributed not only to the formation of the sports industry chain (Huang, 2011) but also to the tourism development caused by the fact that it is considered to be a channel to directly boost the economy (Shao et al., 2018), including event sports tourism and nostalgic sports tourism (Gibson, 1998). This may precipitate urban industrial clusters and optimize industrial structures. The flow of tourists may even set in motion the economic development of peripheral regions (Zhang and Zhao, 2008; Fourie and Santana-Gallego, 2011) because the expansion of the tourist scale can not only bring additional tourism consumption but also drive the development of transportation, hotel services, and other industries (Nie et al., 2016). However, the entry of a large number of foreign tourists may also cause traffic congestion and low work efficiency, which will retard economic development (Matheson, 2005).

As for the social benefits of sports events, scholars have mainly carried out research on the aspects of public crime perception, participation consciousness, and subjective well-being, as well as on government policies. Swart et al. (2017) pointed out that the possibility of tourists visiting the city again after sports events is largely affected by their perception of the city's crime risk. In addition, because social participation has an important impact on the organization and planning of large-scale activities and even on environmental sustainability (Lamberti et al., 2011; Lin R. et al., 2022), scholars have also carried out research from the point of public participation. In essence, large-scale sports events are quasi-public goods, which can improve resident awareness of environmental protection (Wu and Zhang, 2008). Subsequently, Pawlowski et al. (2014) tested the relationship between sports event success and subjective well-being by investigating "resident' perception." Kim et al. (2015) also used this method to verify public support for holding sports events. Moreover, the Beijing Summer Olympics also changed the sports policy of the Chinese government, which is reflected in the transformation from a big sports nation to a world sports power; that is, it began to be guided by the national sports policy (Tan, 2015).

About environmental impacts, many scholars believe that with some measures taken, the holding of sports events promotes the sustainable development of the city (Yu et al., 2021), which is related to increase in public expenditure (Han et al., 2022). Environmental governance in various countries is also closely related to sustainable economic development (Khan et al., 2021b). As mentioned above, consistent with the effect of green supply chain practices of small- and medium-sized enterprises (Khan S. A. R. et al., 2021), the host city can form a green supply chain management practice through traffic control and green innovation so as to reduce pollution emissions and optimize environmental development (Khan et al., 2021e). Specifically, in terms of air quality, Zhou et al. (2010a) utilized a bottom-up methodology to build emission inventories before and during the 2008 Beijing Summer Olympics so as to estimate the role of measures such as traffic control and vehicle technology improvement during the Olympics and found that they helped reduce air pollution. After that, with a simple regression analysis of the effect of the Beijing Summer Olympics on the air quality of the host city, cohost city, and adjacent cities, Chen et al. (2013) proved that the air quality has been improved during the Beijing Summer Olympics, which is inseparable from the traffic control measures taken by the government. Of course, it is also significantly related to the time and location of factory closures. In terms of carbon emissions, Dan et al. (2011) calculated the difference between energy consumption under normal conditions and that under green measures and converted it into carbon dioxide emission. In this way, they estimated the carbon dioxide emission reduction in energy measures, traffic management, and temporary air contamination control during the Beijing Summer Olympics. Similarly, Miettinen et al. (2019) took six measurement activities before, during, and after the Nanjing Youth Olympic Games. It was found that a series of emission control measures during large-scale events greatly cut down the concentration and composition of PM2.5. Furthermore, Chen Y et al. (2021) utilized the super-DDF DEA model to calculate the environmental efficiency. The regression analysis found that the 2014 Nanjing Youth Olympic Games improved the environmental efficiency level of the host city and still affected the surrounding cities. However, different from previous studies that only focus on a certain sports event, this study mainly makes use of the data of 278 cities from 2006 to 2019 to explore how comprehensive sports events affect urban green and low-carbon development and then utilizes the spatial difference-in-differences (SDID) model to decompose its influence on the host city and other cities and further carries out mechanism analysis and heterogeneity analysis.

In summary, the possible marginal contributions of this study are as follows. First, as for the research perspective, this study is the first to systematically assess the impact of China's major comprehensive sports events on the green and low-carbon development of the host city, compared to the case studies of individual sports events, thus filling the gap in the systematic evaluation of the environmental effects of comprehensive sports events. Second, in terms of research methodology, the pollution control measures taken in the process of holding sports events and the effect of hosting the events on the growth of tertiary industries and the possible policy demonstration and technology diffusion effects are taken into account. This study is the first to analyze the direct effect and spatial overflow effect of comprehensive sports events on environmental performance by using the SDID model, which reduces the estimation bias caused by ignoring the spatial correlation of geographic units and identifies the externalities of hosting sports events on the neighboring regions in a more scientific and effective way. Finally, in terms of research content, based on the mediating-effect model and the spatial difference-in-difference-in-differences (SDID) model, the impact mechanisms and possible heterogeneity of comprehensive sports events on green and low-carbon development in cities are identified, which is conducive to a more systematic and thorough understanding of the environmental effects of comprehensive sports events and helps provide a reference for the improvement of environmental problems in comprehensive sports events.

The following structure of this study is as follows: **Section 3** describes the method and data. **Section 4** expounds and verifies how comprehensive sports events affect the green and low-carbon development of cities and then conducts robustness checks. **Section 5** carries out mechanism identification. **Section 6** shows heterogeneity analysis. **Section 7** presents conclusions and policy implications.

3 METHODOLOGY AND DATA

3.1 Spatial Econometric Model

The traditional difference-in-differences (DID) model is often used to assess the effect of policies (Yang et al., 2022). According to the fundamental principles of the DID model, a prerequisite for the validity of DID model parameter estimates is to satisfy the stable unit treatment value assumption (SUTVA) (Rubin, 1986; Rosenbaum, 2010). SUTVA requires that there is no interaction between the potential outcomes of different individuals. In other words, the potential outcome of each individual in the sample does not depend on whether other individuals received the treatment or not. However, as explained in the previous section, influenced by the cross-regional pollution control mechanisms commonly established during the hosting of comprehensive sports events (Chen et al., 2013; Chen Y et al., 2021), the hosting of sports events will not only have an impact on the ecological environment of the host city but also generate inevitable spatial spillover effects on neighboring cities. At the same time, existing studies mostly confirm that hosting comprehensive sports events also generated externalities for other regions through channels such as tourist movement, policy demonstration, and technology diffusion (Tan, 2015; Swart et al., 2017; Kassens-Noor and Fukushige, 2018). Therefore, hosting comprehensive sports events will not only affect the ecological environment and economic development of the local region but will also impact the level of green and low-carbon development of the neighboring territories. Thus, the quasi-natural experiment of hosting comprehensive sports events violated the SUTVA, and using the traditional DID model to assess the impact of hosting comprehensive sports events on the green and low-carbon development will lead to biased estimation results (Delgado and Florax, 2015). In view of this, to ensure the reliability of the estimation results in this study, we reference the study of Jia et al. (2021) to assess the green and low-carbon development effect of comprehensive sports events through spatial econometric methods by using the SDID model. The SDID model is able to control the possible interaction effects among individuals by constructing spatial weight matrices and generating spatial lagged terms (Dubé et al., 2014; Chagas et al., 2016). Consequently, by using the SDID model to deal with the possible spatial spillover effects of comprehensive sports events, it can overcome the deficiency that the traditional DID model cannot obtain effective estimation results in the case of SUTVA violation (Jia et al., 2021) and improve the scientific validity and reliability of the research conclusions. **Eq. 1** gives the specific formulation of the SDID model.

$$green_{it} = \alpha + \rho \sum_j w_{ij} green_{jt} + \beta Treat_i \times Time_t + \theta \sum_j w_{ij} Treat_j \times Time_t + \gamma \boldsymbol{X_{it}} + \boldsymbol{\delta} \sum_j w_{ij} \boldsymbol{X_{jt}} + \mu_i + \upsilon_t + \varepsilon_{it} \tag{1}$$

Generally, in spatial econometric models, spatial correlation characteristics may be generated by independent variables and a dependent variable or error term (Lesage and Pace, 2009). Therefore, to fully reflect the possible spatial correlation between variables, using the spatial Durbin model (SDM) as a base (Jia et al., 2021), we developed **Eq. 1**, where w_{ij} is an element in the weight matrix to characterize the spatial correlation of a city with each other; $Treat_i \times Time_t$ is the independent variable in this study, indicating whether city i has hosted a comprehensive sports event in period t; $Treat_i$ takes the value of 1 if city i has hosted a comprehensive sports event, and conversely, it is 0; the dummy variable $Time_t$ for the treatment group takes the value of 1 during and after the comprehensive sports event and 0 before the event; and all cities in the control group are assigned the value of 0. The remaining variables in **Eq. 1** are the control variable $\boldsymbol{X_{it}}$, which consists of a series of factors affecting the green and low-carbon development; the city fixed effect μ_i; the year fixed effect υ_t; and the random error term ε_{it}.

