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Decoupling CO_2 Emissions from Economic Growth in China's Cities from 2000 to 2020: A Case Study of the Pearl River Delta Agglomeration

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Abstract: As one of the most densely populated, economically developed, and outwardly open urban agglomerations in China, the Pearl River Delta (PRD) urban agglomeration is a key player in achieving China's carbon peak and carbon neutrality targets. This study analyzes low-emission development by examining the evolutionary patterns of carbon dioxide (CO_2) emissions and the decoupling relationship between economic growth and CO_2 emissions, using the latest available data from 2000 to 2020. Here are the main findings: (1) We found a significant fluctuation in the decoupling statuses between economic advancements and CO_2 emissions within the PRD domain. Predominantly, a weak decoupling scenario was observed, where economic proliferations were paralleled by nearly equivalent increments in CO_2 emissions. (2) The growth rate of carbon emissions increased significantly relative to economic expansion during 2015–2020, especially pronounced in cities such as Guangdong, Zhuhai, Foshan, and Dongguan. This delineates the persistent challenges in steering towards a pathway of energy conservation and emission abatement in the region. (3) Furthermore, a differential role of elasticity factors was noted across cities: Guangzhou and Shenzhen witnessed a significant influence of energy-saving elasticity in fostering a decoupling between economic surge and CO_2 emissions, whereas in other cities, the emphasis shifted towards emission-reduction elasticity as a more vital determinant. The results of this study are of great significance for guiding policy makers and stakeholders in urban clusters across China and in similar regions globally to achieve low carbon development goals.

Keywords: CO_2 emissions; decoupling; tapio indicator; urban agglomeration; China

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1. Introduction

The flourishing development of the global economy and acceleration of urbanization and industrialization have led to a significant increase in irreversible fossil energy consumption and an unprecedented rise in carbon dioxide (CO_2) emissions [1–3]. Global warming is now a serious worldwide public environmental concern [4,5]. China, being the largest CO_2 emitter globally, has set emission-reduction targets to reach an emission peak before 2030 [6]. Achieving this ambitious goal will require region-level efforts, particularly in urban carbon reduction. Urban agglomeration has emerged as a key issue in reducing emissions, and China has implemented policy measures to promote the development of urban agglomeration and use its effects to reduce emissions.

The formation, development, and expansion of urban clusters are clearly the next major trend in urban spatial organization, in the dual processes of global urbanization and economic globalization. According to the 2015 Sustainable Competitiveness of Cities Worldwide Report by the United Nations Habitat Assembly, the world's giant cities have begun to merge into super-giants or super-urban clusters [7]. Because urban economic activity accounts for approximately 80% of global gross domestic product (GDP) values, 66% of energy consumption, and a staggering 70% of carbon emissions [8], this trend clearly indicates that urban clusters will become one of the most important geographical units for reducing emissions. Therefore, it is essential to focus on sustainable development strategies in urban clusters to reduce their impact on the environment and promote a low-carbon future. China has undergone industrialization and urbanization at a pace and scale that surpasses any other country in the world, with many new cities emerging and growing in the process [9–11]. Among them, the Pearl River Delta (PRD) Urban Agglomeration is a world-class urban agglomeration in China [12]. The PRD Urban Agglomeration, located in the central-southern part of Guangdong Province. It covers approximately 54,000 km^2 and comprising nine cities, this region encapsulates a mere 20% of Guangdong's land area but contributes over 80% to the provincial GDP [13,14]. This dynamic urban cluster, which contributed 8.65% to the nation's GDP in 2022, not only supports the economic spine of the province but also plays a pivotal role in China's One Belt, One Road (Belt and Road) Initiative.

Despite its economic prowess, the PRD's growth model has leaned heavily on resource consumption, manifesting a high reliance on fossil fuels and a notable environmental toll [15]. The region's transformation of nonurban land into urban spaces to facilitate its growth has been at the expense of natural ecosystems, farmland, and water bodies. The current socio-economic structure, centered on resource consumption, poses a significant obstacle to the transition towards a green and low-carbon urban development, with limited synergistic benefits observed in terms of resource environment, economic development, and social well-being at this stage.

As China navigates the era of low-carbon economies, the PRD stands at the forefront of efforts aiming for sustainable development and emission reduction, notably under the Greater Bay Area project. Addressing greenhouse gas emissions here is not just imperative but holds the promise of showcasing a model of sustainable development in China. However, to truly materialize this vision, understanding and addressing the CO_2 emissions intricacies within the PRD is vital. In this context, previous studies that concentrated primarily on regional CO_2 emission differences appear to have missed the nuanced developmental disparities across cities within the PRD. This leaves a significant gap in our understanding of regional CO_2 emissions and their underlying complexities [16]. Furthermore, overlooking developmental differences within the city cluster can hinder the targeted control of CO_2 emissions, leading to unbalanced regional environmental development. Considering the imbalance in regional development, it is beneficial to formulate emission-reduction policies suitable for the development of different cities rather than using a one-size-fits-all approach. Therefore, this study focuses on analyzing CO_2 emissions in the PRD from the perspective of regional development imbalances and proposes targeted emission-reduction measures for the region.

The complex nexus between regional economic development, energy consumption, and carbon emissions has held a prominent place in scholarly and policy dialogues globally, serving as a critical determinant in shaping sustainable developmental strategies [17–19]. This relationship, often convoluted, brings forward a multi-faceted interaction where the aggressive pursuit of economic growth sometimes translates into escalated levels of energy consumption and heightened carbon footprints, affecting climate change patterns and environmental stability.

