Original Research

Regional and Urban-Rural Differences in Carbon Emissions of Chinese Residents: Dynamic Evolution and Structural Decomposition

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Abstract

Promoting energy conservation and emission reduction and achieving carbon peak and carbon neutrality is a systematic project that requires the joint efforts of the whole society. Accurate measurement and analysis of the basic state and spatial correlation of urban-rural carbon emissions is the basic prerequisite for formulating the "double carbon" policy. This study aims to analyze the regional disparities in urban-rural carbon emissions in China from 2005 to 2021 and to assess the degree of inequality in such emissions. The IPCC methodology was employed to calculate the carbon emissions of urban and rural areas in each province. The Theil coefficient was utilized to delineate the spatial evolution of urban-rural carbon emission disparities in China. The decomposition of the Theil index was adopted to investigate the sources and shifts in spatial disparities. The local Moran's I was applied to analyze the spatial correlation of urban and rural carbon emissions in China. Additionally, the Theil index was employed to measure the degree of urban-rural carbon emission inequality in each province. Based on the natural breakpoint grading method, the spatial heterogeneity of the urban-rural carbon emission inequality across various Chinese provinces was scrutinized. Findings: China's urban-rural carbon emission inequality exhibited a three-phase transformation, predominantly influenced by intra-regional factors, with the Northeast region making a significant contribution. Spatially, eastern coastal and inland provinces like Hebei and Shandong exhibited higher carbon emissions, whereas western provinces such as Gansu and Qinghai showed lower levels. The majority of regions witnessed their emission disparities transition from mid-low to mid-high. However, challenges related to insufficient and imbalanced development remained prominent. Specifically, economically advanced regions like Guangdong and Jiangsu manifested substantial emission disparities, while western provinces like Sichuan displayed smaller disparities.

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Introduction

Climate change is taking a massive toll on human life and economic activity worldwide. In the past few years, the global average temperature has continuously created a record high since the observation of the record, and the probability of various abnormal weather has also increased considerably [1]. It is generally believed that increasing greenhouse gases in the atmosphere are to blame for the abnormal climate. Since the initiation of its economic reforms, China's economic performance on the global stage has been exceptional, serving as a developmental paradigm for numerous countries and regions. This growth represents not merely numerical advancement but signifies a profound societal transformation and material progression. Infrastructure development has been extensively undertaken throughout the nation, forging connections between cities and rural areas, thus facilitating economic fluidity and exchange. Such infrastructural endeavors have not only resulted in tangible assets but have also been instrumental in laying a solid foundation for the nation's sustained growth and the welfare of its citizens [2]. However, such rapid economic development has not been without costs. With the swift increase in consumption among urban and rural residents, concerns over energy consumption and environmental pollution have become increasingly pronounced [3]. Throughout this process, distinct disparities in China's urban-rural structures have been evident. The acceleration of urbanization has resulted in a substantial influx of the population from rural to urban areas, seeking improved living conditions and employment opportunities [4]. This shift has led to significant discrepancies in living environments between urban and rural settings. The rapid advancement of urban areas, juxtaposed with the relative stagnation of rural regions, has manifested marked disparities in resource allocation, environmental quality, and lifestyles. In efforts to bridge these disparities, a series of policies and measures have been introduced by the state, aiming to progressively enhance living conditions, invigorate rural areas, and ensure that all citizens reap the benefits of economic growth [5]. Nevertheless, these measures are insufficient to address all the challenges. As the economy continues to grow, the nation's reliance on fossil fuels has incrementally intensified, exacerbating issues related to energy consumption [6]. To address this challenge, there is an imperative for the state to optimize its energy consumption patterns, diminish its dependence on fossil fuels, and champion sustainable, green energy solutions.

Additionally, significant disparities exist in the consumption patterns of urban and rural residents in China [7]. Urban inhabitants tend to gravitate towards high-carbon, affluent lifestyles, whereas their rural counterparts more often adhere to traditional, low-carbon living habits [8]. Such variations in consumption have resulted in marked discrepancies in carbon emissions between urban and rural areas. In order to reduce carbon emissions and facilitate a transition to low-carbon models, an in-depth investigation into the carbon emissions generated by both urban and rural consumption activities is necessary [9]. Analyzing their driving factors and emission efficiencies will allow for the formulation of effective policies and measures, ensuring simultaneous economic and environmental growth. In summary, as China advances economically, it is concurrently confronted with a multitude of challenges. Adequate attention and resolution to these issues are pivotal to ensuring the nation's sustained, healthy, and eco-friendly development.

In light of the aforementioned considerations, this study employs provincial urban-rural data to investigate regional disparities, dynamic evolutions, and structural decompositions of carbon emissions in China. Initially, the IPCC method for carbon emission estimation is utilized to gauge the carbon emissions from energy consumption by urban and rural residents at the provincial level, forming the focal point of this research. Subsequently, the Theil index and its decomposition are employed to analyze regional disparities and evolving trends in carbon emissions from urban and rural energy consumption. Furthermore, local Moran's I is used to examine the spatial correlation of carbon emissions across various Chinese regions. Finally, the Theil index is applied once again to determine the levels of inequality in carbon emissions from energy consumption among urban and rural residents in different provinces. Based on the natural breakpoint classification, spatial heterogeneity in urban-rural carbon emission disparities within China is analyzed.

Literature Review

With the global consensus shifting towards low-carbon economic development models, nations have introduced a plethora of measures aimed at reducing energy consumption and curtailing carbon emissions [10]. As the world's largest developing country, China, in its bid to address climate change repercussions and shoulder its responsibilities as a major player, has set forth goals to peak carbon emissions by 2030 and achieve carbon neutrality by 2060. These targets not only delineate a trajectory for the nation's low-carbon economic growth but also impose heightened standards for domestic low-carbon advancement [11]. Previous research predominantly focused on energy-saving and emission-reduction efforts within the industrial sector [12, 13], often overlooking the growth of energy consumption and carbon emissions in the household consumption domain. However, as the national economy progresses and living standards rise, carbon emissions resulting from consumer activities have increasingly become a primary driver of emission growth.