3.2 Data Descriptions

3.2.1 Dependent Variable

(1) Green development: With reference to Zheng et al. (2022), based on the SBM-DEA model, this study calculates the green total factor productivity ($GTFP$) of 278 Chinese cities in the sample from 2006 to 2019, and the $GTFP$ is used to proxy the level of green development for each city. The SBM-DEA model was calculated as follows:

$$\rho = min \frac{1 - \frac{1}{m}\sum_{i=1}^{m} \frac{s_i^i}{x_{i0}}}{1 + \frac{1}{s_1+s_2}\left[\sum_{r=1}^{s_1} \frac{s_r^d}{y_{r0}^d} + \sum_{t=1}^{s_2} \frac{s_t^u}{y_{t0}^u}\right]} \tag{2}$$

subject to

$$
\begin{cases}
x_0 = \sum_{j=1}^{n} x_j \lambda_j + s^i \quad (i = 1, \cdots, m) \\
y_{r0}^d = \sum_{j=1}^{n} y_j^d \lambda_j + s^d \ (i = 1, \cdots, s_1) \\
y_{t0}^u = \sum_{j=1}^{n} y_j^u \lambda_j + s^u \ (t = 1, \cdots, s_2) \\
\lambda_j,\ s_i^i,\ y_{r0}^d,\ y_{t0}^u \geq 0\ j = t = (r = 1, \cdots, n)
\end{cases} \tag{3}
$$

Here, ρ is the $GTFP$ calculated by the SBM-DEA model; j represents each decision-making unit (DMU); n represents the number of DMU, m represents the input factors; s_1 and s_2 represent desirable and undesirable outputs, respectively; s_i^i, s_r^d, and s_t^u are slack variables for input, desirable output, and undesirable output, respectively; λ_j is the intensive variable; and x_j, y_j^g, and y_j^b are multidimensional vectors about the jth DMU, with subscript 0 that denotes the DMU to be evaluated.

In continuation of Wang et al. (2022), we use total investment in fixed assets, total employed persons, and total energy consumption as input variables; real GDP per capita based on 2006 as desired output; and industrial wastewater emissions, industrial smog emissions, and industrial SO_2 emissions as undesired outputs. Each city's green total factor productivity is calculated through the SBM-DEA model. The total energy consumptions are calculated using the total gas supply (including coal gas and natural gas), the total LPG supply, and the annual electricity consumption converted to standard coal as published in the statistical yearbook.

(2) Low-carbon development: Consistent with the $GTFP$ measure, this study also calculates the carbon emission efficiency (CE) of each city using the SBM-DEA model, in which investment, employment, and energy consumptions are used as input variables, real GDP per capita is used as desired output, and carbon emissions are used as undesired outputs. Furthermore, we calculate the amount of carbon emissions for each city based on the approach of Chen et al. (2020) using night lighting data (DMSP/OLS and NPP/VIIRS) to measure CO_2 emissions. Compared with conventional carbon emission measurement methods, this method effectively solves the problem of incomparability of carbon emission quantities among cities, makes up for the shortcomings caused by traditional estimation methods that do not fully account for the carbon emissions generated by various production activities, and makes the estimation results of this study more reliable.

3.2.2 Key Independent Variable

$Treat_i \times Time_t$ indicates whether city i has hosted a comprehensive sports event in period t. It is obtained by multiplying the individual dummy variable $Treat_i$ and the time dummy variable $Time_t$. **Table 1** lists the comprehensive sports events held by Chinese cities during the period 2006–2019. Roughly, they can be divided into two categories, international comprehensive sports events and domestic comprehensive sports events. Among them, international comprehensive sports events are official events recognized by the International Olympic Committee; domestic comprehensive sports events are national events hosted by the General Administration of Sports of China and co-organized by cities. To visualize the spatial distribution of individual host cities, we also drew a specific spatial distribution map, which is shown in **Figure 1**.

3.2.3 Control Variables

To ensure the reliability of the study conclusions, we also controlled for a range of variables that potentially affect the $GTFP$ and the CE. Considering the availability of city-level data, citing studies by Wang et al. (2022), Yu et al. (2022a), and Zheng et al. (2022), the following variables are chosen as covariates for this study: 1) economic development level ($pgdp$), expressed using real GDP per capita with 2006 as the base period; 2) industrial structure (is), using the value added of the tertiary industry as a percentage of GDP; 3) urbanization level ($urban$), represented by non-agricultural population as a proportion of total population; 4) population density (pd), represented as total population per unit administrative territory land area; 5) openness to the outside world (op), measured by total exports and imports of goods as a percentage of GDP; 6) science and technology level (rd), expressed using annual R&D expenditure; 7) human capital (hum),represented by the number of college students; 8) government intervention (gov), expressed using the ratio of fiscal expenditure to fiscal revenue; 9) energy consumption (ec), represented using the total energy consumption of the whole society converted to standard coal; and (10) environmental regulation (er), expressed in terms of the harmless disposal rate of municipal domestic garbage. In addition, to alleviate the possible heteroskedasticity problem, this study takes logarithms for all absolute quantities. **Table 2** documents the summary statistics of each variable.

3.2.4 Spatial Weight Matrix

Following the practice of Du et al. (2021), the weight matrix is set as an inverse geographic distance matrix in the benchmark regression section. Specifically, W_1 is set in the down form (W_1 has been standardized).

$$
W_1 = \begin{bmatrix} w_{11} & \cdots & w_{1n} \\ \vdots & \ddots & \vdots \\ w_{n1} & \cdots & w_{nn} \end{bmatrix} \tag{4}
$$

The elements in the matrix are given by

$$
w_{ij} = \begin{cases} \dfrac{1}{d_{ij}} & if\ i \neq j \\ 0 & if\ i = j \end{cases} \tag{5}
$$

where d_{ij} is the distance of cities i and j, geographically.

In addition, we also replace the inverse geographic distance matrix (W_1) with a spatial adjacency matrix (W_2) for robustness checks. In this case, w_{ij} is taken as 1 if city i is adjacent to j. Otherwise, w_{ij} is taken as 0.

3.2.5 Data Sources

The figures in this article are mainly from the official website of the State General Administration of Sports (https://www.sport.gov.cn/); the website of the IOC (https://olympics.com/en/); the

TABLE 1 | Previous comprehensive sports events hosted by mainland China.

Name of the sports event	Event city	Time of the event
International comprehensive sports event		
The 2007 Changchun Asian Winter Games	Changchun	28 January 2007–4 February 2007
The 2007 Special Olympics World Summer Games	Shanghai	2 October 2007–11 October 2007
The 2008 Beijing Summer Olympics	Beijing	8 August 2008–24 August 2008
The 2009 Harbin Winter Universiade	Harbin	18 February 2009–28 February 2009
The 2010 Guangzhou Asian Games	Guangzhou	12 November 2010–27 November 2010
Shenzhen 2011 The 26th Summer Universiade	Shenzhen	12 August 2011–23 August 2011
The 6th East Asia Games	Tianjin	6 October 2013–15 October 2013
The 2014 Nanjing Youth Olympic Games	Nanjing	16 August 2014–28 August 2014
Domestic comprehensive sports event		
The 11th National Games of the P. R. China	Jinan	16 October 2009–28 October 2009
The 11th National Winter Games of the P. R. China	Qiqihar	18 January 2008–28 January 2008
The 12th National Games of the P. R. China	Shenyang	31 August 2013–12 September 2013
The 1st Youth Games of the P. R. China	Fuzhou	18 October 2015–27 October 2015
The 13th National Winter Games of the P. R. China	Urumqi	20 January 2016—30 January 2016

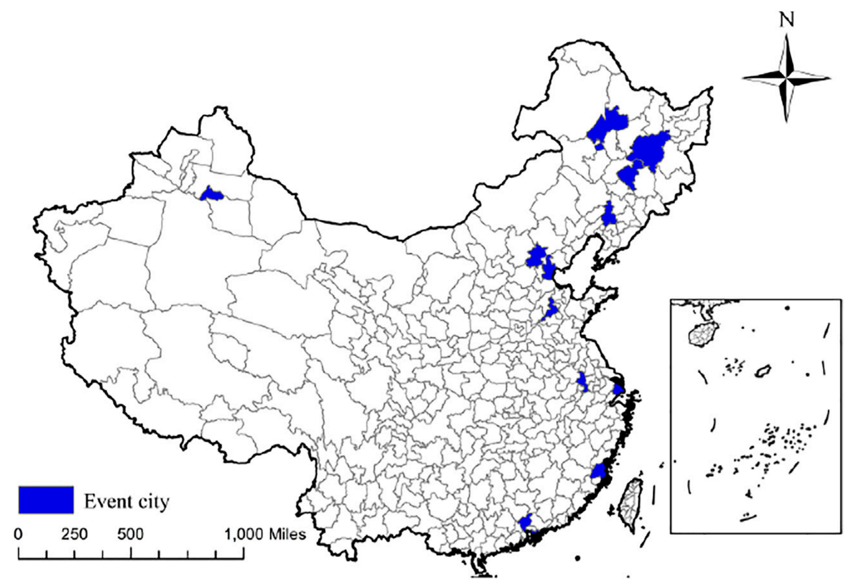

FIGURE 1 | Spatial distribution of cities hosting comprehensive sports events.

