Global NEST Journal, Vol 26, No X, pp 1-7

The impact of climate change on the development of circular economy in China: A perspective on green total factor productivity

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Received: 17/03/2024, Accepted: 13/04/2024, Available online: 15/04/2024
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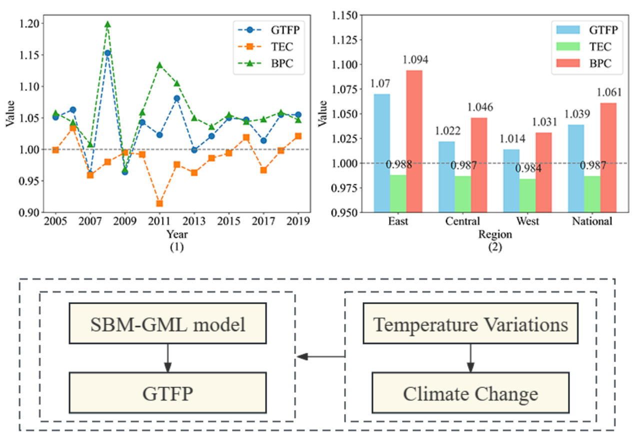
https://doi.org/10.30955/gnj.005923

Graphical abstract



Abstract

In the process of China's transition to high-quality development, the circular economy, as a key strategy for achieving green growth, is of significant importance in addressing climate change and promoting sustainable development. This study employs the SBM-GML model to analyze the Green Total Factor Productivity (GTFP) of 30 provinces in China from 2005 to 2019, exploring the influence of climate change on the development of the circular economy. The research finds that although China's GTFP shows an overall upward trend, indicating some achievements in the circular economy, the performance in the eastern region significantly outperforms other regions, with technological progress being the primary driver of growth. The impact of climate change on GTFP varies with temperature changes and exhibits differentiated characteristics in different regions. Based on these findings, this paper puts forward a series of policy recommendations aimed at strengthening the practice of the circular economy, enhancing resource utilization efficiency, reducing greenhouse gas emissions, and addressing the challenges of climate change through promoting green low-carbon development, optimizing industrial structure, and formulating adaptive environmental regulations.

Keywords: Circular economy; climate change; green total factor productivity; technological progress

1. Introduction

With the increasingly severe global climate change issues, academia and policymakers are paying more attention to its impact on economic activities (Enríquez-de-Salamanca *et al.* 2017; Vrontisi *et al.* 2022; Yagatich *et al.* 2022). Climate change not only threatens the stability of the global ecosystem but also poses new challenges to the development models of various countries (Kirchner *et al.* 2015; Tamaki *et al.* 2017). Especially in countries like China, as the world's largest emitter of carbon dioxide (Zhang *et al.* 2019), its impact on climate change is significant. This compels China to consider how to achieve a green and sustainable development path while pursuing economic growth.

The circular economy, as a key strategy for achieving green growth, is of significant importance in addressing climate change and promoting sustainable development (Al-Jayyousi *et al.* 2022; Hailemariam and Erdiaw-Kwasie 2023; Sajid *et al.* 2024). This study aims to deeply analyze the impact of climate change on China's Green Total Factor Productivity (GTFP), exploring how climate change affects economic efficiency and environmental quality through technological innovation and efficiency improvement under different climate conditions. By analyzing panel data from 2005 to 2019 for 30 provinces in China, this study attempts to fill the gap in existing literature regarding the relationship between climate change and GTFP, particularly considering unexpected outputs, and discussing strategies for addressing climate change.

The significance of this study lies not only in providing new evidence for understanding the micro-level impact of climate change on the Chinese economy but also in providing important guidance for formulating policies to address climate change. Through this study, we can gain a deeper understanding of the heterogeneous impacts of climate change on economic development in different regions, provide scientific basis for local governments to formulate adaptive policies, and further enhance China's role in global climate governance.