Globally, a myriad of studies has ventured deep into understanding these interlinkages, unfolding varying dynamics across different nations and regions. For instance, Chontanawat et al. (2008) embarked on a systematic analysis encompassing over a hundred countries, thereby presenting an elaborate canvas that allows for international comparison and policy crafting [20]. Complementing this, Bella et al. (2014) further analyzed the relationship within OECD countries, examining the interdependencies between CO_2 emissions, electrical power consumption, and GDP, which offers insightful inputs into understanding the dynamics in developed nations [21]. Furthermore, the collective work of Ntanos et al. (2015) charted the global trends in energy consumption and CO_2 emissions, presenting an encompassing view that helps to dissect the global patterns and implications [22].

In this ever-expanding urban landscape marked by relentless industrialization, cities globally are grappling with escalating carbon emissions, which in turn place an enormous strain on the environment. This forms a critical backdrop for the intensified scholarly and policy focus on the decoupling of economic growth from resource consumption and environmental degradation. As cities witness rapid expansion and the continuation of industrialization, there has been an increasing trend in carbon emissions, exerting a substantial burden on the environment. In this context, the decoupling of economic growth from resource consumption and environmental pollution emerges as a pivotal and pressing topic of exploration. In recent years, the theory of decoupling has served as a vital tool in assessing and scrutinizing the relationship between economic growth and CO_2 emissions. Initially rooted in the field of physics to measure disruptions or disconnections between physical quantities, it has evolved to encompass the intricate interplay between the economy and the environment. To mitigate the challenges brought forth by urban expansion, the Organization for Economic Co-operation and Development (OECD) introduced the concept of decoupling, aiming to sever the links between economic growth, resource consumption, and environmental degradation. Using the OECD decoupling theory, de Freitas and Kaneko [23] investigated the complete decoupling of Brazil's energy consumption, CO_2 emissions, and economic growth rate from 2004 to 2009. Tapio's decoupling elasticity method [24] used the European transportation industry to examine the relationship between economic growth and CO_2 emissions, indicating a weak decoupling between CO_2 emissions in the transportation industry and GDP. Since then, Tapio's elasticity decoupling theory has gained widespread application in various fields [8,25,26]. For example, Raza and Lin [27] used Tapio's decoupling method to estimate the decoupling status and mitigation potential of CO_2 emissions from the transport sector in Pakistan for 1984 to 2018. Lin et al. [28] employed the OECD and Tapio decoupling analysis to evaluate the relationship between CO_2 emissions and GDP in South Africa from 1990 to 2012. The findings indicated that South Africa experienced expansive negative decoupling between CO_2 emissions and GDP during 1990 to 1994, followed by weak decoupling between 1994 and 2010, and achieved strong decoupling from 2010 to 2012.

The examination of the decoupling relationships between energy consumption, economic growth, and CO_2 emissions has been extensively studied through various research models. Notwithstanding, the majority of these investigations have been conducted at national or interprovincial scale [29–31], leaving a noticeable gap in literature concerning the urban scale. Moreover, these research models predominantly focus on total CO_2 emissions, offering an overly macroscopic view and neglecting the pivotal aspects of energy conservation and emission reduction elasticity.

In light of the existing literature and methodologies employed, our study ventures to fill this research void by introducing a nuanced approach to the decoupling analysis. We innovatively decompose decoupling elasticity into two distinct facets: emission reduction elasticity and energy-saving elasticity. This methodological innovation permits an in-depth exploration of the primary factors influencing the decoupling of CO_2 emissions from economic growth, extending the understanding of decoupling dynamics at the urban agglomeration level.

This study presents several noteworthy contributions to the existing body of literature. Firstly, it pioneers in spotlighting the disparities in CO_2 emissions within the PRD urban agglomerations, offering a fresh and critical lens to scrutinize emission reduction strategies. This nuanced approach potentially sets a precedent for similar analyses in other urban agglomerations, fostering a more comprehensive understanding of urban-scale decoupling phenomena. Secondly, it enhances the existing decoupling theory which has been primarily applied at broader scales like national, regional, or sectoral levels, by zooming in on the intricacies of urban agglomerations. By meticulously dissecting the decoupling index into emission-reduction and energy-saving elasticity components, this study not only sheds light on the multifaceted nature of decoupling processes but also paves the way for crafting more targeted and effective strategies for sustainable urban development.

2. Data and Methods

2.1. Tapio Decoupling Method

The OECD defined decoupling as breaking the link between economic growth and environmental degradation, and developed a method for calculating decoupling that has been widely used since then [23]. However, the OECD decoupling index is too sensitive to the choice of the base period, and thus the stability of its calculation results is poor [32]. Based on the OECD decoupling model, Tapio introduced the concept of decoupling elasticity to construct the decoupling index, which addressed the difficulties in choosing the base period in the OECD decoupling model [33]. Tapio's decoupling theory provides reasonable decoupling positions for eight possible combinations of environmental pollution variables and economic variables, and is currently the most widely used method to study decoupling relationships [8].

$$E_{(C,\,GDP)} = {}^{\%\Delta C}\Big/_{\%\,\mathrm{GDP}} = \frac{(C^t - C^0)/C^0}{\left(GDP^t - GDP^0\right)/GDP^0} \tag{1}$$

2.2. Decoupling Decomposition Method

In expanding upon the Tapio decoupling method, this study conceptualizes a framework for analyzing the relationships among economic activities, energy consumption, and carbon emissions. The approach integrates insights from the Tapio decoupling model with the Economy–Energy–Environment (3E) system theory to foster a deeper understanding of the interactions between these elements.