On the quantification of carbon emissions resulting from household consumption, numerous studies in recent years have explored the topic using both

the IPCC method and the input-output approach [14-16]. The IPCC method calculates carbon emissions from various consumption activities by referencing emission factors established by the IPCC, contingent on the types of consumer behaviors. Weber and Matthews[2] utilized data on U.S. household consumption, encompassing areas like food, transportation, and housing, and combined this with an environmentally extended input-output model to assess the carbon footprint of American households [17]. Druckman and Jackson, leveraging categorized UK household consumption data and referencing the IPCC's emission factors, estimated carbon emissions from UK household consumption [18]. Feng et al. employed the Chinese input-output table in conjunction with the IPCC's emission factors to assess carbon emissions from urban Chinese households [19].

The input-output approach constructs tables to reflect product and value flows between various industries, calculating carbon emissions driven by household consumption within each industrial sector [20-22]. However, using the input-output tables does not facilitate further differentiation between carbon emissions from energy consumption by urban and rural residents. Wiedmann et al. provided a retrospective and comparison of various environmentally extended input-output models for evaluating environmental impacts embedded in trade [23]. Munksgaard and Pedersen utilized Denmark's input-output table to dissect the attribution of CO2 emissions responsibilities under open economic conditions [24]. Liang and Zhang analyzed the impact of various final demands on CO_2 emissions using the input-output table from China's Jiangsu province [25].

Research into the factors influencing carbon emissions from household consumption has, in recent years, emerged as a significant subfield in carbon emission studies [26-28]. Amid escalating concerns over global climate change, determining effective strategies to control and diminish carbon emissions has become the focal point for governments and academia alike [29-31]. The determinants of household consumption-related carbon emissions can be examined from both intrinsic and extrinsic perspectives [32-34]. In terms of intrinsic factors, household income levels play a pivotal role in shaping carbon emissions from consumption. Wang et al. identified income level as a crucial endogenous factor, suggesting that higher income leads to increased consumption and, consequently, heightened carbon emissions [35]. Yang and Liu posited that the structure of consumption impacts carbon emissions, finding that food and travel expenditures are the primary sources of carbon emissions for urban residents in China [36]. Additionally, societal contexts, encompassing prevailing trends and ideologies, also exert influence [37-40]. For instance, the promotion of a low-carbon lifestyle ethos has been shown to contribute to a reduction in carbon emissions [41].

Upon reviewing the aforementioned literature, several research gaps become evident. Firstly, most existing studies predominantly focus on carbon emissions from a macroscopic perspective [42-44], often neglecting emissions from the consumer demand side. Secondly, as urbanization deepens in China, urban and rural residents manifest pronounced differences in lifestyles and consumption patterns [45, 46]. However, when studying carbon emissions resulting from Chinese household energy consumption, distinctions between urban and rural residents' carbon emissions from energy consumption are seldom made. Thirdly, while much of the current literature primarily employs spatial econometric models [47, 48], there's a relative paucity of quantitative analyses regarding regional disparities and dynamic evolutions in urban-rural differences in carbon emissions from household energy consumption.

Methods and Data

Estimation of Carbon Emissions from Urban and Rural Residents' Energy Consumption

Drawing on the methodologies developed by published literature [49, 50], this study utilizes the electrical coal consumption calculation method to gauge the energy consumption of both urban and rural residents in China. In accordance with the T-carbon emission measurement method introduced by the Intergovernmental Panel on Climate Change (IPCC) in 2006, we ascertain the carbon emissions resulting from the consumption activities of China's urban and rural populations. The IPCC method is a method to estimate carbon emissions according to the types of energy consumption and emission factors, which is suitable for the background of this study. This method can distinguish the energy consumption structure and carbon emission level of urban and rural residents and reflect the influence of urban-rural differences and regional differences. The specific formula employed is detailed below:

$$C_i = \sum_{i=1}^{n} E_i \times SCC_i \times \omega_i \times \frac{44}{12} \tag{1}$$

In Equation (1), E represents the final energy consumption, SCC stands for the standard coal conversion coefficient, and the coefficient for standard coal emissions (as referenced from the Energy Research Institute of the National Development and Reform Commission) is understood to be 0.67, indicating that complete combustion of one ton of standard coal results in a carbon emission coefficient of 0.67. The numbers 44 and 12 correspond to the molecular weights of CO_2 and C respectively. i designates the various categories of energy.

This study selects a sample comprising 30 provinces, municipalities, and autonomous regions of mainland China (excluding Tibet) from the period of 2005-2021.

Data were sourced from the regional energy balance tables (in physical quantities) as documented in the China Energy Statistical Yearbook. The study encompasses 12 energy categories, namely: raw coal, cleaned coal, other washed coal, briquettes, coke, coke oven gas, crude oil, gasoline, diesel, liquefied petroleum gas, natural gas, and heat and electricity. Data on final energy consumption was extracted from the respective annual editions of the China Energy Statistical Yearbook. The conversion coefficients for energy to standard coal are based on the national standard General Principles for Calculation of Total Energy Consumption (GBT2589-2020). Therefore, this paper calculates the carbon emissions of residents' energy consumption and per capita carbon emissions of households in 30 provinces of the Chinese mainland from 2005 to 2021, with a total of 510 sample groups, and further divides them into urban and rural sub-samples.