Although there have been extensive studies on the economic impacts of climate change (Liu *et al.* 2019; Vale

2016), research on how climate change affects economic efficiency and environmental quality under the background of green total factor productivity is still insufficient. Particularly in large economies like China, the impact of climate change exhibits high complexity and regional differences. This study, by constructing an SBM-GML model that includes unexpected outputs, systematically measures GTFP, aims to analyze the relationship between climate change and GTFP, providing a new perspective for research in this field.

The marginal contribution of this study is that we provide a comprehensive analytical framework that closely integrates climate change, technological innovation, and green total factor productivity, offering new strategies for understanding and addressing climate change. Our research not only enables a more accurate assessment of the impact of climate change on the Chinese economy but also provides recommendations for policymakers on how to improve green total factor productivity through technological innovation and efficiency improvement, thereby promoting green transformation and sustainable development of the economy globally.

2. Literature review

Climate change has profound impacts on the global environment and socio-economic systems. In recent years, academic research on climate change has gradually deepened, covering multiple fields such as agriculture, water resources, ecosystems, energy consumption, and industrial output. This paper reviews the research progress of climate change in various fields and explores the impact of climate change on Green Total Factor Productivity (GTFP), aiming to provide theoretical support for relevant policy formulation. In the field of agriculture, the impact of climate change on crop yields has become a research hotspot. Demirdogen *et al.* (2024) found that wheat production in Turkey significantly decreased by 9% after a temperature rise of 1.5 degrees Celsius. Additionally (Demirdogen *et al.* 2024), Hristov *et al.* (2024) analyzed the potential impact of climate change on the EU agricultural market, indicating that climate change may offset the negative impact on crop production through market and trade adjustments (Hristov *et al.* 2024). Water resource management is also an important aspect of climate change impacts. Cotera *et al.* (2024) studied the impact of climate change adaptive water management on agriculture in Lower Saxony, finding that changing crop types and improving irrigation efficiency have significant effects on reducing irrigation water demand and energy consumption (Cotera *et al.* 2024). In terms of energy consumption, the increase in extreme climate events caused by climate change, such as heatwaves and droughts, may affect energy supply and prices (van der Wiel *et al.* 2024). Furthermore, the impact of climate change on infrastructure cannot be ignored. For example, Soleimani-Chamkhorami *et al.* (2024) evaluated the impact of climate change on the life cycle cost of railway infrastructure in northern Sweden, finding that the life cycle cost under future climate scenarios would be about 11% higher than that without climate impacts (Soleimani-Chamkhorami *et al.* 2024). The impact of climate change on industrial output has also received attention. Arias *et al.* (2024) studied the impact of climate change on droughts in Central South America, finding that climate change may reduce water supply in the region, exacerbating agricultural droughts (Arias *et al.* 2024).

Although research on climate change has covered multiple fields, studies on the impact of climate change on green total factor productivity are relatively scarce. Green total factor productivity is an important indicator for measuring economic growth and environmental sustainability, considering factors such as resource input and environmental pollution. The value of this study lies in filling this research gap, providing a new perspective for understanding the comprehensive impact of climate change on economic activities, and offering empirical evidence for formulating policies to address climate change.