In this analysis, energy consumption is introduced as a mediating decomposition variable in the decoupling model between economic growth and CO_2 emissions. Thus, a causal chain for the decoupling model is formulated as shown in Equation (2):

$$E_{(C,\,GDP)} = \frac{\%\Delta C}{\%\Delta EC} \times \frac{\%\Delta EC}{\%\Delta GDP} = \frac{(C^t - C^0)/C^0}{\left(EC^t - EC^0\right)/EC^0} \times \frac{\left(EC^t - EC^0\right)/C^0}{\left(GDP^t - GDP^0\right)/GDP^0} \tag{2}$$

where $\frac{\%\Delta C}{\%\Delta GDP}$ represents the decoupling elasticity between economic growth and CO_2 emissions; $\frac{\%\Delta C}{\%\Delta EC}$ indicates the emission-reduction elasticity between energy consumption and CO_2 emissions; and $\frac{\%\Delta EC}{\%\Delta GDP}$ is the energy-saving elasticity between economic growth and energy consumption.

2.3. Data Sources

The CO_2 emission data used in this paper are based on those provided by the China Carbon Accounts and Datasets (CEADs) (https://www.ceads.net/data/county/, accessed on 10 June 2023), which are derived from the inversion of Defense Meteorological Satellite Program/the Operational Linescan System (DMSP/OLS) and National Polar-orbiting Partnership/Visible Infrared Imager Radiometer Suite (NPP/VIIRS) nighttime lighting data provided by the National Geomatics Center of China (NGCC) from 1997–2017. The two sets of DMSP/OLS and NPP/VIIRS sensors can finely capture low-intensity nighttime light sources produced by urban centers or even by small-scale residential land or traffic, which provides an ideal data source for estimating energy consumption from human activities [34]. In the calibration of nighttime lighting data, Chen et al. [35] adopted the particle swarm optimization-back propagation (PSO-BP) algorithm to unify DMSP/OLS and NPP/VIIRS satellite images, which resulted in high-quality, stable nighttime light data with long time span, wide coverage, and uniform aperture. This data is not only useful for remote sensing, but also for population distribution, urban expansion, GDP prediction, and pollutant estimation [36]. This data is publicly available in the China Carbon Accounting Database, which has been widely used in academic CO_2 emission-related studies [15].

3. Results and Discussion

3.1. Spatiotemporal Characteristics of Energy Consumption and CO_2 Emissions

Figure 1 shows the CO_2 emission structure of the PRD urban agglomeration from 2000 to 2020. The share of carbon emissions from non-PRD cities in the province increased by 10.92% in 2020 relative to the base period of the study as a result of accelerated economic development and urbanization. However, the PRD is still the main area affecting changes in the carbon emission levels in Guangdong Province. Among the cities in the PRD, Guangzhou's total carbon emissions are significantly higher due to the influences of population size, economic growth, industrial manufacturing, and industrial structure. The total carbon emissions of Foshan and Dongguan are just behind those of Guangzhou. This is mainly because these two cities have been influenced by industrial transfers in Hong Kong, Macao, Guangzhou, and Shenzhen in recent years. Shenzhen has knowledge-, technology-, and capital-intensive industries as its pillar industries, among which high-tech, cultural and creative, and financial industries have large shares. Therefore, Shenzhen is less dependent on energy, and even though it has the largest GDP, its carbon emission level is not the highest among the PRD cities.

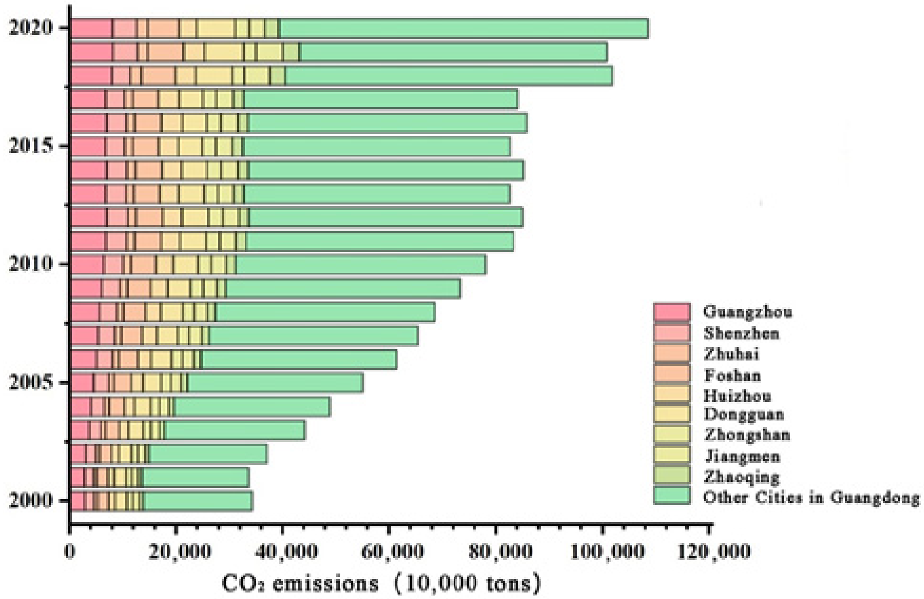

Figure 1. CO_2 Emissions of cities in the Pearl River Delta (PRD) urban agglomeration, 2000–2020.

