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Original Paper

Research on Regional Economic Growth and CO2 Emissions Reduction Targets: A Decoupling Perspective

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Abstract

Elucidating the relationship between economic growth and CO_2 emissions helps promote the coordinated and synergistic development of the economy and the environment. This study utilizes the Tapio decoupling model to analyze the decoupling relationship between economic growth rate and CO_2 emissions in 14 cities of Liaoning Province from 2005 to 2020. Additionally, a model is established with the aim of determining CO_2 reduction targets for achieving strong or weak decoupling states. Results showed that although most cities showed a strong or weak decoupling state, the decoupling performance in specific year was not ideal, the proportion of negative decoupling increased from 2017 to 2020. Liaoning Province faces significant challenges in decoupling economic growth rate from CO_2 emissions, it needs to reduce its CO_2 emissions (CE) by 5659.33 10^7 Kg or 5397.80 10^7 Kg to achieve strong or weak decoupling, respectively. Among the 14 cities, 8 cities have not achieved strong or weak decoupling. Cities such as Anshan, Yingkou, and Benxi face the greatest challenges, with a minimum required reduction of 25.72% in CE, 41.77% in Carbon Emissions per Capita, and 16.62% in Carbon Emissions per Unit of GDP. The research results can provide theoretical support for improving energy efficiency.

Keywords

economic growth rate, CO2 emissions, Decoupling model, Reduction targets, Liaoning Province

1. Introduction

The pursuit of economic growth often relies on resource consumption and has a negative impact on the environment, with the most evident issue being the escalating levels of carbon dioxide (CO2) emissions (Li et al., 2023; Magazzino, 2024; Xie et al., 2023). The complex relationship between economic growth and CO_2 emissions has become critical issues both in economic and sustainable development discourse (Wang et al., 2022; You et al., 2022). As the global community strives to mitigate climate change and promote a sustainable economy, the need to decouple economic growth from resource dependence and environmental degradation has never been more urgent. In China, "carbon neutrality" and "peak carbon" have set clear regulations for CO_2 emission reduction targets. Addressing the issue of economic development that results in carbon emissions has become crucial. Understanding the current relationship between economic growth and CO_2 emissions, as well as estimating emission reduction targets, is foundational work for addressing the issue.

Under different levels of economic development or with different regional industrial structures, the correlation between economic growth and CO_2 emissions shows distinct differences (Sufyanullah et al., 2022; Gaies et al., 2022). Since economic growth is typically closely related to CO_2 emissions, previous studies have indicated that regional CO_2 emissions can be used to characterize the level of economic growth (Li et al., 2023; Jebabli et al., 2023; González-Álvarez & Montañés, 2023). For instance, Liu et al. (2022) indicated that the economic growth of the developed eastern provinces in China are not highly dependent on energy consumption (i.e., low CO_2 emissions), while the provinces at a lower or middle level of economic development rely excessively on energy consumption (i.e., high CO_2 emissions). On the other hand, Ozturk et al. (2022) analyzed the relationship between CO_2 emissions, economic growth, and energy consumption in Saudi Arabia from 1968 to 2017, the findings revealed that energy consumption has a positive impact on CO_2 emissions, while Gross Domestic Product (GDP) growth has a negative impact. Onofrei et al. (2022) examined the correlation between economic growth and CO_2 emissions across the 27 EU member states from 2000 to 2017, they highlighted that, on average, a 1% change in GDP results in a 0.072% change in CO_2 emissions, and emphasized the necessity for crafting environmental policies that can reduce emissions during times of economic growth. Existing studies have indicated that the relationship between economic growth and carbon emissions varies under different levels of economic development and industrial structures.