3. Research hypothesis

The impact of climate change on Green Total Factor Productivity (GTFP) manifests primarily in several aspects. Firstly, it directly affects the output of the agricultural and industrial sectors (Fagbemi *et al.* 2023; Hanslow *et al.* 2014; Khan *et al.* 2020). Excessive or inadequate temperatures and precipitation influence crop growth, thus reducing agricultural productivity. Additionally, climate warming may lead to an increase in extreme weather events such as hurricanes and heavy rainfall, causing production interruptions or equipment damage, consequently lowering industrial output. Secondly, climate change affects GTFP through the labor market channel (Huang *et al.* 2020; Malerba. and Wiebe 2021). Weather conditions directly impact work efficiency, while climate instability may lead to health issues, indirectly affecting labor productivity. Moreover, climate change also influences labor costs and population migration, thereby altering the quantity of labor in different regions and affecting economic growth. Thirdly, climate change affects GTFP through the energy consumption channel (Hunjra *et al.* 2022; Katircioglu 2014). Fluctuations in energy prices and supply-demand changes caused by climate change affect stable economic growth. National emission reduction measures and the promotion of clean energy alter industrial structures, impacting economic growth patterns. Finally, government environmental regulation is also a significant factor influencing the impact of climate change on GTFP (Song *et al.* 2018; Yang 2022). Its effects can be positive, negative, or uncertain, necessitating the establishment of a flexible regulatory framework tailored to individual industry standards. This approach avoids excessively raising environmental regulatory standards and promotes the sustainable development of the green economy. Based on this premise, the following hypothesis is proposed:

H1: The impact of climate change on GTFP is significant and may exhibit positive or negative effects.

4. Materials and methods

4.1. Data source

The data used in this study cover economic and climate information for 30 provinces in China from 2005 to 2019 (excluding Tibet, Hong Kong, Macau, and Taiwan), totaling

450 samples. Economic data mainly come from the "China Statistical Yearbook," the China Economic Information Network statistical database, and the statistical yearbooks of various provinces. Some missing data were supplemented through linear interpolation. Climate data are sourced from the China National Meteorological Science Data Sharing Service Platform.

4.2. Variable description

Dependent Variable (Green Total Factor Productivity): In this study, the dependent variable is Green Total Factor Productivity (GTFP), which measures how effectively provinces in China save resources and reduce environmental pollution while achieving economic growth. GTFP calculation integrates input variables (labor, capital, and energy) and output variables (expected output and unexpected output). Labor input is measured by the number of employees at the end of the year, capital input is calculated through total fixed capital formation and perpetual inventory method, and energy input is represented by total electricity consumption. Expected output is based on regional GDP, adjusted for price levels, while unexpected output includes wastewater, sulfur dioxide emissions, and industrial solid waste generation, reflecting the negative environmental impacts of economic activities. By employing the SBM-GML model incorporating unexpected output, efficiency and effectiveness in promoting sustainable development among provinces can be more comprehensively evaluated. The SBM-GML model integrates Slacks-Based Measure (SBM) and Global Malmquist-Luenberger (GML) methods, considering non-desirable outputs such as wastewater, SO2 emissions, and industrial solid waste generation, to assess the efficiency and effectiveness of provinces in promoting sustainable development. This enables the model to comprehensively account for environmental negative impacts when evaluating productivity and efficiency.

Independent Variable (Climate Change): In this study, the independent variable is climate change, specifically quantified through temperature variations. Climate change is regarded as a statistical description of long-term climate trends, while temperature changes refer to short-term temperature fluctuations. To capture the impact of climate change on GTFP, this paper adopts a method based on temperature distribution functions to identify the causal effect of climate change (Deryugina. and Hsiang 2014). The study constructs temperature interval variables TC_{it}^{n}, which represent the number of days the average daily temperature falls into the nth temperature interval for the ith province in the tth year. Temperature intervals are segmented into 9 categories, each spanning 6°C, covering a range from extreme cold to extreme heat (King *et al.* 2020). This segmentation method allows for the analysis of potential impacts of different temperature intervals on GTFP, thus more accurately assessing the long-term effects of climate change on economic activities and environmental efficiency.

In this study, to more accurately assess the impact of climate change on Green Total Factor Productivity, a series of control variables are considered, including Economic Development Level (EDL), Government Intervention Level (GIL), Industrial Structure (IS), and Environmental Regulation (ER). Economic development level is reflected in the logarithmic form of per capita GDP, indicating regional economic strength and the amount of disposable resources. Government intervention level is measured by the proportion of fiscal expenditure to GDP, reflecting the government's regulatory role in the market economy and its potential impact on resource allocation efficiency. Industrial structure is represented by the proportion of the tertiary industry to GDP, demonstrating the rationality of resource allocation and the quality of regional economic development. Lastly, environmental regulation is indicated by the proportion of investment in industrial pollution control to GDP, which may stimulate enterprise innovation, improve green production efficiency, or increase enterprise costs, affecting production efficiency. The comprehensive consideration of these control variables helps to better understand the factors influencing the growth of Green Total Factor Productivity.