Theil Index

Traditional inequality metrics, such as the classical Gini coefficient and the Theil index, are constructed upon the assumptions of a normal distribution and homoscedasticity. These metrics strictly delineate that there should be no overlapping sections between grouped samples, making it challenging to decompose them into several sub-indices with meaningful economic interpretations. Addressing these limitations, Theil introduced the Theil index, drawing from the entropy concept in information theory [51]. This index allows for the decomposition of the overall sample variance into within-group and between-group variances. Compared to the Gini coefficient, the Theil index has seen a shorter time span from introduction to application. It is better suited for decomposition based on features. Consequently, this study employs the Theil index to analyze the disparities in carbon emissions both between and within regions while also assessing their significance in the overall variance. The specific formula is as follows:

$$T = \sum_{i=1}^{n} \left(\frac{y_i}{Y} \right) \ln \left(\frac{y_i}{Y} \right) \quad (2)$$

In Equation (2), T represents the Theil index for carbon emissions, y_i denotes the carbon emission level of the ith region, and $\bar{y}$ stands for the average carbon emission level across regions. $T \in [0,1]$, a larger value of T indicates greater disparities in regional carbon emissions, whereas a smaller T suggests lesser disparities. The Theil index can further be decomposed into the within-group Theil index and the between-group Theil index. Assuming the n samples are divided into K groups, the decomposition of the Theil index can be expressed as:

$$T = T_{within} + T_{between} = \sum_{k=1}^{K} y_k \log \frac{y_k}{n_k/n} + \sum_{k=1}^{K} y_k \left(\sum_{i \in \varepsilon_k} \frac{y_i}{y_k} \log \frac{y_i/y_k}{1/n_k} \right) \quad (3)$$

In Equation (3), T_{within} represents the inter-regional disparities in carbon emissions, and $T_{between}$ denotes the intra-regional disparities. y_k represents the carbon emission of the k-th group, n_k represents the sample number of the k-th group, n represents the sample number of the whole country.

It should be noted that this study employs carbon emission data as a foundation to compute the weighted Theil index, which reflects the disparities in carbon emissions from energy consumption by Chinese residents. To comprehensively capture the national disparities in carbon emissions both from urban-rural and regional perspectives, slight modifications were made to the traditional Theil index computation and decomposition methodologies. The 30 provinces' urban and rural areas were treated as distinct samples, amounting to a total of 60 samples across the nation. By incorporating these into equation (3), an overall Theil index was derived, representing disparities in residents' income distribution. Subsequently, the 60 samples were grouped into 30 sets by region, with each set comprising one urban and one rural sample. Based on this configuration, the overall Theil index was decomposed into the between-group Theil index, T_w (illustrating carbon emission disparities among the 31 regions), and the within-group Theil index, T_g (highlighting the disparities between urban and rural areas across the nation).

Spatial Correlation

Carbon emissions display pronounced disparities across different areas. To ascertain interregional connections, it is imperative to further investigate their spatial correlation, which encompasses both global and local correlations. Local Moran's I analysis is a method for analyzing spatial correlation that was proposed by Anselin in 1995. This method can test whether there is a positive or negative correlation between the carbon emissions of each region and the carbon emissions of its neighboring regions and the significance of this relationship. Compared with the global Moran's I analysis, the local Moran's I analysis can reveal the spatial correlation characteristics of each region in more detail. The specific calculation formula is as follows:

$$I_i = \frac{y_i - \bar{y}}{\frac{1}{n} \sum (y_i - \bar{y})^2} \sum_{j \neq i}^{n} \omega_{ij} (y_i - \bar{y}) \quad (4)$$

Where I_i represents the local Moran's I of the i-th region, y_i represents the carbon emission of the i-th region, $\bar{y}$ represents the national average carbon emission, ω_{ij} represents the spatial weight between the i-th region and the j-th region, and n represents the number of regions. The range of I_i is [1,1]. The closer I_i is to 1, it means that the carbon emissions of the I-th region are positively correlated with those of its neighboring regions, that is, high-high or low-low aggregation. The

closer I_i is to -1, it means that the carbon emissions of the I-th region are negatively correlated with those of its neighboring regions, that is, high-low or low-high dispersion, and I_i is close to 0, which means that the carbon emissions of the I-th region are adjacent to it.

Result

Evolution of Regional Differences in Carbon Emissions Among Chinese Residents

From a national perspective, as depicted in Fig. 1, the inequality of carbon emissions has experienced three phases: an increase, a decrease, and a stabilization. Between 2005 and 2010, the Theil Index showed a consistent rise, especially between 2009 and 2010. From 2010 to 2013, the index declined, followed by a slight fluctuation from 2013 to 2016. Starting in 2017, it declined annually until reaching its lowest point in 2021. The inequality of urban carbon emissions increased from 2005 to 2010, peaking in 2010. However, there was a significant reduction from 2010 to 2013. From 2013 to 2021, it largely remained stable, but with a slight downward trend. In contrast, rural carbon emission inequality decreased from 0.2275 in 2005 to 0.1707 in 2008 and continued to decline until 2011. It then saw a slight increase from 2011 to 2017, followed by a decline until 2021.

In the Northeast region, carbon emission inequality generally increased. Urban carbon emission inequality in this area remained relatively stable initially, but experienced a significant rise after 2017, peaking at 0.1333 in 2020. In contrast, rural inequality began high in 2005 but subsequently dropped quickly, showing fluctuations in the following years. Coastal regions in the East experienced several fluctuations in carbon emission inequality. The decline in rural areas was more rapid and played a pivotal role in reducing overall inequality. This inequality first peaked in 2007 and then gradually decreased until 2021. Meanwhile, urban areas saw an increase from 2005 to 2016, followed by a consistent decrease. Rural areas peaked in 2005-2006, then continued to decline. Coastal regions in the North displayed multiple fluctuations in carbon emission inequality, with significant increases during 2007-2009 and 2018-2019. Urban areas in this region rose gradually from 0.0941 in 2005 to 0.2124 in 2019 before experiencing a slight decline. However, rural areas saw significant growth between 2017 and 2019.