TABLE 2 | Summary statistics of variables.

Variables	Obs	Mean	Std	Min	Max
GTFP	3,892	0.385	0.159	0.111	1.000
CE	3,892	0.400	0.151	0.134	1.000
$Treat_i \times Time_t$	3,892	0.031	0.173	0.000	1.000
ln(pgdp)	3,892	10.424	0.721	4.595	13.056
is	3,892	0.392	0.098	0.086	0.835
urban	3,892	0.392	0.228	0.075	0.982
ln(pd)	3,892	-3.470	0.918	-7.663	-1.288
op	3,892	0.200	0.382	0.000	8.134
ln(rd)	3,892	9.829	1.609	3.526	15.529
ln(hum)	3,892	10.328	1.657	0.000	13.897
gov	3,892	2.815	1.900	0.649	18.399
ln (ec)	3,892	4.284	1.228	0.088	8.347
er	3,892	0.847	0.249	0.231	1.000

website of the COC (http://www.olympic.cn/); the Figshare database (https://figshare.com); and *the China City Statistical Yearbook*, *China Energy Statistical Yearbook*, *China Regional Economic Statistical Yearbook*, *China Urban and Rural Construction Statistical Yearbook*, the statistical yearbook of each province and city in previous years, and the statistical bulletin of each city and other information.

4 EMPIRICAL RESULTS AND ANALYSIS

4.1 Exploratory Spatial Analysis

4.1.1 Spatial Correlation Analysis

Based on models (2) and (3), the GTFP and CE were measured for each city from 2006 to 2019 in this study, and on this basis,

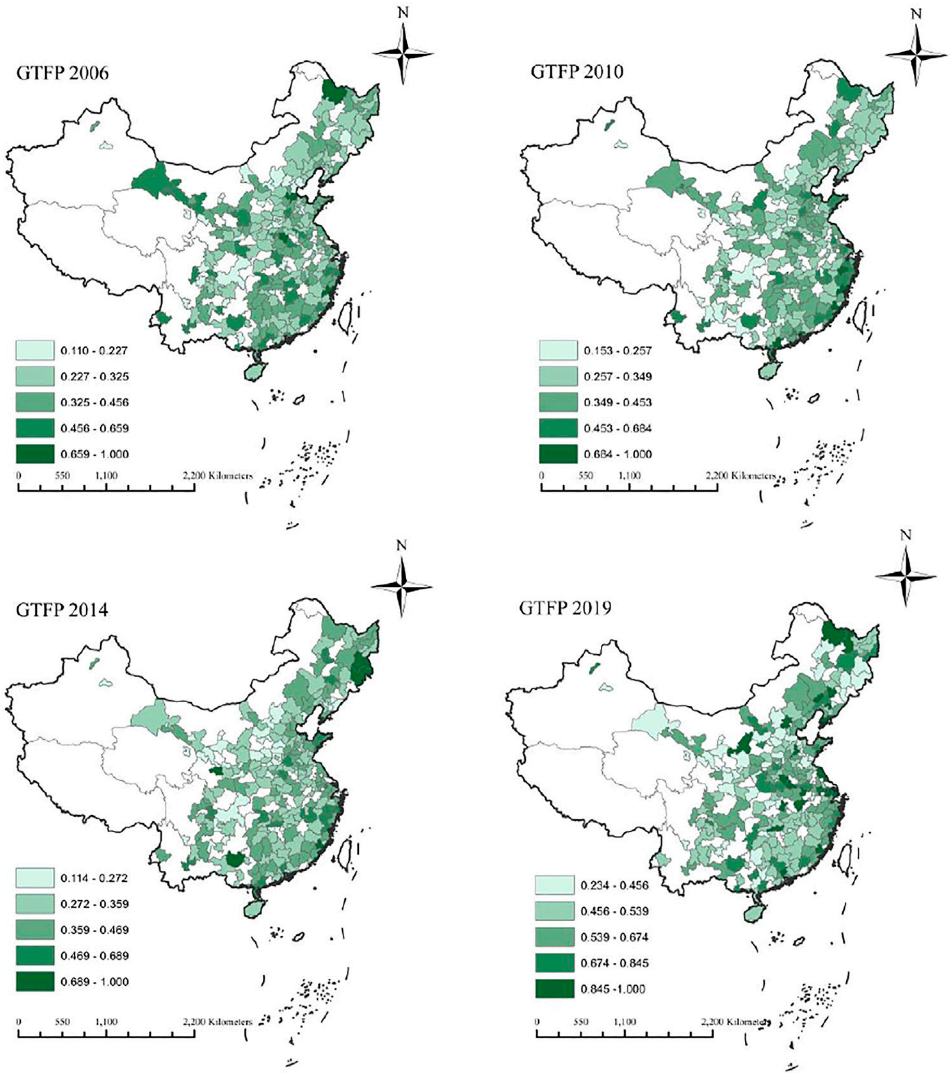

FIGURE 2 | Spatial distribution map of GTFP.

the spatial distribution of GTFP (**Figure 2**) and CE (**Supplementary Appendix Figure A1**) in 2006, 2010, 2014, and 2019 is mapped using ArcGIS 10.7. From **Figure 2** and **Supplementary Appendix Figure A1**, it can be found that the GTFP and CE of all Chinese cities have improved from 2006 to 2019. In particular, there is an obvious spatial agglomeration characteristic of GTFP. The coastal and central region cities have a relatively high GTFP, while those in the northwest and southwest regions have a low one. In addition, the spatial distribution characteristics of CE are similar to those of GTFP. CE is relatively high in coastal and southern cities and low in northern cities. The abovementioned phenomenon may be related to the centralized winter heating policy in the northern region (Wang et al., 2020), and the carbon emissions generated by centralized winter heating reduce the CE in northern cities.

Furthermore, the global Moran index was used to more accurately characterize the spatial autocorrelation of GTFP and CE. **Eq. 6** presents the formula of global Moran's index.

$$Moran's\,I = \frac{n}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}} \times \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \quad (6)$$

where n refers to the total number of cities in the sample; w_{ij} is the element in the inverse geographic distance matrix; x_i and x_j are the GTFP (CE), respectively, for city i and city j; and $\bar{x}$ is the mean of the GTFP (CE) of the variable in the current period. The global Moran index takes values ranging from −1 to 1. If $Moran's\,I = 0$, it demonstrates that the spatial autocorrelation among the dependent variables does not exist; if $Moran's\,I > 0$, it indicates that the positive autocorrelation exists among the variables; and if $Moran's\,I < 0$, it indicates that negative

TABLE 3 | Test results of global Moran's index.

GTFP				CE			
year	Moran's I	Z(I)	P	year	Moran's I	Z(I)	P
2006	0.055	1.997	0.023	2006	0.028	1.081	0.140
2007	0.054	1.950	0.026	2007	0.040	1.463	0.072
2008	0.060	2.164	0.015	2008	0.059	2.117	0.017
2009	0.101	3.549	0.000	2009	0.075	2.637	0.004
2010	0.108	3.780	0.000	2010	0.101	3.533	0.000
2011	0.128	4.465	0.000	2011	0.108	3.770	0.000
2012	0.155	5.377	0.000	2012	0.150	5.161	0.000
2013	0.094	3.300	0.000	2013	0.104	3.643	0.000
2014	0.082	2.924	0.002	2014	0.099	3.461	0.000
2015	0.098	3.469	0.000	2015	0.116	4.049	0.000
2016	0.118	4.114	0.000	2017	0.130	4.501	0.000
2017	0.127	4.428	0.000	2018	0.175	6.037	0.000
2018	0.093	3.257	0.001	2019	0.189	6.514	0.000
2019	0.172	5.885	0.000	2017	0.248	8.468	0.000

autocorrelation exists among the variables. The global Moran index values for GTFP and CE are reported in **Table 3**. As can be found, the global Moran index value of GTFP and CE is larger than 0, which illustrates that GTFP and CE are both significantly characterized by positive spatial autocorrelation. Therefore, the spatial effects should not be ignored when exploring the effects of comprehensive sports events on GTFP and CE.