4.3. Model setting

This study employs a fixed-effects model to analyze the impact of climate change on GTFP. The fixed-effects model effectively controls individual characteristics that do not vary over time and time characteristics shared by all observation units, thus reducing endogeneity bias. The model is set as follows:

$$GTFP_{it} = \beta_0 + \sum_{n=1}^{N} \beta_n \, \mathrm{TC}_{it}^{n} + \mathrm{controls}_{it} + u_i + v_t + \varepsilon_{it} \quad (1)$$

In the model, GTFP serves as the dependent variable, and climate change is measured through temperature interval variables of average daily temperature. Control variables are included, along with individual and time fixed effects, to control for province-specific characteristics and common time trends, accurately assessing the long-term impact of climate change on green production efficiency.

5. Results

5.1. Exploratory data analysis

In the exploratory data analysis of Green Total Factor Productivity (GTFP) for 30 provinces in China from 2005 to 2019, as depicted in Figure 1, we observe an overall upward trend in GTFP, with an average value of 1.039, indicating a 3.9% increase in green total factor productivity over these 15 years. Except for slight declines in 2007 2009, and 2013, GTFP indices for other years are mostly above 1, reflecting that green productivity was in a growth stage for most of the time. Further analysis reveals that the mean index of Technological Efficiency Change (TEC) is 0.987, indicating a slight overall decrease in technological efficiency (1.3%), while the mean index of Bias Change (BPC) is 1.061, indicating an overall increase in bias change by 6.1%. This underscores the crucial role of technological progress in driving the growth of Green Total Factor Productivity, especially in the eastern region where both GTFP indices and average annual growth rates exceed the national average, demonstrating that technological progress primarily drives the growth of green productivity in the eastern region. In contrast, the lowest GTFP levels are observed in the western region, indicating relatively weak coordination between economic development and environmental protection. Overall, this analysis highlights the importance of technological progress in promoting the enhancement of Green Total Factor Productivity in China and reveals differences in green production efficiency among different regions.

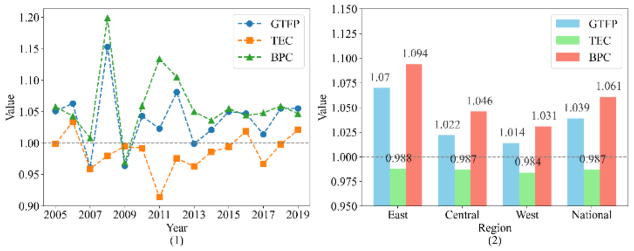


Figure 1. Changes in GTFP index data

Table 1 provides a descriptive statistical analysis covering the Green Total Factor Productivity (GTFP) and its related variables across 30 provinces in China from 2005 to 2019. The average value of GTFP is 1.039, indicating an average growth of 3.9% during the study period. The temperature interval variable displays the distribution of days across different temperature ranges, with an average of 38.902 days between 0°C to 6°C, being the highest. Additionally, the temperature interval data indicates fewer days under extreme climate conditions, and significant temperature differences among provinces, reflecting China's extensive climate diversity and its potential impact on green production efficiency. The average values for Economic Development Level (EDL), Government Intervention Level (GIL), Industrial Structure (IS), and Environmental Regulation (ER) are 10.411, 0.224, 0.457, and 0.001, respectively. These statistical findings reveal the trends and regional disparities in green production efficiency and its influencing factors across provinces in China.