In the Southwest coastal region, the inequality of carbon emissions substantially decreased. The Theil Index dropped from 0.0355 in 2005 to 0.0204 in 2021. Both urban and rural areas showed declining trends during this period. In the Northwest, the overall carbon emission inequality was somewhat volatile, but the overall levels were relatively low. The Theil Index increased slightly from 0.0217 in 2005 to 0.0252 in 2021. Urban areas mostly declined during this period, while

rural areas slightly increased. The carbon emission inequality in the Southwest region exhibited a downward trend. The Theil Index drastically decreased from 0.1919 in 2005 to 0.051 in 2021. While urban areas saw their carbon emission inequality drop from 0.0836 in 2005 to 0.0166 in 2014, rural areas decreased from 0.3485 to 0.1349 in 2021.

Considering the Yangtze River's midstream region, carbon emission inequality generally declined. Both urban and rural areas saw declining trends, with urban areas showing a more pronounced decrease. The Yellow River's midstream region experienced notable fluctuations in the Theil Index. In 2005, the index for this area was 0.0757, with urban areas at 0.1323 and rural areas at 0.1619. By 2010, the overall, urban, and rural indexes were 0.2214, 0.3734, and 0.1219, respectively. Although the overall carbon emission inequality increased slightly between 2010 and 2015, a declining trend emerged starting in 2016. Urban carbon emission inequality decreased from 0.3485 in 2016 to 0.2734 in 2021, while rural areas declined from 0.3845 to 0.2876. In general, although the Yellow River's midstream region displayed short-term growth in carbon emission inequality, the long-term trend indicates a gradual reduction.

Comparing the overall carbon emission inequalities across the eight major regions, the Southwest and the Yellow River's midstream regions stand out, while the others remain relatively stable or show signs of mitigation. From 2018 to 2021, the Theil Index in most regions gradually declined, indicating a softening of carbon emission inequalities. In 2005, the Southwest region had a remarkably high Theil Index of 0.1919, significantly exceeding other regions. In contrast, the Northeast region had an index of just 0.0004 in 2007, showcasing almost negligible carbon emission inequality. The Yangtze River's midstream and East Coast regions were relatively stable, with the Yellow River's midstream region experiencing a sharp increase to 0.2214 in 2010, making it the highest that year. Starting in 2015, the Northwest region's inequality grew annually, peaking at 0.0549 in 2018.

Comparing urban carbon emission inequalities across the eight major regions, the Yellow River's midstream and Northern Coastal areas are most pronounced, while the Northeast and Yangtze River's midstream areas are lower. The Northeast region's carbon emission inequality remained low for most of the time but saw a notable increase from 2017 to 2020. The Yellow River's midstream region reached its peak of carbon emission inequality in 2010, followed by consecutive declines. The Southern and Northern coastal regions maintained relatively high carbon emission inequalities for several years, especially the Northern coastal region, which peaked in 2019. Both the Northwest and Southwest regions gradually mitigated their carbon emission inequalities, especially the Southwest, which saw a substantial reduction after 2015.

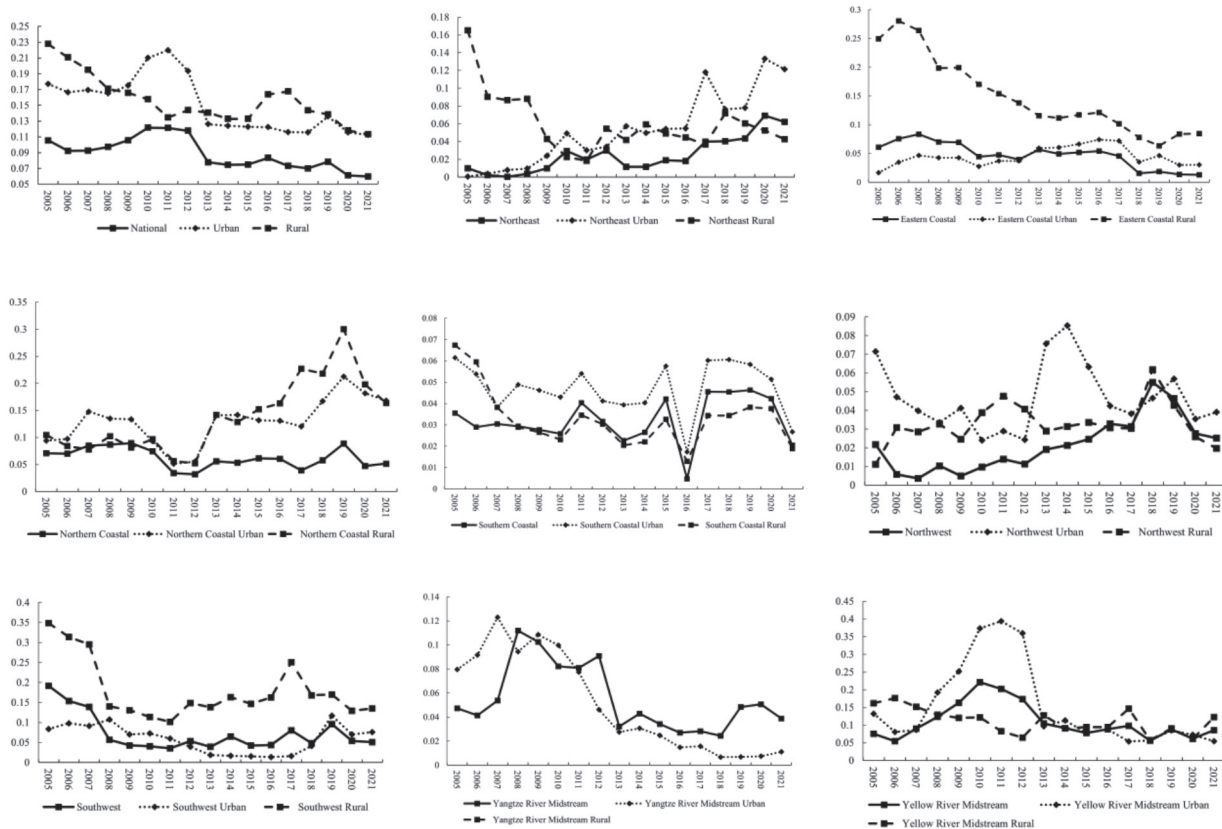In terms of rural carbon emission inequalities