The per capita CO_2 emissions and CO_2 intensity indicators exclude the influences of city size and total economic volume; thus, they can more objectively compare the environmental pressures brought by socioeconomic activities (Figure 2). The overall CO_2 intensities of PRD cities show fluctuating declines from 2000 to 2020, indicating that the environmental pressure brought by economic development has decreased. and the development mode gradually changed from high emissions and high pollution to low-carbon and efficient development. The CO_2 intensities of Guangzhou, Shenzhen, and Foshan cities declined more slowly than those of the other six PRD cities. However, the effect of energy consumption due to technological progress may have caused the CO_2 intensity of cities such as Jiangmen, Zhaoqing, Dongguan, and Foshan to rebound after 2018. As of 2020, Guangzhou and Shenzhen have reached low levels of carbon emission intensity at 0.32 t per million yuan and 0.16 t per million yuan, respectively. This indicates that these two cities have reduced carbon emissions through efficient use of energy and application of carbon-reducing technologies while experiencing steady economic growth. Zhaoqing is at the highest level in the PRD region with 1.12 t per million yuan.

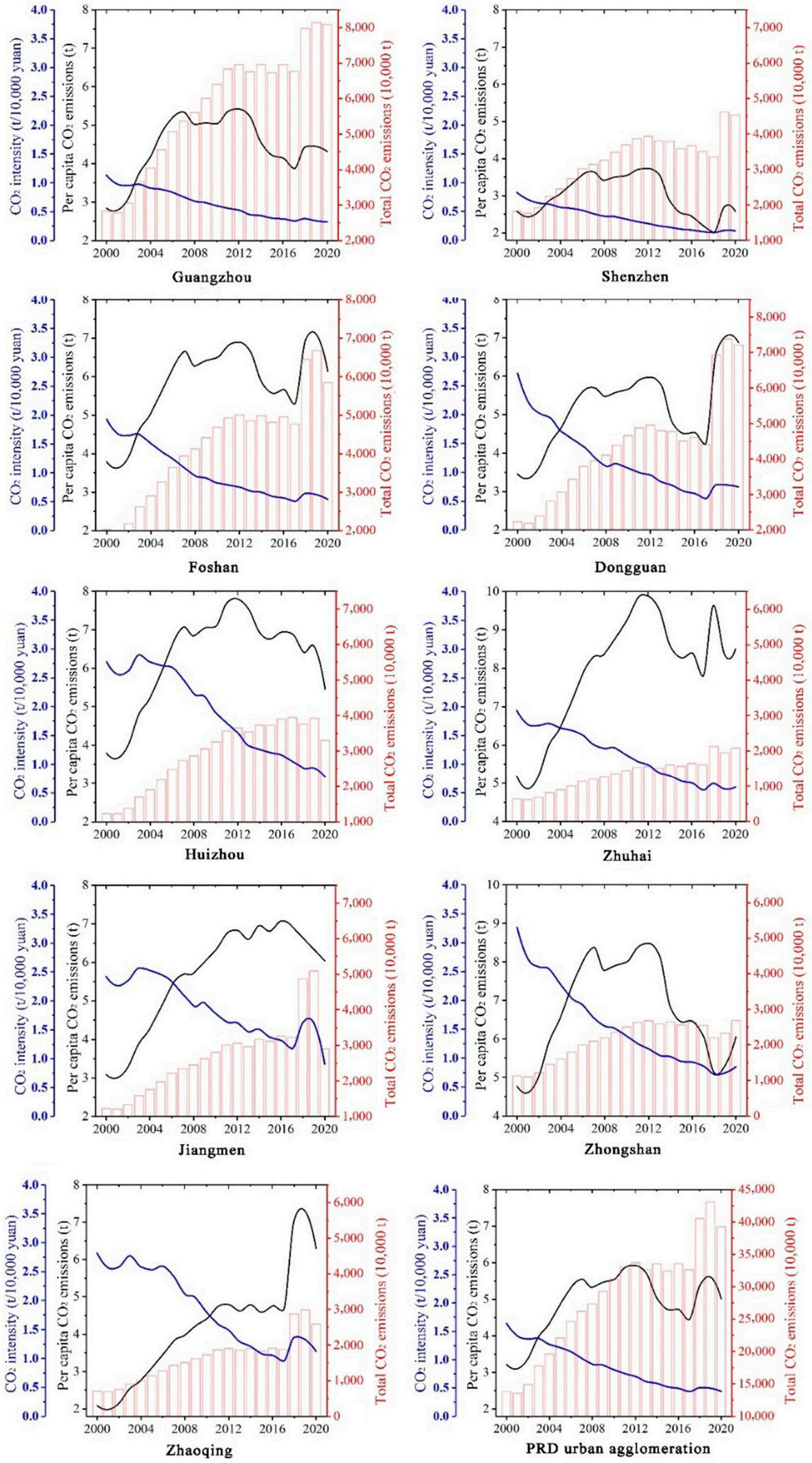

Figure 2. Trends of total CO_2 emissions, CO_2 intensity (blue lines), and per capita CO_2 emissions (black lines) in the Pearl River Delta (PRD) urban agglomeration, 2000–2020.