The global Moran index investigates the agglomeration of GTFP and CE over the entire spatial series, and to obtain insight into the spatial characteristics of the neighborhood of a particular city *i*, we also analyzed spatial correlations within specific regions by drawing Moran's scatter plots. **Figure 3** and **Supplementary Appendix Figure A2** show the Moran scatter plots of GTFP and CE in 2006, 2010, 2014, and 2019. From the figures, it can be found that most of the scatter points are clustered within the first and third quadrants, which demonstrates that both GTFP and CE of Chinese cities in the sample exhibit significant spatial agglomeration characteristics.

4.1.2 Spatial Econometric Modeling Setup Test

This study requires identifying whether spatial dependence exists or not. Specifically, we first perform the LM-lag test and the robust LM-lag test by constructing a spatial lag model (SLM) and an OLS model to determine the existence of a spatial lag effect. Second, the LM-error test and robust LM-error test are conducted by constructing spatial error models (SEMs) and OLS models to judge the existence of spatial error effects (Wang et al., 2021). The abovementioned tests are employed to examine whether the spatial econometric model is necessary to analyze the effect of comprehensive sports events on GTFP and CE. From **Table 4**, it can be found that all the aforementioned four tests have significantly rejected the null hypothesis, which initially illustrates that the spatial econometric modeling is reasonable in this study.

Based on the abovementioned analysis, this study refers to Jia et al. (2021) to identify the SDM as degradable to the SLM or the SEM by conducting the LR test and the Wald test. The test results in **Table 4** show that the LR-lag tests, LR-error tests, Wald-lag tests, and Wald-error tests are all significant at the 1% level. Thus, the SDM failed to degrade as the SLM or the SEM (Elhorst, 2014). Moreover, the Hausman tests have rejected the null hypothesis at a significance level of 1%, implying that the fixed-effects model should be used for panel data analysis. Consequently, the setting of **Eq. 1** in this study is reasonable and reliable.

4.2 Benchmark Regressions

Columns (4) and (8) in **Table 5** show the estimation results of **Eq. 1**. It can be observed that hosting comprehensive sports events

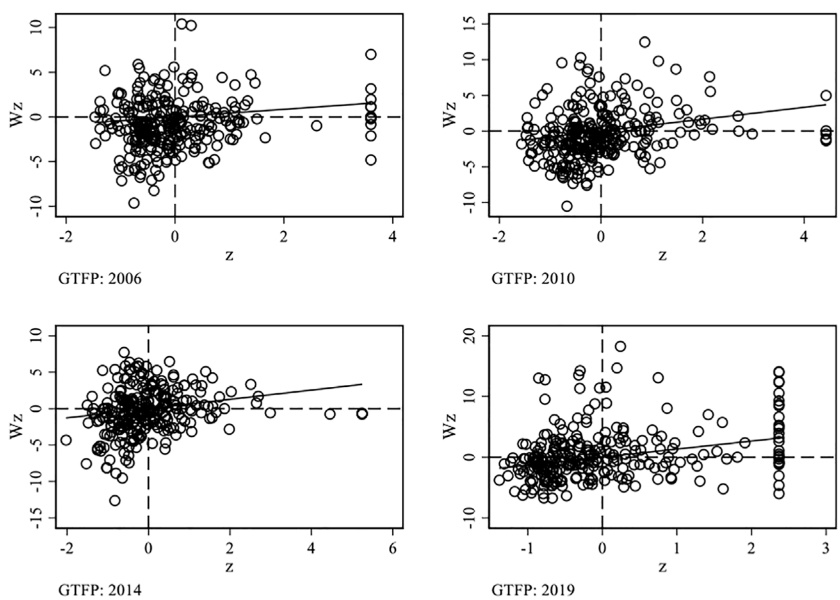

FIGURE 3 | Moran's scatterplot of GTFP by city in 2006, 2010, 2014, and 2019.

TABLE 4 | Test results of the setting model.

Test		*GTFP*	*CE*
Spatial dependence	LM-lag test	128.28 (0.000)	100.68 (0.000)
	Robust LM-lag test	67.85 (0.000)	55.36 (0.000)
	LM-error test	197.93 (0.000)	181.94 (0.000)
	Robust LM-error test	70.07 (0.000)	81.68 (0.000)
Simplified model	LR-lag test	146.62 (0.000)	142.59 (0.000)
	LR-error test	258.18 (0.000)	272.21 (0.000)
	Wald-lag test	76.34 (0.000)	88.44 (0.000)
	Wald-error test	69.81 (0.000)	87.67 (0.000)
	Hausman's test	85.01 (0.000)	116.18 (0.000)

significantly enhances the GTFP and CE of host cities, while the spatial lag of $Treat_i \times Time_t$ is also significantly positive, indicating that holding sports events not only promotes the green and low-carbon development of the host city but also drives the neighboring areas of the host city. Since the estimated coefficients of the SDM do not directly reflect the marginal effects of the events, a decomposition is needed (Elhorst, 2014), so we also report the decomposition results of the SDM in **Table 5**. It can be found that organizing sports events can drive the GTFP of the host city to improve by approximately 14.4% and the CE by approximately 16.2%. Meanwhile, the spatial spillover effects from the events can improve the GTFP of other cities in the sample by approximately 225.6% and the CE by approximately 251.3%; that is, on average, each city can increase its GTFP and CE by 0.851 and 0.948%, respectively, through the comprehensive sports event. In addition to taking into account the studies of Jia et al. (2021) and Wang et al. (2022), we also have the results of SEM, SLM, and SLX estimation reported in **Table 5** as components of the robustness test. It is observed that the direct and indirect impacts (spatial spillover) of hosting comprehensive sports events remain significantly positive under different forms of spatial econometric model settings. Preliminarily, it is indicated that the estimation results of this study are relatively reliable.

4.3 Robustness Checks

4.3.1 Parallel Trend Tests

Satisfying the parallel trend assumption is the precondition for the valid estimation results of the DID model. Therefore, we need to judge whether there are significant systematic differences in the change trends of the dependent variables across the treatment and control groups pre and post the hosting of comprehensive sports events. Here, this study continues the method of Lin (2017) and establishes the following equation for the parallel trend test based on the event study method.

$$green_{it} = \alpha + \rho \sum_j w_{ij} green_{jt} + \beta D_{it}^k + \theta \sum_j w_{ij} D_{it}^k + \boldsymbol{\gamma X_{it}} + \boldsymbol{\delta} \sum_j w_{ij} \boldsymbol{X_{jt}} + \mu_i + \upsilon_t + \varepsilon_{it} \quad (7)$$

where D_{it}^k is a dummy variable indicating the event hosting and the superscript k of D_{it}^k is represented by the year corresponding

TABLE 5 | Estimates of the green and low-carbon development effects on sports events.

	GTFP				*CE*			
	SEM (W_1)	SLM (W_1)	SLX (W_1)	SDM (W_1)	SEM (W_1)	SLM (W_1)	SLX (W_1)	SDM (W_1)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$Treat_i \times Time_t$	0.129*** (7.09)	0.130*** (7.18)	0.137*** (7.43)	0.134*** (7.35)	0.145*** (9.69)	0.147*** (9.80)	0.156*** (10.21)	0.150*** (10.00)
$W \times Treat_i \times Time_t$			1.119*** (5.46)	0.657*** (3.19)			0.993*** (5.86)	0.602*** (3.55)
Direct effect				0.144*** (7.67)				0.162*** (10.32)
Indirect effect				2.256*** (3.14)				2.513*** (3.28)
Total effect				2.401*** (3.32)				2.675*** (3.46)
ρ(λ)	0.809*** (15.76)	0.741*** (12.85)		0.704*** (10.97)	0.828*** (18.36)	0.780*** (15.13)		0.748*** (12.98)
sigma	0.100*** (84.63)	0.100*** (84.75)	0.101*** (85.02)	0.100*** (84.77)	0.0826*** (84.66)	0.0826*** (84.72)	0.0839*** (85.02)	0.0825*** (84.73)
CV	YES	YES	YES	YES	YES	YES	YES	YES
City FE	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES
N	3,892	3,892	3,892	3,892	3,892	3,892	3,892	3,892
Log-l	2,909.1	2,914.1	2,884.9	2,916.2	3,462.5	3,464.9	3,432.5	3,466.8
Pseudo-R^2	0.0046	0.0055	0.0077	0.0060	0.0008	0.0018	0.0024	0.0019

*Notes: ***, **, and * represent significance levels of 1, 5, and 10%, respectively; the values in parentheses are t(z) statistics; ρ represents the spatial lag term of $Treat_i \times Time_t$; and λ represents the spatial lag term of error term, the same below.*