Table 1. Descriptive statistics

Variable	Size	Mean	SD	Min	Max
GTFP	450	1.039	0.296	0.338	2.969
<-12°C	450	7.956	20.257	0.000	101.000
-12°C ~ -6°C	450	13.829	20.175	0.000	82.000
-6°C ~ 0°C	450	25.827	26.308	0.000	86.000
0°C ~ 6°C	450	38.902	21.515	0.000	84.000
6°C ~ 12°C	450	54.509	20.680	0.000	110.000
12°C ~ 18°C	450	63.689	17.949	16.000	128.000
18°C ~ 24°C	450	86.120	26.910	0.000	196.000
24°C ~ 30°C	450	68.384	51.890	0.000	242.000
>30°C	450	5.984	9.142	0.000	51.000
EDL	450	10.411	0.643	8.560	11.994
GIL	450	0.224	0.098	0.079	0.628
IS	450	0.457	0.093	0.297	0.837
ER	450	0.001	0.001	0.000	0.010

5.2. Baseline regression

In the baseline regression analysis of this study, we employed a two-way fixed effects model to investigate the impact of climate change on the Green Total Factor Productivity (GTFP) across 30 provinces in China. The regression results in Table 2 reveal significant variations in the influence of climate change on GTFP across different temperature intervals after controlling for time and individual effects. Specifically, when the daily average temperature is below 6°C, climate change exhibits a negative effect on GTFP. Particularly noteworthy is the pronounced negative impact observed in temperature intervals below -12°C, where for every 1% increase in cold days, GTFP significantly decreases by 0.082 units. Conversely, within the temperature range of 6°C to 30°C, the impact of climate change on GTFP turns positive, especially notable within the interval of 18°C to 24°C, where for every 1% increase in warm days, GTFP increases by 0.104 units. These findings suggest that within favorable temperature ranges, climate change may enhance green production efficiency by boosting labor productivity and reducing energy consumption.

Further analysis reveals that within temperature intervals exceeding 30°C, climate change once again exerts a negative impact on GTFP. For every 1% increase in hot days, GTFP decreases by 0.013 units. This implies that high temperatures may adversely affect green production efficiency by influencing workers' health and productivity, as well as increasing the consumption of cooling energy. Overall, the baseline regression results of this study highlight the complex impact of climate change on Green Total Factor Productivity, emphasizing the necessity of considering the specific effects of different temperature intervals on economic activities when formulating climate change adaptation strategies.

Table 2. Baseline model

Variable	GTFP	Variable	GTFP
<-12°C	-0.082***	18°C ~ 24°C	0.104*
	(-5.33)		(1.84)
-12°C ~ -6°C	-0.024	24°C ~ 30°C	0.063**
	(-0.49)		(2.61)
-6°C ~ 0°C	-0.046	>30°C	-0.013
	(-1.61)		(-0.38)
0°C ~ 6°C	-0.062**	Constant	-1.504
	(-2.29)		(-1.34)
6°C ~ 12°C	0.115	Controls	Y
	(1.09)	Province	Y
12°C ~ 18°C	0.222	Time	Y
	(1.73)	Size	450

Note: ** denotes significance level, t-values are in parentheses*

5.3. Robustness checks

To validate the robustness of the baseline regression results, this study employed two methods for robustness checks: changing the dependent variable and altering the sample size. Firstly, considering the close relationship between green economic development and technological innovation, we selected the Technological Progress Change Index (BPC) as an alternative variable for Green

Total Factor Productivity (GTFP). In the baseline regression, GTFP served as the dependent variable, whereas in the robustness checks, we replaced GTFP with BPC for regression analysis. The results in Table 3 indicate that the regression coefficients across different climate intervals maintain similar characteristics even after replacing the dependent variable, suggesting the model's robustness against outliers and extreme values, thus confirming the reliability of the baseline regression results.