Fig. 1. Dynamic Evolution of Carbon Emission Distribution.

across the eight major regions, the Southwest and East Coastalareas are particularly pronounced, while the other regions are relatively steady. In 2005, the Southwest region's carbon emission inequality was exceptionally high but decreased annually, with a slight rebound in 2017. Starting in 2005, the East Coast region had high carbon emission inequality, which was considerably reduced by 2018. The Northern coastal region's inequality sharply increased from 2017 to 2019, with 2019 being particularly notable. Conversely, the Northeast, Southern coastal, and Yangtze River's midstream regions displayed stable carbon emission inequalities. The Yellow River's midstream region consistently declined from 2005 to 2021, while the Northwest region showed significant fluctuations during the same period.

The decomposition of the Theil index reflects the changes in national and urban-rural disparities in carbon emissions. As depicted in Fig. 2, at the national level, intra-regional inequality (TWR) increased from 63.92% in 2005 to 70.40% in 2021, while inter-regional inequality (TBR) declined from 36.08% to 29.60%. This indicates that the rise in national carbon emission disparities is primarily driven by factors within regions. From 2005 to 2021, intra-regional inequality in urban areas grew from 41.69% to 65.48%, whereas in rural areas it rose from 70.46% to 78.96%. Although rural areas had higher disparities than urban areas, the growth was more pronounced. Regarding inter-regional

inequality, urban areas saw a decrease from 58.31% in 2005 to 34.52% in 2021, and rural areas experienced a decline from 29.54% to 21.04%. Both trends indicate a decreasing disparity. Overall, the internal carbon emission inequality in urban and rural areas has been gradually increasing, while the disparity between regions has been reducing, potentially attributable to national policies, regional economic dynamics, and environmental protection strategies.

The spatial correlation of carbon emissions across various provinces in China has seen significant variations in recent years, indicating a pronounced spatial clustering of carbon emissions. Table 1 revealed that coastal eastern regions and certain inland areas, such as Hebei, Shandong, and Jiangsu, experience higher carbon emissions. These regions are hubs for the nation's heavy industries, and their industrial and energy consumption structures are primary contributors to high carbon emissions. Conversely, the western regions, such as Gansu, Qinghai, and Xinjiang, exhibit lower carbon emissions and show positive correlations with their neighboring areas. The underlying reasons for this can be attributed to their less developed economies, lower levels of industrialization, and favorable natural environments that facilitate carbon absorption. Throughout the research period, the carbon emissions of most regions remained stable. However, areas like Tianjin, Jilin, and Shanghai transitioned from high to low carbon emissions, exhibiting negative correlations
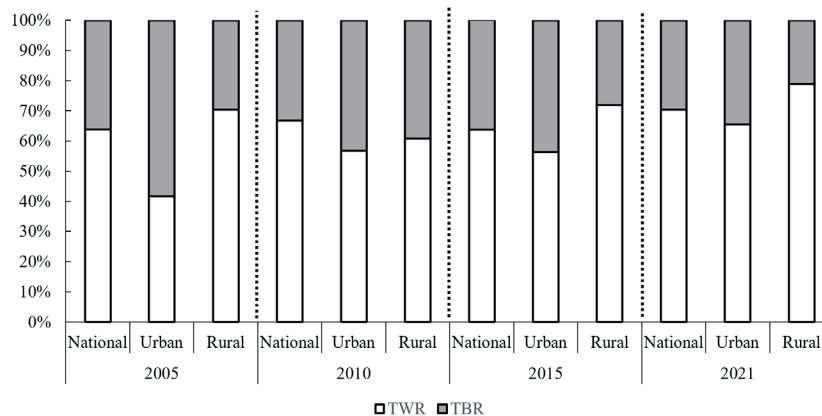
Fig. 2. Overall Discrepancies and Decomposition of Carbon Emissions.

with low-carbon regions. This reflects their enhanced environmental protection measures and carbon reduction policies. Regions like Hunan, Jiangxi, Guangxi, and Hainan have displayed transitional phases between low and high carbon emissions in some years, suggesting they are at a pivotal moment of economic transformation and carbon emission adjustments. Notably, economically developed areas like Beijing, Shanghai, and Guangdong showed negative correlations with low-carbon regions in certain years, which indicates effective carbon emission control despite their economic prosperity. In summary, there's evident heterogeneity in carbon emissions across China, closely tied to its economy, industry, and policies. Achieving efficient carbon emission control, narrowing inter-regional disparities, and enhancing overall regulatory effectiveness are crucial challenges China must address.