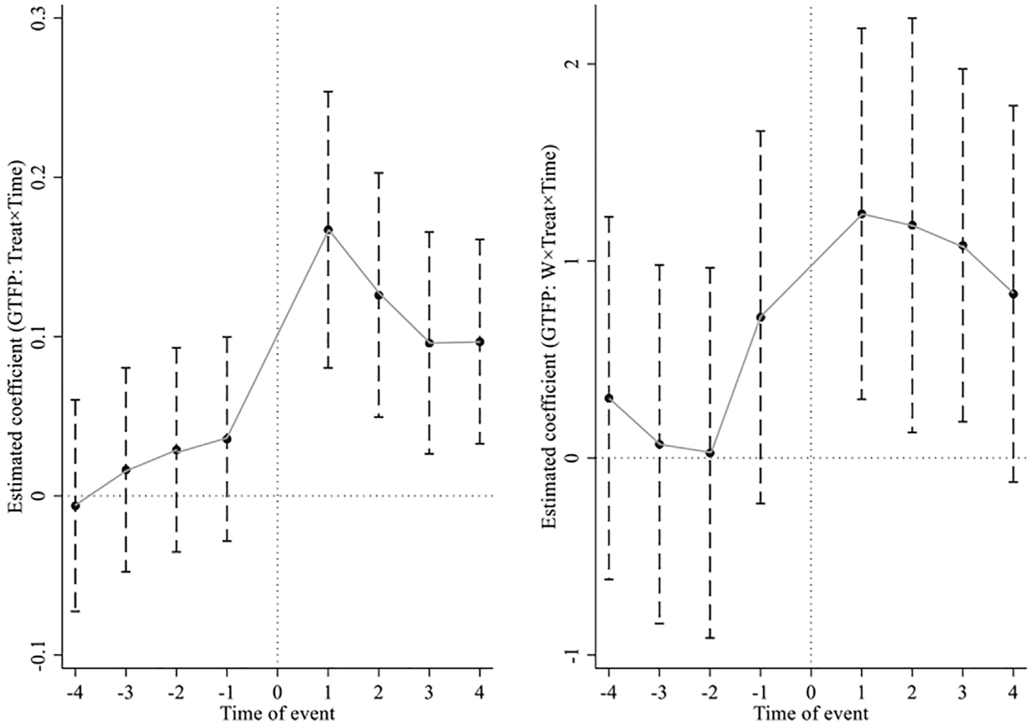

FIGURE 4 | Parallel trend test results of GTFP.

to the period t minus the year in which the sports event was held in that city. The implications of the other variables in **Eq. 7** are the same as in **Eq. 1**. **Figure 4** shows the estimation results for parameter β and parameter θ. The dots in the figure indicate the specific estimates of parameter β and parameter θ, and the dashed lines are their corresponding 95% confidence intervals. As can be seen, the parameter estimates of both β and θ are not significant until period 0, indicating that the trends in the treatment and control groups are not significantly different before the sports event, satisfying the parallel trend assumption, and the estimates in **Table 5** are robust. Meanwhile, a significant increase at the first post-event stage is observed in GTFP of the treatment group, but the effect continued to decline in the 2nd period after the event, suggesting that the impact of comprehensive sports events on GTFP may not be sustainable in the long run. In addition, **Supplementary Appendix Figure B1** depicts the results of the CE parallel trend test, whose findings are consistent with those of GTFP and are omitted here.

4.3.2 Placebo Tests

Omission of important variables may lead to biased estimation results. For this reason, we refer to Jia, et al. (2021) and perform placebo tests using a random sampling method. The idea is to generate false dummy variables $Treat_i \times Time_t^f$ by randomly selecting treatment groups in the sample, adding them to **Eq. 1** in place of $Treat_i \times Time_t$ for regression, and plotting the distribution of estimated coefficients to determine whether **Eq. 1** is missing important variables. Specifically, first, the equivalent quantity of cities to the true treatment group was randomly and non-repeatedly selected from 278 cities as the false treatment group, which in turn generated the false dummy variable $Treat_i \times Time_t^f$. Second, keeping the remaining variables unchanged, $Treat_i \times Time_t^f$ was substituted into **Eq. 1** for regression to obtain the estimated values of $Treat_i \times Time_t^f$ and $W \times Treat_i \times Time_t^f$, and the abovementioned operation was repeated 200 times. Finally, the frequency distributions were plotted based on the estimated parameters obtained from 200 random samples. **Figure 5** and **Supplementary Appendix Figure B2** show the specific results of the placebo test. It can be found that the estimated coefficients of $Treat_i \times Time_t^f$ and $W \times Treat_i \times Time_t^f$ are centrally distributed at 0 in both GTFP and CE conditions and are significantly different from the benchmark regression results, indicating that the model setting of **Eq. 1** is reasonable, no important variables are omitted, and the benchmark regression results are robust.

4.3.3 Non-Spatial Perspective Robustness Checks

To guarantee the robustness of the study's conclusions, we conducted robustness checks from both spatial and non-spatial perspectives.

(1) Using the traditional DID model

Following Feng et al. (2021), we performed robustness checks using the traditional DID model without spatial lag term. Columns (1) and (2) of **Table 6** report the estimates of the traditional DID model. It can be found that the $Treat_i \times Time_t$ term is significantly positive in both GTFP and CE conditions,

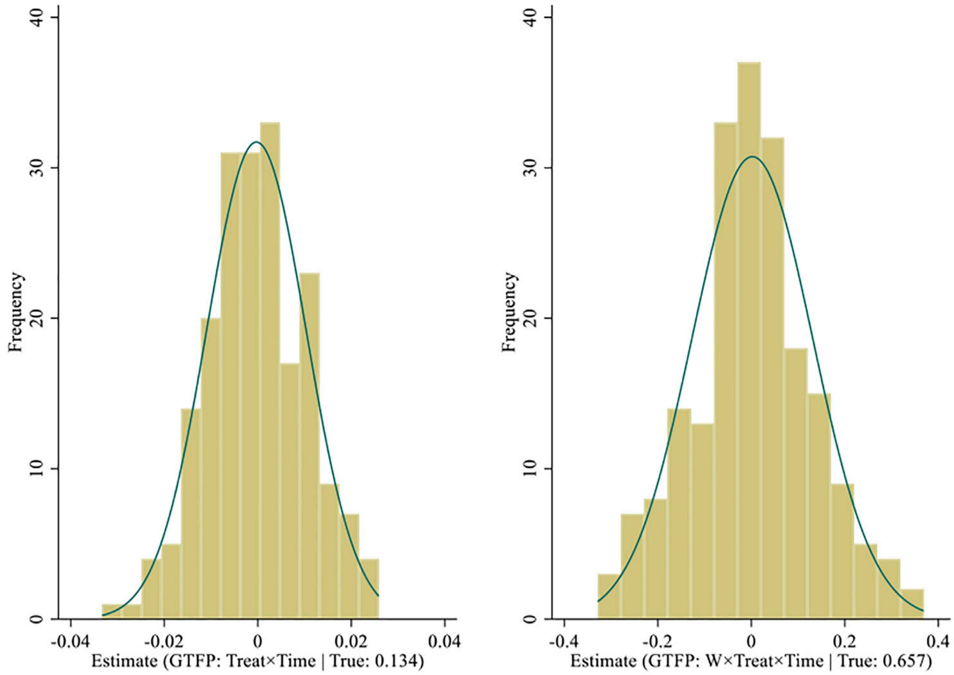

FIGURE 5 | Placebo test results of GTFP.

TABLE 6 | Robustness test I.

	DID		Synthetic DID		Bootstrap random tobit regression	
	GTFP	***CE***	***GTFP***	***CE***	***GTFP***	***CE***
	(1)	**(2)**	**(1)**	**(2)**	**(5)**	**(6)**
$Treat_i \times Time_t$	0.132***	0.151***	0.125***	0.140***	0.149***	0.167***
	(3.95)	(4.92)	(3.73)	(4.07)	(2.92)	(13.34)
CV	YES	YES	YES	YES	YES	YES
City FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Constant	1.292***	1.341***			0.547***	0.600***
	(3.13)	(3.04)			(3.53)	(5.18)
N	3,892	3,892	3,892	3,892	3,892	3,892
Log-l					2,993.7	3,649.3
R^2	0.671	0.695				

indicating that organizing comprehensive sports events can still promote low-carbon and green development in the host city without considering spatial effects.