To explore the decoupling relationship between economic growth and CO_2 emissions, a series of theoretical frameworks and methodologies have been developed (Gao et al., 2021; Wang et al., 2024). For example, the Environmental Kuznets Curve (EKC) theory provides an framework for analyzing the relationship between environmental pressure and economic development (Dinda 2004), but it contains unreasonable assumptions such as that economic growth will lead to the improvement of environmental quality (Uchiyama & Uchiyama, 2016; Leal et al., 2022). The limitations of the EKC theory have prompted researchers to explore more dynamic decoupling theories. To measure the level of decoupling, some decoupling indices (such as the Tapio decoupling model, the Organisation for Economic Co-operation and Development Decoupling Index) are utilized to evaluate the evolving connection between carbon emissions and GDP growth (Yang et al., 2023; Liu et al., 2023). Among these indices, the Tapio decoupling model serves as robust and versatile tool widely used for quantifying and analyzing the dynamic relationship between economic growth and environmental pressures. For example, Zhang and Sharifi (2024) adopted the Tapio decoupling model to examine the the relationship between economic growth and CO_2 emissions across China's provincial capitals, and quantified the decoupling relationship. Song et al. (2020), Gyamerah and Gil-Alana (2023) have also demonstrated the effectiveness of the Tapio decoupling model. In addition, structural decomposition analysis and index decomposition analysis methods are used to identify and quantify the key factors driving changes in economic growth and CO_2 emissions (Cansino et al., 2016; Wang et al., 2017, Ang & Goh, 2019). Some scholars developed new models to evaluate the relationship between economic growth and carbon emissions (Mardani et al., 2019). Liu et al. (2022) employed the new two-dimensional decoupling model to scrutinize the dynamics of decoupling between energy-related CO_2 emissions and economic growth. The integrated application of these theories and methods not only deepens our understanding of the economic and behavioral factors behind the decoupling phenomenon, but also provides a scientific basis for formulating effective low-carbon development strategies.

This study aims to analyze the regional economic growth and CO2 emissions reduction targets from a decoupling perspective. The Tapio decoupling model is used to examine the the decoupling relationship between economic growth rate and CO_2 emissions (i.e., CO_2 emissions (CE), CO_2 emissions per capita (CEP), and CO_2 emissions per unit of GDP (CEPGDP)) in 14 cities of Liaoning Province from 2005 to 2020. Additionally, a regional economic growth and CO_2 emissions reduction target model is established with the aim of determining CO_2 reduction targets for achieving strong or weak decoupling states, and understanding the degree of dependence of CO_2 emissions on economic growth in different cities. The primary reason for selecting Liaoning Province as the study area is that it epitomizes the complex dynamics between industrial development and environmental sustainability.

2. Method

2.1 Tapio Decoupling Model

Tapio Decoupling Model serves as a crucial analytical framework for dissecting the complex interplay relationship between economic growth and its environmental implications (Duan et al., 2021). The model was initially proposed by the Organisation for Economic Co-operation and Development (OECD). It has been effectively utilized across various domains, including environmental policy anfalysis, resource management, energy efficiency strategies, and climate change mitigation. The model provides a powerful analytical tool for reducing greenhouse gas emissions, improving energy efficiency, and promoting the development of green technologies. Based on the Tapio Decoupling Model, the dynamic relationship between economic growth and environmental pressure can be clearly revealed. The model considers various periods as distinct time scales, thereby eliminating the need to select a specific base period. The model comprehensively considers both total and relative quantity changes, refining the measurement of the decoupling degree between variables.

The Tapio Decoupling Model is utilized to establish a regional economic growth- CO_2 emissions decoupling model, to explore the degree of coupling and decoupling between economic growth and

CO_2 emissions. The regional economic growth-CO_2 emissions decoupling model is represented as follows:

$$f_i = \frac{\Delta C_i}{\Delta GDP} = \frac{\dfrac{C_n^i - C_{n-1}^i}{C_{n-1}^i}}{\dfrac{GDP_n - GDP_{n-1}}{GDP_{n-1}}}$$

Where f_i is the decoupling coefficient between economic growth and the CO_2 emissions of CE (i=1), CEPP (i=2), or CEPGDP (i=3); C_n^i and C_{n-1}^i represent the CO2 emissions of i in the nth and (n-1)th year (n = 2006, 2007, …, 2020), respectively; ΔC_i refers the CO_2 emissions of i in the nth year difference from the emissions of i in the (n-1)th year; GDP_n and GDP_{n-1} represent the GDP in the nth and (n-1)th year, respectively; ΔGDP refers the GDP in the nth year difference from the emissions of i in the (n-1)th year.

The regional economic growth-CO_2 emissions decoupling model takes into account both total and relative changes, categorizing decoupling into three states: decoupling, negative decoupling, and connection; and further divides them into eight levels of decoupling intensity (Table 1).