Secondly, the size of the sample has a significant impact on the stability of statistical inferences. To examine the effect of changes in sample size on the regression results, we conducted robustness checks by reducing the sample size. Specifically, we removed the data from the year 2019, reducing the sample size from 450 to 420 observations. The regression results demonstrate that even after the reduction in sample size, the sign and significance of the regression coefficients across various climate intervals remain consistent with the results from the full sample, further corroborating the robustness of the baseline regression results.

In summary, through robustness checks involving changing the dependent variable and altering the sample size, we have confirmed the reliability and stability of the baseline regression results. These robustness check results enhance our understanding of the relationship between climate change and its impact on Green Total Factor Productivity, providing a solid empirical basis for relevant policy formulation.

Table 3. Robustness analysis

Variable	BPC	GTFP
<-12℃	-0.092***	-0.085***
	(-5.87)	(-5.83)
-12℃ ~ -6℃	-0.050	-0.001
	(-1.08)	(-0.02)
-6℃ ~ 0℃	-0.053**	-0.042
	(-2.30)	(-1.58)
0℃ ~ 6℃	-0.052*	-0.075***
	(-1.87)	(-3.23)
6℃ ~ 12℃	0.135	0.088
	(1.33)	(0.83)
12℃ ~ 18℃	0.267*	0.171
	(2.12)	(1.44)
18℃ ~ 24℃	0.113**	0.102*
	(2.22)	(1.87)
24℃ ~ 30℃	0.071**	0.076***
	(2.51)	(3.92)
>30℃	-0.018	0.006
	(-0.47)	(0.32)
Constant	-3.081**	-1.034
	(-2.46)	(-0.92)
Controls	Y	Y
Province	Y	Y
Time	Y	Y
Size	450	420

Note: *Same table as above*

6. Discussion

In the analysis of the heterogeneity in the relationship between climate change and Green Total Factor Productivity (GTFP) in northern and southern regions of China, we observed significant differences in the impact of climatic conditions on economic growth in these areas. The southern region benefits from higher temperatures and ample rainfall, conducive to the development of industries such as water resources management and port logistics, while also exhibiting faster growth in the service and tourism sectors. In contrast, the northern region, despite its advantages in industries like coal, electricity, and heavy manufacturing, faces limitations due to water scarcity, resulting in a slowdown in economic growth in certain areas.

As evidenced by the regression results in Table 4, in the colder temperature intervals (below -12°C, -6 to 0°C, and 6 to 12°C), climate change has a significant negative impact on GTFP in the northern region, particularly under extreme cold conditions where GTFP decreases significantly with an increase in cold days. This may be attributed to the increased heating demand and restricted production activities in the northern region during low-temperature conditions. Conversely, in the warm temperature interval of 18 to 30°C, climate change shows a significant positive effect on GTFP, indicating that favorable temperature conditions contribute to improved production efficiency and energy utilization efficiency, thereby promoting the growth of green productivity.

The analysis of the southern region reveals that climate change also negatively affects GTFP in the colder temperature intervals (-12 to -6°C and 0 to 6°C). However, in the warmer temperature intervals (6 to 12°C, 12 to 18°C, and 24 to 30°C), the positive impact of climate change on GTFP is more pronounced. Particularly in the temperature interval of 18 to 24°C, the enhancement of GTFP is most significant, possibly due to the higher labor productivity and lower energy consumption in this temperature range in the southern region. Although the temperature interval of 24 to 30°C shows a positive impact, it does not pass the significance level test, indicating that the positive effect under high-temperature conditions may not be as significant as in the 18 to 24°C interval.

Overall, the heterogeneity analysis between northern and southern regions reveals that the impact of climate change on Green Total Factor Productivity exhibits different characteristics in different regions. The northern region faces greater challenges under cold conditions, necessitating attention to technological innovation and policy adjustments to enhance cold resistance and energy efficiency. The southern region demonstrates better green production efficiency in warmer temperature intervals but still needs to be cautious of the negative impacts of high temperatures. These findings provide important guidance for formulating targeted climate change adaptation strategies and promoting regional green development, contributing to achieving nationwide green growth and continuous improvement of the ecological environment.