(2) Using the synthetic DID Model

This study also employs the synthetic DID approach developed by Arkhangelsky et al. (2021) for robustness checks. The synthetic DID approach incorporates the advantages of both the DID method and the synthetic control method (SCM) to identify causal relationships without satisfying the large sample and parallel trend assumptions and has the properties of double robustness, which is a superior estimation method. The basic idea of synthetic DID is to synthesize a control group by taking a weighted approach to potential control groups and identify the policy effects of the intervention by comparing the differences pre and post intervention between the treatment and control groups. Since the synthetic control group is an optimal "counterfactual" fitness of the pre-intervention treatment group, the same change trends in dependent variables existed for the synthetic control and treatment groups before the intervention, which naturally satisfies the parallel trend assumption. At the same time, compared with the SCM, the synthetic DID approach introduces an intercept term to distinguish the synthetic control group from the treatment group and also adjusts the policy base period using time weights (v_t), which makes the estimation results more reliable. Therefore, we performed robustness checks using the synthetic DID method to give further assurance on the credibility of conclusions. The results of the synthetic DID model are reported for columns (3) and (4) in **Table 6**, and it is easy to see that holding comprehensive sports events still significantly elevated the GTFP and CE of the host city, indicating the study results of this study with robust conclusions.

(3) Using the tobit regression model

Considering that both GTFP and CE are truncated–tailed data, and following the research of Chen S et al. (2021), this article also uses the bootstrap tobit regression model for robustness checks. The estimation results of tobit are reported in columns (5) and (6) of **Table 6**. It is observed that the coefficients estimated for $Treat_i \times Time_t$ do not fundamentally change after replacing the estimated model, indicating that the basic conclusions of this study are reliable.

4.3.4 Spatial Perspective Robustness Checks

(1) Using the PSM-SDID model

To overcome the estimation bias due to possible systematic differences in individual characteristics across the treatment and control groups, we further used the PSM-SDID approach for robustness tests. Specifically, the PSM nearest neighbor matching method to search for similar control groups to the treatment group was used, and the propensity score values were estimated by logit regression on the dummy variable $Treat_i$. The sample with the most similar propensity score is the matched sample of the treatment group. The new control group obtained through PSM matching can minimize the systematic differences in individual characteristics with the treatment group, thus improving the reliability of the SDID model estimation results. In addition, the validity of the matched variables needs to be tested before using PSM-SDID to ensure that covariates in the treatment and control groups do not have significant systematic differences after matching. The control variables in model (1) are matched as matching covariates using the "4 nearest neighbor matching" method, and the specific results of the PSM-SDID balance test are shown in **Supplementary Appendix Table C1**. As can be seen in **Supplementary Appendix Table C1**, before matching, there were significant group differences between the host city and the other cities in terms of the control covariates, the standard bias of each variable was reduced by more than 75% after matching, and the systematic differences were significantly reduced by the treatment and control groups, which satisfied the requirement of balance between variables and could be further analyzed using the SDID method. The estimates of PSM-SDID are presented in columns (1) and (2) of **Table 7**, and it can be found that to host comprehensive sports events, the direct and spatial spillover effects on GTFP and CE are still statistically significantly positive, reinforcing the reliability of the benchmark results.

(2) Excluding the CET policy interference

Existing literature suggests that the carbon emissions trading (CET) pilot policy affects cities' GTFP and CO_2 emissions (Wen et al., 2021; Zhang and Wang, 2021; Cheng and Kong, 2022). Since 2013, China has launched the pilot CET programs in seven provinces and municipalities. The CET pilot policy has improved the carbon emission performance and GTFP of the pilot cities to some extent. To address the possible effects of the CET policy on the environmental effects of comprehensive sports events, this study introduces a dummy variable CET, indicating the CET policy into the model to investigate more about the robustness of the estimates in this study. The variable CET is assigned with a value of 1 for the cities in the pilot provinces (cities) in the year of the pilot policy and thereafter, and 0 for the other cases. On this basis, the CET and its spatial lag term $W \times CET$ are put into **Eq. 1** for regression, and the estimates are displayed in columns 3) and 4) of **Table 7**. From **Table 7**, it is observed that the direct and spatial spillover effects continue to be significantly positive after the introduction of policy dummy variables, indicating that the conclusions of this study are still valid after the introduction of the CET policy intervention.

(3) Replacing the spatial weight matrix

This section substitutes the inverse geographic distance matrix (W_1) for the adjacency matrix (W_2) in the benchmark regression to perform robustness tests. The estimation results of the SDID model on the basis of the adjacency matrix in columns (5) and (6) of **Table 7** are reported. It can be found that the direct and spatial spillover effects of hosting comprehensive sports events on GTFP and CE are still significantly positive after replacing the spatial weight matrix, further indicating the estimation results of this study are considered reliable. In addition, for the 51 non-host cities adjacent to the 13 host cities, the spatial spillover effects of hosting the events on the GTFP and CE of each neighboring city are about 1.20 and 1.37%, respectively, on average. Thus, the neighboring cities of the host cities benefit more from the sports events than the other cities.

(4) Reducing the sample size

Considering that cities at different hierarchical levels in China may have different urban governance capabilities, the environmental governance effectiveness of cities may vary significantly at diverse levels of governance. Therefore, borrowing from Yang et al. (2019), this study reduces the sample to provincial capitals and planned cities for testing whether the control group changes have substantial effects on the estimation conclusions. The regression results in columns (7) and (8) of **Table 7** demonstrate that the direct effects and spatial spillover of hosting comprehensive sports events on GTFP and CE are still significantly positive, which is sufficient to indicate that the basic conclusions of this study are solid and robust.

TABLE 7 | Robustness test II.

	PSM-SDID		CET		W_2		Reducing the sample size	
	GTFP	*CE*	*GTFP*	*CE*	*GTFP*	*CE*	*GTFP*	*CE*
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$Treat_i \times Time_t$	0.124***	0.136***	0.126***	0.141***	0.132***	0.148***	0.104**	0.105***
	(5.89)	(7.66)	(6.85)	(9.35)	(7.25)	(9.91)	(2.55)	(3.20)
$W \times Treat_i \times Time_t$	0.316**	0.196*	0.671***	0.623***	0.301**	0.274**	0.430***	0.310***
	(2.55)	(1.85)	(3.25)	(3.67)	(2.02)	(2.25)	(3.96)	(3.28)
Direct effect	0.137***	0.143***	0.136***	0.152***	0.137***	0.155***	0.105***	0.107***
	(7.65)	(7.82)	(7.19)	(9.69)	(7.42)	(10.09)	(2.84)	(3.40)
Indirect effect	1.201***	0.681***	2.259***	2.371***	0.612**	0.703***	0.552***	0.382***
	(2.93)	(2.63)	(3.17)	(3.36)	(2.58)	(2.99)	(4.23)	(3.85)
Total effect	1.338***	0.824***	2.395***	2.524***	0.750***	0.859***	0.657***	0.489***
	(3.20)	(3.18)	(3.34)	(3.55)	(3.10)	(3.58)	(4.48)	(4.25)
ρ	0.717***	0.647***	0.701***	0.728***	0.603***	0.669***	0.258**	0.218**
	(13.28)	(10.39)	(10.85)	(11.95)	(10.29)	(12.35)	(2.12)	(2.06)
sigma	0.112***	0.095***	0.099***	0.082***	0.100***	0.082***	0.088***	0.073***
	(56.96)	(57.01)	(84.77)	(84.75)	(84.74)	(84.66)	(30.12)	(30.13)
CET (W×CET)	NO	NO	YES	YES	NO	NO	NO	NO
CV	YES	YES	YES	YES	YES	YES	YES	YES
W×CV	YES	YES	YES	YES	YES	YES	YES	YES
City FE	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES
N	1764	1764	3,892	3,892	3,892	3,892	490	490
Log-l	1,245.4	1,530.1	3,185.1	3,883.3	3,179.1	3,877.8	456.7	542.5
Pseudo-R^2	0.022	0.031	0.0156	0.0087	0.0205	0.0126	0.3013	0.1963

5 MECHANISM IDENTIFICATION

5.1 Mechanism Analysis

The previous section demonstrated that hosting comprehensive sports events can significantly improve GTFP and CE but cannot analyze the reasons for this. In this section, we discuss the mechanisms by which comprehensive sports events influence environmental performance improvement. Overall, the results in the previous section may be achieved through technological innovation, sports industry development, and foreign investment.