Figures 3 and 4 depict the spatial and temporal evolutions of the total CO_2 emissions, per capita CO_2 emissions, and CO_2 intensities of the PRD from 2000 to 2020. The gaps among the total CO_2 emissions of the cities in the PRD have widened significantly, and the polarization is more serious by 2020 (Figure 3). The overall spatial distribution revolves around the three cities of Guangzhou, Foshan, and Dongguan, presenting a high center and low periphery pattern indicating a close correlation between carbon emissions and the level of urban economic development with central aggregation.

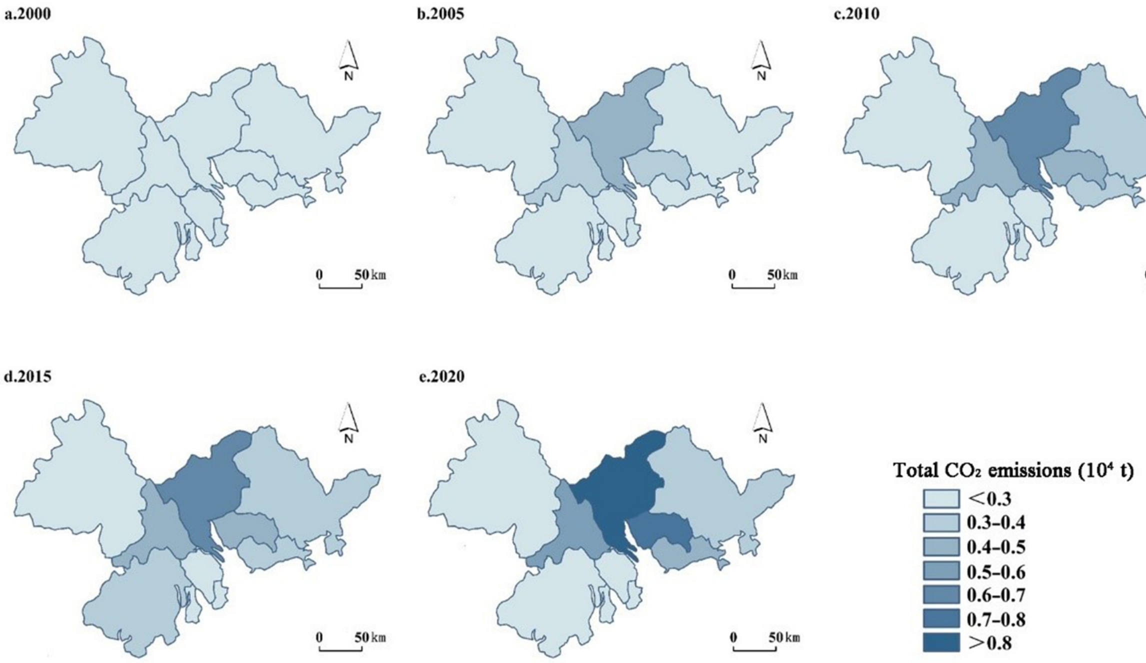

Figure 3. Spatiotemporal evolution of total CO_2 emissions in the Pearl River Delta (PRD) urban agglomeration, 2000–2020.

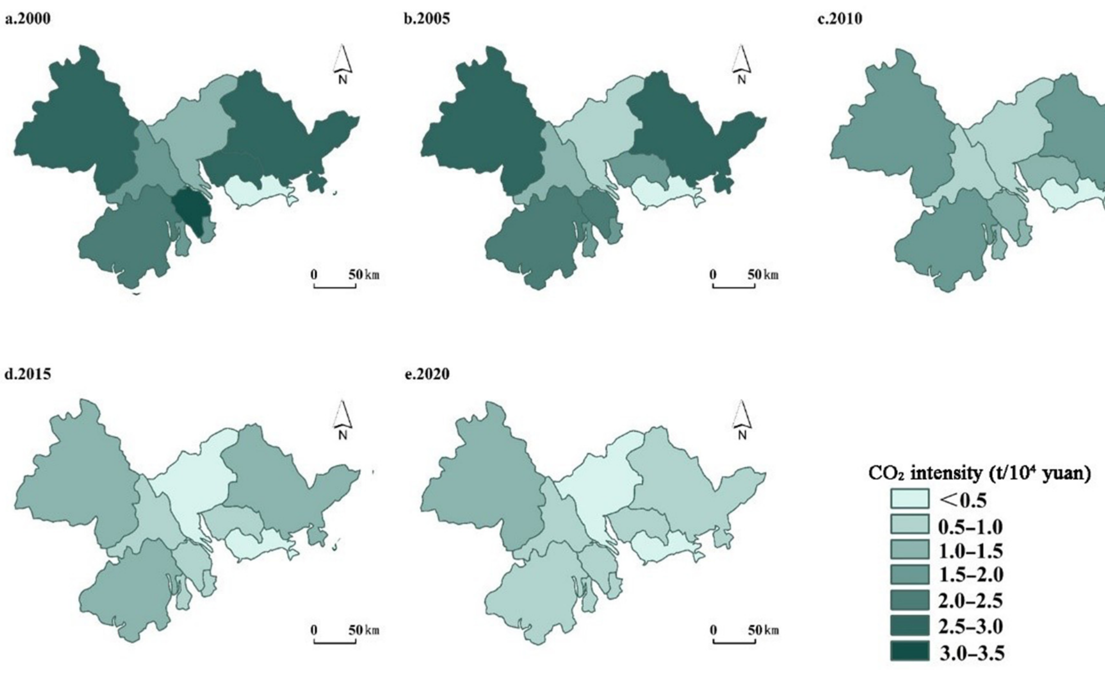

Figure 4. Spatiotemporal evolution of CO_2 intensity in the Pearl River Delta (PRD) urban agglomeration, 2000–2020.