The potential reasons for these changes are closely associated with China's economic development, policy formulation, and environmental management. The rapid economic growth in China, especially the industrialization and urbanization in the eastern coastal regions, has led to an increase in carbon emissions and their inequality. However, with the rise in environmental awareness and the implementation of green development policies, including energy-saving, emission reduction, and the promotion of renewable energy, there has been a decrease in carbon emission inequality in certain regions and nationally. The government has implemented a series of measures in response to climate change and carbon emission control, including setting emission reduction targets, promoting clean energy, and optimizing the energy structure. These measures have not only facilitated the green transition of the economy but also helped to reduce regional disparities in carbon emissions. Moreover, the changing spatial correlation of carbon emissions across Chinese provinces indicates significant spatial clustering characteristics of carbon emissions, reflecting differences in economic development levels, industrial structures, and energy consumption patterns among regions. For instance, higher carbon emissions are observed in the heavy

industrial areas of the eastern coastal and some inland regions, while the economically less developed and less industrialized western regions exhibit lower carbon emissions. Shen et al. [52] found that the development of digital finance can improve the efficiency of land circulation in rural areas, thereby enhancing the productivity and sustainable development of the agricultural sector. Existing literature using panel data from 216 Chinese cities found that the establishment of a carbon trading market mechanism can enhance the synergistic effects of environmental regulation and low-carbon policies [53].

Decomposition of the Theil Index for Urban-Rural Areas

Utilizing the aforementioned method, the overall disparity in the sample data can be decomposed into three distinct components. The TBR (Theil's Between-Region Index) elucidates the carbon emission inequality among major regions. The TBP (Theil's Between-Province Index Within Region) denotes the inequality in carbon emissions among provinces within a specific region. Meanwhile, the TWP (Theil's Within-Province Index) specifically gauges the inequality within an individual province, such as the disparities in carbon emissions between urban and rural areas. The relative shares of each component, along with the Theil index, are presented in Fig. 3.

From Fig. 3, it can be observed that the Theil index commenced at 0.1823 in 2005, declined to 0.1441 in 2008, and then surged to 0.168 in 2010. Subsequently, despite minor fluctuations, it displayed an overall decreasing trend, reaching 0.1064 by 2021. This signifies that the overall disparity in carbon emissions between urban and rural areas across Chinese provinces has progressively diminished. This is attributed to the fact that the industrialization and urbanization processes in China's central and western regions have spurred economic growth and enhanced energy efficiency [54, 55]. In rural areas, there has been a gradual shift towards the adoption of cleaner and more efficient

Table 1. Distribution of Local Moran's I by Region.

Year	High-High	Low-High	Low-Low	High-Low
2005	Hebei, Shanxi, Inner Mongolia, Anhui, Shandong, Henan, Hunan	Liaoning, Zhejiang, Guangdong, Sichuan, Guizhou	Heilongjiang, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang	Beijing, Tianjin, Jilin, Shanghai, Jiangsu, Fujian, Jiangxi, Hubei, Guangxi, Hainan, Chongqing, Yunnan
2010	Beijing, Hebei, Shanxi, Inner Mongolia, Jiangsu, Shandong, Henan	Liaoning, Heilongjiang, Zhejiang, Hubei, Guangdong, Sichuan	Guangxi, Chongqing, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Xinjiang	Tianjin, Jilin, Shanghai, Anhui, Fujian, Jiangxi, Hunan, Hainan, Ningxia
2015	Beijing, Hebei, Shanxi, Liaoning, Jiangsu, Shandong, Henan, Hubei, Hunan	Zhejiang, Guangdong, Sichuan	Heilongjiang, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang	Tianjin, Inner Mongolia, Jilin, Shanghai, Anhui, Fujian, Jiangxi, Guangxi, Hainan, Chongqing
2021	Beijing, Hebei, Jiangsu, Anhui, Shandong, Henan, Hubei, Hunan	Inner Mongolia, Liaoning, Zhejiang, Guangdong, Sichuan	Heilongjiang, Guizhou, Yunnan, Gansu, Qinghai, Ningxia, Xinjiang	Tianjin, Shanxi, Jilin, Shanghai, Fujian, Jiangxi, Guangxi, Hainan, Chongqing, Shaanxi

energy sources, supplanting traditional biomass fuels. Concurrently, China has achieved significant progress in the development of renewable energy sources, thereby reducing its reliance on fossil fuels. Additionally, the regional coordinated development strategy implemented by China has effectively fostered the growth of the central and western regions.

Upon decomposing the Theil index, the TBR (Theil's Between-Region index) was 0.0381 in 2005, accounting for 20.89% of the total index. Over time, the TBR was reduced to 0.0256 by 2007, with its proportion dropping to 16.77%. However, by 2012, it had risen to 0.0498, constituting 32.82% of the total. After this peak, both the value and proportion of TBR consistently diminished, declining to 0.0177 (or 16.62% of the total) by 2021. This trajectory suggests that the TBR initially decreased, subsequently increased, and then diminished again over the span under consideration.

In 2005, the TBP (Theil's Between-Province Index Within Region) was 0.0675, making up 37.04% of the total Theil index. Contrary to TBR, TBP remained relatively stable during 2007 and 2008. Yet, by 2010, it had risen to 0.0812, representing 48.33% of the total. Thereafter, both the absolute value and proportion of TBP gradually decreased, standing at 0.0421 (or 39.56% of the total) by 2021. This underscores a pattern where the TBP remained steady initially, then ascended, and subsequently descended.

TWP (Theil's Within-Province Index) was 0.0767 in 2005, comprising 42.07% of the total Theil index. By 2007, the TWP had been reduced to 0.0601, holding 39.39% of the overall index. However, it had escalated to 0.0465 (or 27.68% of the total) by 2010. After this, the value and proportion of TWP consistently decreased, reaching 0.0466 (or 43.82% of the total) by 2021. This trajectory suggests that TWP first descended and then climbed within the period.