5.1.1 Technological Innovation Effect

Comprehensive sports events have become an important policy instrument to promote green technology innovation (Kassens-Noor and Fukushige, 2018). In the building industry, for example, stadiums built to host events have higher environmental standards, and hosting sports events can promote scientific and technological innovation in the architecture sector, thereby reducing the carbon emissions of stadiums and other infrastructure and improving environmental performance (Wu and Zhang, 2008). At the same time, mega-sports events are a testing ground for new transportation technologies. The demand for transportation during sports events far exceeds the daily situation, necessitating that transportation authorities optimize and innovate transportation management technologies to meet passenger demand. Therefore, hosting sports events can objectively promote transportation technology innovation, optimize urban transportation efficiency, and increase the GTFP of the host city (Zhou et al., 2010b; Yan et al., 2010). In addition, sports events also facilitate innovation in information and communication technology and ecological protection technology (Wu and Zhang, 2008; Zhang et al., 2021). Communication technology innovation can reduce resource waste and achieve energy saving and environmental protection (Wu et al., 2021). The ecological protection technology innovation can explore a new urbanization development pattern of coordinated development of urban construction and ecological protection and provide ecological environmental technical support for the green development of the host city and other cities after the tournament (Zhang et al., 2021). Notably, the Athletes' Village built for the sports events can be considered a typical case of circular economy. By operating the Athletes' Village, it is possible to explore and practice the application of circular economy in the community, which will provide technical support for the future large-scale promotion of cleaner and more environmentally friendly production and living systems, thus contributing to sustainable development of the hosts (Khan et al., 2021c). Therefore, this study believes that organizing comprehensive sports events can realize the green and low-carbon development of each city through green technology innovation.

5.1.2 Sports Industry Development Effect

The organization of comprehensive sports events will facilitate the formation and promotion of the sports sector. On the one hand, organizing sports events can stimulate the public's enthusiasm for participating in sports activities and develop consumption demand for sports goods or services (Chen S et al., 2021). When producers anticipate that holding sports events may boost people's demand for sports products and services, they will influence the production and investment decisions of enterprises, which in turn will improve the supply capacity of sports products and services (Zhang et al., 2018). The sports industry develops through the hosting of events under the mutual influence of supply and demand. On the other hand, using sports events as a policy instrument essentially enhances the sports infrastructure of the host city, optimizes the hardware conditions for consumers to participate in sports activities, and creates an environment conducive to the promotion of the sports sector (Tan, 2015; Zhang et al., 2018). Therefore, holding comprehensive sports events is advantageous to the sports sector's progress. In addition, as a green industry, the stable and healthy development of the sports industry is conducive to promoting sustainable regional development (Yang et al., 2020). The energy-saving and efficiency-enhancing functions of the sports sector are beneficial to facilitating industrial structure optimization and modernization, which effectively stimulates the green and low-carbon transition of the economy (Xu and Yang, 2019). Consequently, we assume that hosting comprehensive sports events is conducive to improving the GTFP and CE of the hosts by driving the development of the sports industry.

5.1.3 Foreign Investment Attraction Effect

The success of a comprehensive sports event can optimize the host city's infrastructure and business environment (Zhang et al., 2018; Yu et al., 2021), reflecting the efficiency of the host city's government and social governance (Malchrowicz-Mośko and Poczta, 2018). This helps establish the national image and the city's influence, which in turn attracts foreign investment through the "signaling mechanism" to affect the ecological environment and carbon emissions of the host city (Kim et al., 2014; Long et al., 2018; Yu et al., 2022a). However, the effect of foreign direct investment (FDI) on the environment is still controversial in academic community. The "pollution haven" hypothesis asserts that developed countries exacerbate the environmental pressure in host countries by transferring high pollution and energy-intensive industries, while the " pollution halo" hypothesis believes that the FDI contributes to the improvement of the host country's environmental quality by upgrading its production technology (Lin H. et al., 2022). Both of these hypotheses have received substantial empirical support, but the environmental performance of FDI induced by comprehensive international sports events is not known. Therefore, this study tries to answer this question through mechanism identification.

5.2 Mechanism Testing

In order to verify whether hosting comprehensive sports events can achieve green and low-carbon development of the host city through technological innovation, sports industry development, and attracting foreign investment, this study uses the mediating-effects model for mechanism identification, with reference to the method of Baron and Kenny (1986). The specific model is as follows:

$$M_{it} = \alpha + \rho \sum_j w_{ij} M_{jt} + \beta_1 Treat_i \times Time_t + \theta_1 \sum_j w_{ij} Treat_i \times Time_t + \boldsymbol{\gamma X_{it}} + \boldsymbol{\delta} \sum_j w_{ij} \boldsymbol{X_{jt}} + \mu_i + \upsilon_t + \varepsilon_{it} \tag{8}$$

$$green_{it} = \alpha_1 + \rho_1 \sum_j w_{ij} green_{it} + \beta_1 Treat_i \times Time_t + \theta_1 \sum_j w_{ij} Treat_i \times Time_t + \partial_1 M_{it} + \partial_2 \sum_j w_{ij} M_{jt} + \gamma X_{it} + \delta \sum_j w_{ij} X_{jt} + \mu_i + \upsilon_t + \varepsilon_{it} \tag{9}$$

Here, M_{it} is the mediating variable, and the remaining variables carry the same implication as **Eq. 1**. Referring to existing studies and considering the availability of the municipality-level data, the logarithm of the total green patents granted (Deng et al., 2022), the share of sports sector employees in the number of employments (Xu and Yang, 2019), and the logarithm of the total foreign direct investment (Hille et al., 2019) are selected as mediating variables to be substituted into **Eqs 8** and **9** for mechanism identification, respectively. The regression results of mechanism identification are reported in **Table 8**.

From columns (1), (4), and (7), it is observed that the estimated coefficients of $Treat_i \times Time_t$ are statistically significantly positive, which indicates that hosting comprehensive sports events significantly increases the level of green technological innovation, sports industry development, and foreign investment in the host city. Meanwhile, from columns (2), (3), (5), and (6), it can be found that the estimated coefficients of $Treat_i \times Time_t$, INN, and SI are both positive and significant, which indicates that organizing sports events can achieve green and low-carbon development of the host city by increasing the level of technological innovation and developing the sports industry. However, as shown in columns (8) and (9), the estimated coefficients of foreign direct investment (FDI) are not significant, which illustrates that the green development effect of attracting foreign investment does not support that, and although hosting sports events can attract foreign investment, it does not achieve the green and low-carbon development. After reviewing the literature (Baron and Kenny, 1986; Hille et al., 2019; Pan et al., 2020; Yu et al., 2022b), we concluded that a possible explanation is that there are both inhibitory and promotional effects of FDI on the environment in China. The inhibitory effect is mostly realized through the investment scale of FDI, while the promotional effect is realized by technological upgrading. In other words, FDI generated more energy consumption, carbon emissions, and environmental pollution through the scale effect when it created agricultural, industrial, and service companies in the host country. However, the companies invested by FDI also brought advanced production technology to the host country, which helped improve energy utilization efficiency and reduce environmental pollution through technological progress. Therefore, the FDI attracted by sports events may have both inhibitory and promotional effects. The superposition of the two types of effects leads to the fact that FDI does not have a significant impact on the environmental performance. Therefore, FDI induced by comprehensive sports events did not significantly improve the GTFP and CE of the host city.

TABLE 8 | Mechanism identification.

	Innovation			Sports industry			Foreign direct investment		
	INN	*GTFP*	*CE*	*SI*	*GTFP*	*CE*	*FDI*	*GTFP*	*CE*
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
$Treat_i \times Time_t$	0.319***	0.125***	0.145***	0.062***	0.129***	0.140***	0.309*	0.133***	0.148***
	(2.72)	(7.43)	(10.04)	(4.78)	(7.59)	(9.97)	(1.77)	(7.85)	(10.01)
INN		0.021***	0.014***						
		(7.36)	(6.47)						
SI					0.005***	0.003***			
					(5.60)	(4.01)			
FDI								0.044	0.036
								(0.26)	(0.51)
CV	YES	YES	YES	YES	YES	YES	YES	YES	YES
W×CV	YES	YES	YES	YES	YES	YES	YES	YES	YES
City FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
N	3,892	3,892	3,892	3,892	3,892	3,892	3,892	3,892	3,892
Log-l	4,379.6	3,183.8	3,873.6	3,575.4	3,181.0	3,874.9	5,031.2	3,132.1	3,876.5
Pseudo-R^2	0.0138	0.0155	0.0074	0.0099	0.0152	0.0070	0.0525	0.0067	0.0064