Table 4. Heterogeneity Analysis

Variable	National	Northern	Southern
	GTFP	GTFP	GTFP
<-12℃	-0.082***	-0.093***	-0.002
	(-5.33)	(-3.23)	(-0.001)
-12℃ ~ -6℃	-0.024	-0.034	-0.141**
	(-0.49)	(-0.89)	(-2.15)
-6℃ ~ 0℃	-0.046	-0.118***	-0.052
	(-1.61)	(-3.70)	(-1.25)
0℃ ~ 6℃	-0.062**	-0.089	-0.092**
	(-2.29)	(-0.40)	(-2.21)
6℃ ~ 12℃	0.115	-0.212**	0.232**
	(1.09)	(-2.40)	(2.25)
12℃ ~ 18℃	0.222	-0.133	0.391*
	(1.73)	(-1.03)	(1.89)
18℃ ~ 24℃	0.104*	0.057***	0.321
	(1.84)	(3.36)	(1.41)
24℃ ~ 30℃	0.063**	0.026	0.120*
	(2.61)	(1.20)	(1.98)
>30℃	-0.013	-0.102	0.055
	(-0.38)	(-1.51)	(1.42)
Constant	-1.504	0.900	-2.073
	(-1.34)	(0.65)	(-0.79)
Controls	Y	Y	Y
Province	Y	Y	Y
Time	Y	Y	Y
Size	450	225	225

Note: *Same table as above*

7. Conclusion and policy implications

7.1. Conclusion

This study analyzed panel data from 30 provinces in China from 2005 to 2019, using the SBM-GML model incorporating unexpected outputs to calculate the Green Total Factor Productivity (GTFP) of each province and decomposing it into technological progress and efficiency changes. The study found that overall GTFP in China exhibited an upward trend, increasing by an average of 3.9%, with technological progress being the primary driver of growth. Regional analysis revealed the leading role of the eastern region and the heterogeneous impacts of temperature intervals on GTFP in the north and south. Additionally, the study found that the impact of climate change on GTFP varies with temperature, with both low and high temperatures negatively affecting productivity, while moderate temperature intervals are conducive to productivity improvement. These findings provide new insights into the impact of climate change on economic activities and offer empirical evidence for formulating climate change mitigation policies.

Based on the research conclusions, the following policy suggestions are proposed in this paper: Firstly, efforts should be made to promote green and low-carbon development by improving energy efficiency, reducing greenhouse gas emissions, and adjusting energy structures to enhance GTFP. Secondly, there is a need to deepen industrial restructuring and vigorously develop green and low-carbon industries. This can be achieved by providing policy incentives and investment guidance to facilitate the transformation of traditional industries towards green practices, thus achieving a harmonious balance between economic growth and environmental protection. Finally, it is recommended that local governments formulate differentiated environmental regulations and adopt adaptive measures based on the regional impacts of climate change to maintain a balance between environmental sustainability and economic development, thereby jointly promoting green and sustainable economic growth.

7.2. Research limitations and future directions

While this study sheds light on the impact of climate change on the development of China's circular economy, it has certain limitations. Firstly, the use of provincial-level data may not capture the nuances of variations within regions, potentially affecting the accuracy of assessing the impact of climate change. Secondly, the SBM-GML model used, although comprehensive, may not account for all factors influencing GTFP, such as regional policies and market dynamics. Additionally, focusing on temperature as a proxy for climate change overlooks other critical climate variables like precipitation patterns and extreme weather events, which could significantly affect GTFP.

Future research should consider incorporating a broader range of climate variables for a more holistic understanding of their impact on GTFP. Moreover, utilizing more detailed geographical data, such as city or county-level information, could better understand the localized effects of climate change. Studies could also explore the circular economy's adaptability and resilience to climate change, including the role of technological innovation and policy interventions in mitigating adverse effects on GTFP.

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