In summary, the changes in TBR, TBP, and TWP were relatively steady over time. Notably, TBR and TBP had higher proportions, while TWP had a lower share. Specifically, from 2005 to 2008, TBP had the highest

share in the Theil index. Between 2009 and 2013, the proportion of TBR surpassed that of TBP, indicating a rise in carbon emissions in rural regions. From 2014 to 2021, the shares of the three indices became more balanced, illustrating a stabilization in China's urban-rural carbon emission structure during this period. Overall, TBR and TBP have a more significant contribution to carbon emissions, while TWP's contribution is relatively minor. Further investigation into the causes reveals that from 2005 to 2008, rapid industrialization in the eastern region led to an expansion in the urban-rural carbon emission gap. Between 2009 and 2013, accelerated development in the western region, coupled with increased energy consumption in rural areas, further widened this disparity. However, from 2014 to 2021, as the central region emerged, the economies of the eastern, central, and western regions began to converge, gradually leading to a more balanced carbon emission gap.

To further explore the spatial heterogeneity of urban-rural carbon emissions inequality in China, the natural breakpoint grading method [3] was employed to categorize China's level of urban-rural carbon emissions inequality into high, upper-middle, lower-middle, and low levels [56]. As gleaned from Table 2, in 2005, there were 14 provinces in China with a low level of carbon emissions disparity: 5 at the lower-middle level, 3 at the upper-middle level, and 5 at the high level. By 2010, 17 provinces fell under the low level, 8 at the lower-middle level, and 5 at the upper-middle level, with no provinces at the high level. In 2015, provinces at the low level rose to 20, 9 at the lower-middle level, with only Hainan province at the upper-middle level. By 2021, 21 provinces were at the low level, 5 at the lower-middle level, and 4 at the upper-middle level.

From a temporal perspective, the urban-rural carbon emissions disparity in Chinese provinces has been gradually transitioning from the lower-middle and low levels towards the low and upper-middle levels over recent years. However, this trajectory exhibits two primary characteristics: temporal developmental
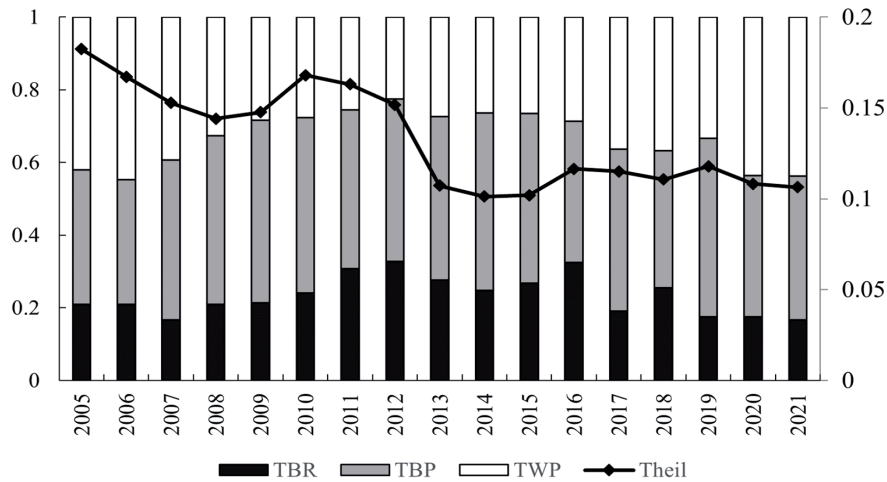
Fig. 3. Decomposition of the Theil Index, 2005-2021.

insufficiency and spatial developmental imbalance. Firstly, the insufficiency in development is evident. From 2005 to 2021, the disparities in urban-rural carbon emissions among provinces exhibited significant fluctuations. For instance, provinces such as Guangdong, Jiangsu, and Shanghai started with a pronounced carbon emissions disparity, which diminished in later years. Conversely, provinces like Gansu, Ningxia, and Qinghai maintained a relatively modest carbon emissions gap, potentially due to their industrial structures, economic development stages, and energy consumption patterns.

Secondly, there's an evident developmental imbalance. Some economically advanced provinces, like Guangdong, Jiangsu, and Shanghai, persistently exhibited significant urban-rural carbon emissions disparities. This might be attributable to their rapid industrialization and urbanization processes, with rural areas still relying on traditional energy consumption methods. In contrast, certain western provinces, such

as Sichuan, displayed a minimal carbon emissions disparity, potentially benefiting from the region's resource endowments and energy policies. Moreover, some provinces like Gansu and Xinjiang, with initially low levels of carbon emissions, experienced a relatively slow increase, ensuring the overall urban-rural carbon emissions disparity remained at a relatively low level.

It can thus be inferred that the uneven spatial distribution of carbon emissions is attributed to the significant industrial-structural disparities between urban and rural areas in the eastern region, driven by high levels of industrialization. In the central and western regions, the industrial structure is relatively homogenous, with some high-carbon industries relocating from the east. Concurrently, rapid urbanization in the eastern region has led to a substantial migration of rural populations to urban areas. Meanwhile, the central and western regions,

Table 2. Distribution of Urban-Rural Carbon Emissions Inequality in China.

Year	Low	Lower-Middle	Upper-Middle	High
2005	Yunnan, Sichuan, Tianjin, Ningxia, Shandong, Shanxi, Guangdong, Xinjiang, Jiangxi, Hebei, Zhejiang, Hubei, Hunan, Gansu, Fujian, Liaoning, Qinghai	Inner Mongolia, Beijing, Jilin, Henan, Guizhou	Anhui, Jiangsu, Chongqing	Shanghai, Guangxi, Hainan, Shaanxi, Heilongjiang
2010	Yunnan, Inner Mongolia, Tianjin, Shanxi, Guangdong, Xinjiang, Jiangxi, Hebei, Henan, Zhejiang, Hubei, Hunan, Gansu, Fujian, Guizhou, Liaoning, Shaanxi	Shanghai, Beijing, Sichuan, Ningxia, Shandong, Jiangsu, Chongqing, Qinghai	Jilin, Anhui, Guangxi, Hainan, Heilongjiang	
2015	Shanghai, Inner Mongolia, Beijing, Jilin, Sichuan, Tianjin, Anhui, Shandong, Guangdong, Xinjiang, Jiangsu, Jiangxi, Henan, Hubei, Hunan, Gansu, Fujian, Liaoning, Chongqing, Shaanxi	Yunnan, Ningxia, Shanxi, Guangxi, Hebei, Zhejiang, Guizhou, Qinghai, Heilongjiang	Hainan	
2021	Shanghai, Beijing, Sichuan, Tianjin, Anhui, Shandong, Guangdong, Guangxi, Xinjiang, Jiangsu, Jiangxi, Henan, Hainan, Hubei, Hunan, Gansu, Liaoning, Chongqing, Shaanxi, Qinghai, Heilongjiang	Yunnan, Ningxia, Hebei, Zhejiang, Fujian	Inner Mongolia, Jilin, Shanxi, Guizhou	