Table 1. Grade Classification of Decoupling of the Economic Growth and CO_2 Emissions

Decoupling Relationship		Type	ΔC_i	ΔGDP	f_i
Decoupling states	Decoupling levels				
Decoupling	Strong decoupling	I	＜0	＞0	≤0
	Weak decoupling	II	＞0	＞0	(0,0.8)
	Recession decoupling	III	＜0	＜0	≥1.2
Negative decoupling	Strong negative decoupling	IV	＞0	＜0	≤0
	Weak negative decoupling	V	＜0	＜0	(0,0.8)
	Growth negative decoupling	VI	＞0	＞0	≥1.2
Connection	Growth link	VII	＞0	＞0	（0.8,1.2）
	Recession connection	VIII	＜0	＜0	（0.8,1.2）

For the decoupling states, the decoupling state is the most desirable state, the connection state is the next best, and the negative decoupling state is the least desirable. In the strong decoupling state, economic growth is realized independently of the expense associated with CO_2 emissions, while economic growth continues to be significantly tied to CO_2 dioxide emissions in both negative decoupling and connection states. For the decoupling levels, the strong decoupling level is the most desirable level, i.e., economic growth does not lead to an increase in CO_2 dioxide emissions.

2.1 Regional Economic Growth and CO_2 Emissions Reduction Target Model

Based on the regional economic growth-CO_2 emissions decoupling model and the grade classification of decoupling of the regional economic growth and CO_2 emissions, the regional economic growth and

CO_2 emissions reduction target model is established to analyze the CO_2 emissions reduction target for the different decoupling levevls (i.e., strong decoupling, weak decoupling, and recession decoupling). In the computation of CO_2 emission reduction targets, the results for weak decoupling and recession decoupling are consolidated and presented as weak decoupling for clarity. This study takes 2020 as the current period and 2019 as the base period, and calculates the CO_2 emission reduction targets for achieving strong decoupling, weak decoupling, and recession decoupling based on the relationship between economic growth and CO_2 emissions.

Let DC_{2020}^{i} represent the CO_2 emissions in 2020 where economic growth and CO_2 emissions are decoupled, the CO_2 emissions reduction target is RC_{2020}^{i} (i.e., the difference between the CO_2 emissions in 2020 and DC_{2020}^{i}). The regional economic growth and CO_2 emissions reduction target model is represented as follows:

(1) If $\Delta GDP > 0$, it is necessary to ensure that $f_i \le 0$ to guarantee that economic growth and CO_2 emissions are in a state of strong decoupling, i.e.:

$$f_i = \frac{\Delta C_i}{\Delta GDP} = \frac{\dfrac{C_{2020}^{i} - C_{2019}^{i}}{C_{2019}^{i}}}{\dfrac{GDP_{2020} - GDP_{2019}}{GDP_{2019}}} \le 0$$

Therefore, the CO_2 emissions in 2020 should statisfy $0 \le DC_{2020}^{i} \le C_{2019}^{i}$.

(2) If $\Delta GDP > 0$, it is necessary to ensure that $0 < f_i < 0$ to guarantee that economic growth and CO_2 emissions are in a state of weak decoupling, i.e.:

$$0 < f_i = \frac{\Delta C_i}{\Delta GDP} = \frac{\dfrac{C_{2020}^{i} - C_{2019}^{i}}{C_{2019}^{i}}}{\dfrac{GDP_{2020} - GDP_{2019}}{GDP_{2019}}} < 0.8$$

Therefore, the CO_2 emissions in 2020 should statisfy $C_{2019}^{i} \le DC_{2020}^{i} \le C_{2019}^{i} + 0.8C_{2019}^{i}\Delta GDP$.

(3) If $\Delta GDP < 0$, it is necessary to ensure that $f_i \ge 1.2$ to guarantee that economic growth and CO_2 emissions are in a state of weak decoupling, i.e.:

$$f_i = \frac{\Delta C_i}{\Delta GDP} = \frac{\dfrac{C_{2020}^{i} - C_{2019}^{i}}{C_{2019}^{i}}}{\dfrac{GDP_{2020} - GDP_{2019}}{GDP_{2019}}} \ge 1.2 .$$

Therefore, the CO_2 emissions in 2020 should statisfy $0 \le DC_{2020}^{i} \le C_{2019}^{i} + 1.2C_{2019}^{i}\Delta GDP$.

As mentioned above, if $DC_{2020}^{i} \ge C_{2019}^{i}$,then $RC_{2020}^{i} = 0$; if $DC_{2020}^{i} < C_{2019}^{i}$,then $RC_{2020}^{i} \ge C_{2020}^{i} - DC_{2020}^{i}$.