6 HETEROGENEITY ANALYSIS

Since cities at different levels may have different low-carbon green development capabilities (Wang et al., 2022), there is a possibility of heterogeneity in the environmental effects of comprehensive sports events. Meanwhile, considering the differences in preparation requirements and event scale between different ranks of events (Malchrowicz-Mośko and Poczta, 2018), those discrepancies may lead to heterogeneity in the environmental performance. Therefore, to check the possible heterogeneous characteristics for the environmental effects of comprehensive sports events in terms of the development level of the host city and the rank of the event, the spatial difference-in-difference-in-differences (SDDD) model is employed in this study to conduct the analysis, and its model is set as follows:

$$
\begin{aligned}
green_{it} = \alpha + \rho \sum\nolimits_j w_{ij} green_{it} + \beta_1 Treat_i \times Time_t \\
+ \theta_1 \sum\nolimits_j w_{ij} Treat_i \times Time_t \\
+ \beta_2 Treat_i \times Time_t \times \mathrm{City}_i \\
+ \theta_2 \sum\nolimits_j w_{ij} Treat_i \times Time_t \times \mathrm{City}_i + \boldsymbol{\gamma X_{it}} \\
+ \boldsymbol{\delta} \sum\nolimits_j w_{ij} \boldsymbol{X_{jt}} + \mu_i + v_t + \varepsilon_{it}
\end{aligned} \tag{10}
$$

$$
\begin{aligned}
green_{it} = \alpha + \rho \sum\nolimits_j w_{ij} green_{it} + \beta_1 Treat_i \times Time_t \\
+ \theta_1 \sum\nolimits_j w_{ij} Treat_i \times Time_t \\
+ \beta_2 Treat_i \times Time_t \times \mathrm{Rank}_i \\
+ \theta_2 \sum\nolimits_j w_{ij} Treat_i \times Time_t \times \mathrm{Rank}_i + \boldsymbol{\gamma X_{it}} \\
+ \boldsymbol{\delta} \sum\nolimits_j w_{ij} \boldsymbol{X_{jt}} + \mu_i + v_t + \varepsilon_{it}
\end{aligned} \tag{11}
$$

In **Eqs 10** and **11**, the variables are the same as those in **Eq. 1** except for City_i and Rank_i. City_i is a dummy variable to define the city development level, and City_i is assigned a value of 1 if city i is a first-tier city and 0 if it is not. Rank_i is a dummy variable for defining the sports event ranking, and Rank_i is valued as 1 if the sports event held in city i is an international sports event, and Rank_i is valued as 0 if the event is a domestic sports event.

TABLE 9 | Heterogeneity analysis of green and low-carbon development effects in sports events.

	GTFP		*CE*	
	(1)	(2)	(3)	(4)
$Treat_i \times Time_t \times \mathrm{City}_i$	0.265***		0.289***	
	(7.39)		(9.73)	
$Treat_i \times Time_t \times \mathrm{Rank}_i$		0.186***		0.203***
		(7.70)		(10.12)
$W \times Treat_i \times Time_t \times \mathrm{City}_i$	0.850***		0.375***	
	(2.89)		(2.62)	
$W \times Treat_i \times Time_t \times \mathrm{Rank}_i$		1.212***		0.747***
		(4.80)		(3.57)
CV	YES	YES	YES	YES
W×CV	YES	YES	YES	YES
City FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
N	3,892	3,892	3,892	3,892
Log-l	3,133.1	3,141.6	3,810.1	3,817.8
Pseudo-R^2	0.0573	0.0614	0.0703	0.0701

Note: Referring to the conventional practice, the first-tier cities include Beijing, Shanghai, Guangzhou, and Shenzhen. Refer to Table 1 for the classification of race ranks.

Table 9 documents the results of the heterogeneity analysis. From column (1) and column (3), it is evident that the direct and spatial spillover effects of hosting comprehensive sports events in first-tier cities on GTFP and CE are higher than those of other cities. This may be due to the greater technological innovation capability of first-tier cities than other cities, and hosting sports events is more likely to achieve improvements in GTFP and CE through technological innovation. Meanwhile, from column (2) and column (4), it is noticeable that the direct and spatial spillover effects of international sports events on environmental performance improvement are greater in comparison with domestic sports events. This may be due to the preparation requirements and higher influence of international comprehensive sports events, which are more likely to stimulate the technological innovation and sports industry development of the hosting regions, which in turn leads to their green and low-carbon development.

7 CONCLUSION AND DISCUSSION

Using the annual panel data of 278 cities in China from 2006 to 2019, this study empirically examines the effects of hosting comprehensive sports events on green total factor productivity and carbon emission efficiency through the SDID model. The main conclusions are as follows:

1. Hosting comprehensive sports events can significantly improve the green total factor productivity and carbon emission efficiency of host cities, and this result still holds after robustness tests using the traditional DID model, synthetic DID model, and panel tobit model.
2. The spatial spillover effect of comprehensive sports events on green total factor productivity and carbon emission efficiency is also statistically significant. It indicates that hosting comprehensive sports events is not only conducive to guiding the host city to develop in a green and low-carbon direction but also generates significant positive externalities to other cities in the neighborhood. The abovementioned observations still hold after robustness tests utilizing the PSM-SDID model, excluding the interference of other policies, replacing the spatial weight matrix, and reducing the sample size.
3. Mechanism identification suggests that hosting comprehensive sports events can significantly strengthen the host city's technological innovation capacity, promote its sports industry, and attract more foreign direct investment. Comprehensive sports events can realize the green and low-carbon development of the host city by improving its science and technology innovation capacity and sports industry development. However, the FDI attracted by the sports events did not contribute to the green total factor productivity and carbon emission efficiency of the host city.
4. Heterogeneity analysis shows that international comprehensive sports events and sports events hosted by first-tier cities play a more obvious role in promoting the green total factor productivity and carbon emission efficiency of the host city and its neighboring regions.

Based on the abovementioned findings, this study presents the following policy implications. First, from 2022 to 2023, China will host a number of comprehensive sports events, and the host cities should take the events as an opportunity to effectively optimize urban transportation infrastructure, promote urban renovation, and promote green and low-carbon development of urban construction. Second, the crucial way to reinforce the environmental effect of comprehensive sports events is to strengthen the ability of technological innovation and promote the development of the sports industry. The hosts should attach importance to scientific and technological innovation, take the hosting of the event as an opportunity to develop technological innovation activities, and strive to form a series of urban scientific innovation clusters, through which the clusters can effectively enhance the innovation capacity. Simultaneously, we should put stress on and direct the development of the sports industry, make reasonable utilization of the "legacy of the event," improve the post-event utilization efficiency of the event venues on the basis of adequate planning, and give impetus to the development of the sports service industry in a low-carbon direction. Third, it is recommended to fulfill the role of comprehensive sports events in attracting foreign investment, enforce environmental supervision of foreign investment, correctly guide the flow of all kinds of foreign investment to high-tech and low-energy industries, maximize the "promotion effect" of foreign investment on environmental performance, and promote the long-term green and low-carbon development of the host city. Finally, to build an information-sharing platform, cities should publicize the concept of low-carbon environmental protection and raise public environmental awareness with the help of events. Meanwhile, it can also carry out full linkages in technological innovation and pollution prevention and control, so as to take advantage of the spillover effect of comprehensive sports events even better.

At last, there are some inevitable shortcomings in this study. First, in the heterogeneity analysis section, this study only classifies comprehensive sports events into two categories: international events and domestic events. However, due to the restrictions of the event rank and economic development base of the host city, each event can be regarded as a quasi-natural experiment, and a more detailed analysis method is needed to identify the policy effects of each event. Second, in terms of the spatial weight matrix, only the inverse geographic distance weight matrix and the adjacency matrix are chosen to describe the interconnection between cities. The two classical spatial weight matrices do not take into account the influence of factors such as economic links and transportation networks on the intercity linkages; thus, the identification of spatial spillover effects in this study may not be comprehensive. Furthermore, due to the constraints of the research scale, this study only assesses the overall impact of comprehensive sports events on host cities and does not identify the impact of sports events on the spatial pattern changes within cities and the evolution of economic centers of gravity. Therefore, based on the abovementioned shortcomings, further research can be embarked on the following three aspects:

1. The treatment effect of a single comprehensive sports event can be identified by the synthetic control method. This method is suitable for assessing policies with only a few or unique "pilots" (Abadie et al., 2010), which helps improve the knowledge of the existing literature on the environmental effects of sports events.
2. The spatial weight matrix can be further analyzed by creating an economic weight matrix and a traffic time weight matrix. Of course, this also does not fully reflect the spatial correlation between the two cities, and the actual situation may be more complicated.

3. In future studies, a further combination of statistical data at district and county levels with satellite remote sensing data can depict the impact of comprehensive sports events on the internal development of cities more meticulously. The authors believe this will be an interesting field of research.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**; further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

XZ conceptualized the study and designed the methodology. XZ and YW designed the software, performed formal analysis and data curation, visualized the study, wrote and prepared the original draft, and wrote, reviewed, and edited the manuscript. YW supervised the study. All authors have read and agreed to the published version of the manuscript.

FUNDING

This research was supported by the Fundamental Research Funds for the Central Universities, Southwestern University of Finance and Economics (JBK2102035), and the National Natural Science Foundation of China (71503212).

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.946993/full#supplementary-material

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