The spatial distribution of carbon emission intensity (Figure 4) is opposite to that of the total carbon emissions, with low values in the center and high values on the periphery. Comparing the spatial distribution patterns of 2000 and 2020, this depression-like feature tends to weaken, indicating a narrowing of regional differences in carbon emission intensity and a more balanced impact of economic development on environmental pressure within the region.

3.2. Decoupling Statuses of Economic Growth from CO_2 Emissions

In recent years, the topic of regional economic development and its correlation with carbon emissions has become a focal point of research. This study undertakes a profound investigation into the decoupling statuses and their transformations over the period of 2000–2020, shedding light on the dynamics and underlying factors steering the decoupling trajectory in the PRD region.

Our analysis, encapsulated in Table 1, reveals marked fluctuations in the decoupling statuses between the PRD's economic development and CO_2 emissions over the study period. This trend of fluctuating decoupling statuses resonates with other research, including a study by Zhao et al. (2017) [37], which also identified variations in decoupling states across different time spans in China. Within the study period of 2000–2020, both weak decoupling and strong decoupling can be observed between economic growth and CO_2 emissions. The majority of years experienced weak decoupling, indicating insufficient decoupling between CO_2 emissions and economic development. These fluctuations can be traced back to various factors such as high urbanization, policy shifts favoring rapid industrialization, which sometimes heightened CO_2 emission [38], and strides in technological advancements and renewable energy adoption contributing to phases of strong decoupling [26].

Table 1. The decoupling of CO_2 emissions from economic development and the trend of decoupling elasticity in the whole Pearl River Delta (PRD) region.

Time Period	ΔC/C	ΔGDP/GDP	ΔEC/EC	$E_{C, GDP}$	Decoupling State	$E_{C, EC}$	$E_{EC, GDP}$
The whole PRD region							
2000–2005	0.105	0.171	2.097	0.614	Weak decoupling	0.050	12.286
2006–2010	0.025	0.094	0.379	0.271	Weak decoupling	0.067	4.055
2011–2015	−0.031	0.041	0.078	−0.769	Strong decoupling	−0.402	1.912
2016–2020	0.012	0.028	0.195	0.442	Weak decoupling	0.064	6.938

The years 2011–2015 notably demonstrated strong decoupling, a positive indication of a shift towards a more sustainable economic model, less reliant on energy-intensive industries. This transformation hints at a burgeoning commitment to sustainable practices within the region, spurred by technological innovations and policy directives aimed at fostering energy efficiency and curtailing carbon footprints. Comparative analysis with preceding studies illustrates a consistent pattern of evolving towards a more sustainable model, a critical step in mitigating the adverse effects of economic growth on the environment.

However, the progress appears somewhat stalled in the period 2016–2020, where a reversion to weak decoupling was observed. This transition signals persistent challenges in sustaining energy conservation and emissions reduction efforts, warranting a deeper scrutiny of the underlying causal factors. The period saw a resurgence in the reliance on energy-consuming industries, dampening the gains achieved in the previous years.

In general, the decoupling of carbon emissions from economic development in the PRD improved during 2000–2015, followed by a slight deterioration during 2016–2020. Specifically, strong decoupling marked the period of 2011–2015, as carbon emissions decreased under economic growth. This indicates that during this period, the economic development of the PRD region has reduced its dependence on energy-intensive and carbon-intensive industries and has transformed towards a low-carbon and sustainable economic development model. However, during the 2016–2020, the relationship between CO_2 emissions and economic development transformed from strong decoupling in the previous period to weak decoupling. This suggests that energy conservation and emissions reduction in the PRD are still challenging.

The trends of energy-saving elasticity and emissions reduction elasticity show a significant gap. Energy-saving elasticity has high volatility, with a particularly sharp decrease in 2010–2015. Compared with the period of 2000–2015, the energy-saving elasticity has picked up in recent years, indicating that the industry in the PRD is still heavily reliant on energy consumption, and energy efficiency should increase. Expansive negative decoupling dominated the emissions reduction elasticity during all periods, indicating that the economic growth of the PRD city cluster still relies on extensive energy consumption at the cost of environmental degradation. However, during the study period, the emissions reduction elasticity has decreased, indicating that the PRD cities are placing greater emphasis on social and economic development while seeking a more low-carbon and environmentally friendly development path. They are improving energy efficiency through technological innovation.

There is significant heterogeneity in the decoupling statuses among the nine cities within the PRD (Table 2). From 2011 to 2015, seven out of nine cities in the PRD achieved strong decoupling, indicating that economic development had the least environmental pressure, and an increase in economic output was accompanied by a decrease in CO_2 emissions. This phenomenon was particularly marked in cities experiencing rapid urban expansion, where strategies to mitigate environmental impacts were more pronounced. However, with further technological advances, a rebound effect has begun to appear, in which the growth rate of the economy was larger than the increase in CO_2 emissions, leading to a worsening decoupling status from strong decoupling in 2016–2020 to weak decoupling (or expansive negative decoupling) in 2016–2020 in Guangdong, Zhuhai, Foshan, and Dongguan. This reiterates the persistent challenge of maintaining an environmental equilibrium amidst booming economic growth, a focal point of discussion in numerous previous analyses [39].