starting from a lower baseline of total carbon emissions, have a greater capacity for growth in emissions. Consequently, addressing how to effectively narrow and manage the urban-rural carbon emissions disparities both between and within China's regions, and ensuring a balanced and sustainable evolution of carbon emissions disparities, has emerged as a pressing mandate.

Conclusion

Utilizing the carbon emission estimation methodology of the IPCC, this study quantified the carbon emissions from energy consumption of urban and rural residents in China at the provincial level from 2005 to 2021 and analyzed the temporal trends and spatial distribution characteristics of these emissions. Building on this, the degree of urban-rural carbon emission inequality in different regions was further computed, with the application of the natural breakpoint grading method to assess the spatial correlation of carbon emission disparities. The findings from this investigation are summarized as follows:

Firstly, between 2005 and 2021, the inequality in residents' carbon emissions in China underwent three distinct phases: rise, decline, and stabilization. Notably, between 2005 and 2010, the Theil index witnessed a rapid ascent, but from 2017 onward, a yearly decrease was observed. The inequality in urban carbon emissions increased from 2005 to 2010, while the rural emission disparities significantly diminished between 2005 and 2008. In contrast, the Northeast region showed an overall increase in carbon emission inequality, especially with a notable surge in urban areas post-2017. Conversely, coastal areas in the East and South demonstrated a declining trend in emission disparities. The Northwest region exhibited fluctuations in inequality but maintained a relatively low overall level. Both the Southwest and the Yangtze River's middle regions experienced downward trajectories in emission disparities. The Yellow River's middle region saw significant fluctuations in the Theil index, but the long-term trend indicates a gradual decrease. From 2005 to 2021, the increase in national carbon emission inequality was primarily induced by intra-regional factors, whereas inter-regional disparities decreased. The growing inequality within urban and rural areas could be linked to national policies, regional economic developments, and environmental protection strategies.

Secondly, a spatial aggregation trend in carbon emissions is evident across Chinese provinces. Coastal eastern regions and certain inland areas, such as Hebei, Shandong, and Jiangsu, due to their roles as heavy industrial hubs, exhibit higher carbon emissions. In contrast, western areas like Gansu, Qinghai, and Xinjiang have lower emissions, correlating with their less developed economies, lower levels of industrialization, and pristine natural environments.

Places like Tianjin, Jilin, and Shanghai have transitioned from high to low emissions, reflecting effective environmental policies in place. Regions like Hunan, Jiangxi, Guangxi, and Hainan are in a transitional phase regarding carbon emissions and economic dynamics. Despite the economic prosperity of areas like Beijing, Shanghai, and Guangdong, their carbon emissions have been effectively controlled.

Thirdly, viewing the trend in urban-rural carbon emission inequality in China, the overall disparity in carbon emissions has been gradually narrowing. Notably, the inequality contributions of TBR and TBP are significantly higher than thoseat of TWP. Chronologically, TBR, TBP, and TWP have each showcased dynamic characteristics, but overall, they have followed a relatively stable trajectory. From 2005-2008, TBP had the most pronounced contribution; between 2009-2013, rural carbon emissions surged, amplifying the contribution of TBR; and from 2014-2021, contributions from all three indices have leveled out.

Lastly, between 2005 and 2021, the inequality in urban-rural carbon emissions in China demonstrated pronounced spatial heterogeneity and dynamic changes. The natural breakpoint grading method has illuminated the categorization of carbon emission inequality levels across different provinces. Over time, most Chinese provinces have seen their emission disparities shift from mid-low and low levels towards low and mid-high levels. However, this developmental trajectory is characterized by two main features: the insufficiency of development and spatial imbalances. Some are economically advanced regions, such as Guangdong, Jiangsu, and Shanghai, have prominent carbon emission disparities due to rapid industrialization and urbanization processes. Conversely, some western areas, like Sichuan, display relatively minor disparities due to their resource endowments and energy policies. The persistence of this inequality poses a challenge: how can China ensure a balanced and sustainable development in carbon emissions while pursuing reductions?

This paper employs the IPCC methodology to estimate the carbon emissions from urban and rural residents' energy consumption. However, this approach is subject to certain assumptions and uncertainties, such as the selection of carbon emission factors, the source and quality of energy consumption data, and the criteria for urban-rural classification. These factors could potentially impact the accuracy of carbon emission calculations and comparative analyses. Future research could benefit from using more refined and precise energy consumption data, as well as more scientifically valid and reasonable carbon emission factors. Additionally, this study does not account for other factors that may influence urban-rural carbon emission inequality, such as population structure, consumption preferences, technological advancement, and environmental awareness. Future studies could explore the spatial transmission mechanisms and influencing factors of

carbon emissions, analyze the dynamic changes and trends in carbon emissions, and assess the economic costs and social benefits of carbon emissions.

Acknowledgments

Data Availability Statement

All of the data are publicly available, and proper sources are cited in the text. The data used to support the findings of this study are available from the corresponding author upon request.

Conflict of Interest

The authors declare no conflict of interest.

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