Further, the analysis of the energy-saving elasticity revealed an encouraging trend of decreased dependency on energy consumption for economic development, a sentiment echoed in other contemporary studies focusing on China's sustainable urban development trajectory [40]. Particularly in cities like Guangzhou and Shenzhen, the significant role of energy-saving elasticity in fostering sustainable economic development has been highlighted, showcasing similar patterns to other metropolises globally, where energy efficiency has emerged as a linchpin for sustainable growth [29].

The patterns of decoupling statuses observed within the PRD region serve as a significant indicator of the larger narrative of China's rapid urbanization and strategic regional development. This era of swift urban expansion is marked by an ambitious drive towards economic growth, intricately coupled with sustainable environmental practices. Within the context of the PRD region, the nuanced interplay between escalating urbanization rates, expanding city sizes, intricacies of the social system, and the pace of technological progress serves as central determinants steering both economic and environmental developments.

Within this landscape, cities like Guangzhou and Shenzhen have emerged as frontrunners, exemplifying how advancements in energy efficiency can spearhead sustainable growth, a trend echoed in other global metropolises. The variances in decoupling statuses across different cities within the PRD region underscore the necessity for nuanced approaches in policy formulation and implementation, adapting to the unique characteristics and developmental phases of each city.

Looking forward, the trajectory of the PRD region will be significantly influenced by the intertwining forces of technological advancements and green policy initiatives. The challenge lies in harnessing these dynamic forces effectively to pave a path towards a more sustainable urban development, where economic growth harmonizes with environmental conservation. Thus, leveraging the insights gained from the fluctuations in decoupling statuses, it is incumbent upon policymakers and urban planners to craft strategies that synergize economic growth objectives with sustainable environmental practices, fostering a future where prosperity and ecology exist in harmony.

Table 2. The decoupling of CO_2 emissions from economic development and the trend of decoupling elasticity in the nine cities of the Pearl River Delta (PRD) urban agglomeration.

	ΔC/C	ΔGDP/GDP	ΔEC/EC	$E_{C, GDP}$	Decoupling State	$E_{C, EC}$	$E_{EC, GDP}$
Guangzhou							
2000–2005	0.144	0.160	1.935	0.897	Expansive coupling	0.074	12.088
2006–2010	0.010	0.052	0.200	0.188	Weak decoupling	0.048	3.872
2011–2015	−0.039	0.027	−0.016	−1.436	Strong decoupling	2.412	−0.595
2016–2020	0.005	0.018	0.166	0.301	Weak decoupling	0.032	9.387
Shenzhen							
2000–2005	0.084	0.083	1.804	1.013	Expansive coupling	0.047	21.679
2006–2010	0.020	0.062	0.307	0.314	Weak decoupling	0.064	4.944
2011–2015	−0.111	0.013	−0.180	−8.466	Strong decoupling	0.619	−13.681
2016–2020	0.006	0.009	−0.040	0.640	Strong decoupling	−0.145	−4.416
Zhuhai							
2000–2005	0.053	0.105	1.713	0.500	Weak decoupling	0.031	16.295
2006–2010	0.032	0.095	0.772	0.337	Weak decoupling	0.041	8.130
2011–2015	−0.012	0.030	0.222	−0.422	Strong decoupling	−0.056	7.515
2016–2020	0.003	0.003	0.037	0.992	Expansive coupling	0.087	11.464
Foshan							
2000–2005	0.086	0.162	1.329	0.530	Weak decoupling	0.065	8.203
2006–2010	0.024	0.095	0.279	0.252	Weak decoupling	0.086	2.948
2011–2015	−0.026	0.045	0.084	−0.567	Strong decoupling	−0.306	1.855
2016–2020	0.017	0.034	0.130	0.490	Weak decoupling	0.129	3.797
Huizhou							
2000–2005	0.094	0.203	3.870	0.460	Weak decoupling	0.024	19.039
2006–2010	0.029	0.145	1.132	0.200	Weak decoupling	0.026	7.822
2011–2015	−0.007	0.071	0.497	−0.097	Strong decoupling	−0.014	7.039
2016–2020	−0.035	0.052	0.541	−0.676	Strong decoupling	−0.065	10.326
Dongguan							
2000–2005	0.098	0.284	2.024	0.345	Weak decoupling	0.049	7.117
2006–2010	0.014	0.134	0.099	0.108	Weak decoupling	0.146	0.743
2011–2015	−0.045	0.063	−0.035	−0.720	Strong decoupling	1.274	−0.565
2016–2020	0.077	0.063	0.299	1.216	Expansive negative decoupling	0.256	4.756
Zhongshan							
2000–2005	0.074	0.242	2.366	0.305	Weak decoupling	0.031	9.761
2006–2010	0.011	0.110	0.296	0.098	Weak decoupling	0.036	2.689
2011–2015	−0.030	0.044	0.056	−0.688	Strong decoupling	−0.538	1.279
2016–2020	−0.010	0.045	0.217	−0.224	Strong decoupling	−0.046	4.866
Jiangmen							
2000–2005	0.117	0.273	2.503	0.427	Weak decoupling	0.047	9.162
2006–2010	0.049	0.186	0.917	0.263	Weak decoupling	0.053	4.925
2011–2015	0.012	0.096	0.763	0.121	Weak decoupling	0.015	7.912
2016–2020	−0.019	0.047	0.377	−0.399	Strong decoupling	−0.050	8.049
Zhaoqing							
2000–2005	0.157	0.429	6.504	0.367	Weak decoupling	0.024	15.169
2006–2010	0.096	0.347	3.834	0.276	Weak decoupling	0.025	11.063
2011–2015	0.008	0.175	1.104	0.048	Weak decoupling	0.008	6.313
2016–2020	0.059	0.089	0.370	0.668	Weak decoupling	0.161	4.157

4. Conclusions and Policy Implications

4.1. Conclusions

This study estimated the imbalances of CO_2 emissions and emission intensity in the PRD urban agglomeration from 2000 to 2020, and discussed the decoupling states between CO_2 emissions and economic growth. Urban agglomerations play important roles as China's regional economic development engines and are an important geographical unit driving coordinated regional development, as well as a key node in China's low-carbon sustainable transition development. This work provides a reference for regional emission-reduction policies and low-carbon development. The main conclusions are as follows.

Firstly, the unbalanced development of the PRD urban agglomeration is a major concern, as it leads to significant disparities in economic development and CO_2 emissions. The spatial pattern of total CO_2 emissions is high in the center and low on the periphery, indicating that urban areas in the center of the region emit more CO_2 than those on the outskirts. In contrast, CO_2 intensity is lower in the center and higher on the periphery.

Secondly, the decoupling analysis show that there is significant volatility in the decoupling of economic development and CO_2 emissions in the PRD. Weak decoupling occurred in most years, indicating economic growth leading to an increase in CO_2 emissions. Overall, the decoupling between CO_2 emissions and economic development in the PRD shows an improving trend from 2000 to 2015, meaning that economic growth and growth in carbon emissions are becoming less correlated, but the decoupling then worsens slightly from 2016 to 2020, especially in Guangdong, Zhuhai, Foshan, and Dongguan. This indicates that the PRD region still faces challenges in energy conservation and emission reduction.

Thirdly, a detailed examination of energy-saving and emission-reduction elasticities underscore a clear divergence in trends. The energy-saving elasticity has high volatility, with an especially significant decline from 2010 to 2015. Compared with 2000–2015, the energy-saving elasticity has rebounded in recent years, indicating that the dependence of industries in the PRD region on energy consumption is still high, and energy efficiency needs to improve. Emission-reduction elasticities have declined over the study period, indicating that the PRD cities are emphasizing social and economic development while seeking a low-carbon and environmentally friendly development path. In Guangzhou and Shenzhen, the trends of energy-efficiency elasticity and decoupling elasticity are the same, indicating that energy-efficiency elasticity plays a more critical role in decoupling economic development from carbon emissions. In other cities, the decoupling elasticity is more important than the energy-efficiency elasticity.

Given the dynamic and multi-faceted nature of economic and environmental developments, future research can take a deeper dive into analyzing the intricate relationship between CO_2 emission decoupling and various influential variables such as urbanization rate, city size, social system, and technological progress. In addition, it would be immensely beneficial to verify the findings of this study through the application of regression models. Such analytical approaches can provide a more granular understanding of the factors influencing decoupling statuses in the PRD region, aiding in the creation of more nuanced and effective policies. Furthermore, studies could explore the potential synergies between technological innovations and urban policies in fostering sustainable growth, drawing from a wider pool of data that encompasses recent developments and trends in the region.

4.2. Policy Implications

To forge a resilient and sustainable path for urban agglomerations, it is critical to focus on actionable strategies that can significantly influence the trajectory of environmental sustainability while fostering economic growth.

Firstly, the establishment of a data-driven policy-making framework would serve as a cornerstone in crafting policies that are sensitive to regional discrepancies [41–44]. This involves not only monitoring but also leveraging insights from a centralized database that keeps track of environmental parameters across various cities. This dynamic repository can foster intelligent decision-making, enabling cities to adapt strategies that focus on economic agglomeration effects and industrial restructuring based on real-time data and trends. Furthermore, it can serve as a blueprint for other cities in identifying sectors ripe for low-carbon transformations.

Secondly, in fostering collaboration, the creation of regional knowledge platforms can be a vital asset [45–47]. Regular forums and dialogue platforms can be institutionalized to foster a culture of knowledge exchange and collaboration. These platforms should be equipped to facilitate technical know-how exchange, and sharing of successful case studies, thereby fostering a culture of collaborative growth and learning.

Thirdly, to streamline regional cooperation, a regional coordination entity should be established, tasked with the orchestration of collaborative projects, overseeing efficient resource allocation, and maximizing synergies [48–50]. This entity could act as a nerve center, standardizing tools and methodologies for monitoring and management of carbon emission initiatives across various regions, promoting a cohesive approach to sustainable development.

Lastly, policy formulation should be fine-tuned to the unique attributes of individual cities within urban conglomerates, taking into cognizance their respective economic stages, energy consumption patterns, and carbon emission levels. Governments could develop comprehensive guidelines and training programs to aid local policy-makers in crafting policies that resonate with both local conditions and overarching regional emission-reduction objectives, fostering a harmonized approach to sustainable development.

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