3. Study Area and Data

3.1 Study Area

Liaoning Province is located at the southern end of Northeast China and is a province with a long history and well-developed industry. It borders the east of the Yellow Sea and the west of Bohai Sea;

has belongs to the temperate monsoon climate, with hot and humid summers and cold and dry winters. According to the statistical data from the Liaoning Provincial Bureau of Statistics, the GDP of Liaoning Province in 2020 was 2,515.0 billion yuan. Among them, the value added of the primary, secondary, and tertiary industries were 228.46, 940.09, and 1,342.94 billion yuan. It has maintained a relatively high economic growth rate overall, with the long-term average GDP growth rates of various cities from 2005 to 2020 ranging between 7.18% and 11.01%. As an important part of China's industrial base, it has a strong manufacturing industry foundation. Liaoning Province plays a significant role in fields such as steel, petrochemicals, and equipment manufacturing. Meanwhile, it is actively fostering the growth of modern service sectors and high-tech industries to attain diversified economic development. With the rapid development of industrialization and urbanization, issues related to energy consumption and CO_2 emissions have become increasingly prominent. From 2005 to 2020, CO_2 emissions in Liaoning Province increased relatively steadily, with an average annual CO_2 emission of 34.68 million tons. There is significant spatial variation, with the average annual CO_2 emissions in various cities ranging from 13.45 to 60.78 million tons.

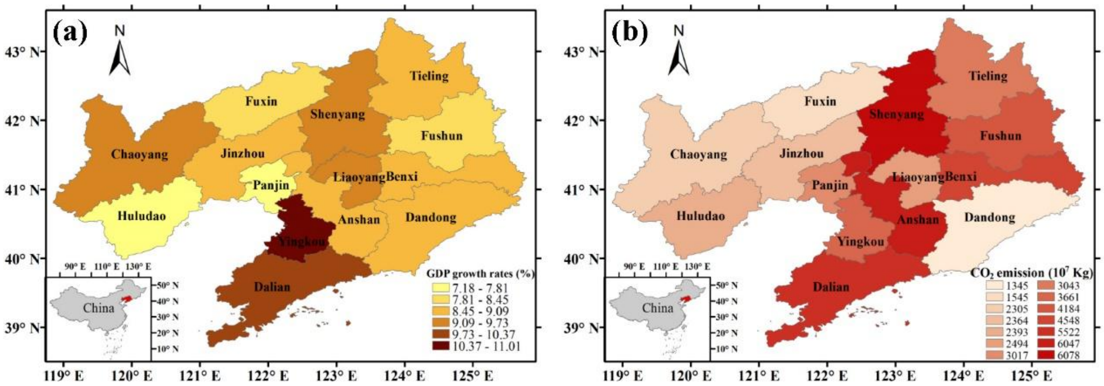

Figure 1. The Average Yearly GDP Growth Rates (a) and CO_2 Emissions (b) in Different Cities of Liaoning Province During the Period from 2005 to 2020

3.2 Data

This study focuses on the 14 cities in Liaoning Province, examining the decoupling relationship between economic growth and CO_2 emissions in each city, as well as their targets for reducing CO_2 emissions. The economic growth rate data is selected from the Liaoning Statistical Yearbook, which is published by the Liaoning Provincial Bureau of Statistics (https://tjj.ln.gov.cn/tjj/tjsj/tjnj/index.shtml), covering the years 2005 to 2020. The CO2 emissions data spanning from 2005 to 2020 is derived from the Carbon Emission Accounts and Datasets (https://www.ceads.net.cn/data/city/), with missing data supplemented by publications from the Institute of Public and Environmental Affairs. (https://www.ipe.org.cn/MapLowCarbon/LowCarbon.html).

4. Results and Discussion

4.1 The Decoupling Relationship Between Regional Economic Growth and CO_2 Emissions

During the period from 2006 to 2020, the economic growth rates of various cities in Liaoning Province generally showed a strong or weak decoupling state with CE, CEPP, or CEPGDP (Figure 2), but the decoupling status was not as favorable in certain years. The economic growth and CO_2 emissions typically maintain a rather well-coordinated connection in Liaoning Province. On average, over 50% of cities exhibit a state of strong or weak decoupling between economic growth and CE, CEPP, or CEPGDP; 20% to 30% of cities are in a state of negative decoupling, with 16% to 25% exhibiting growth negative decoupling, meaning that the majority of cities in Liaoning Province are primarily characterized by a state of negative decoupling. The period between 2006 and 2016 showed a more favorable decoupling status; however, conditions deteriorated from 2017 to 2020, as the negative decoupling ratio rose to between 52% and 59%. This shift is primarily attributed to the economic deceleration in Liaoning Province, coupled with CO_2 emissions that have stayed at comparatively elevated levels.

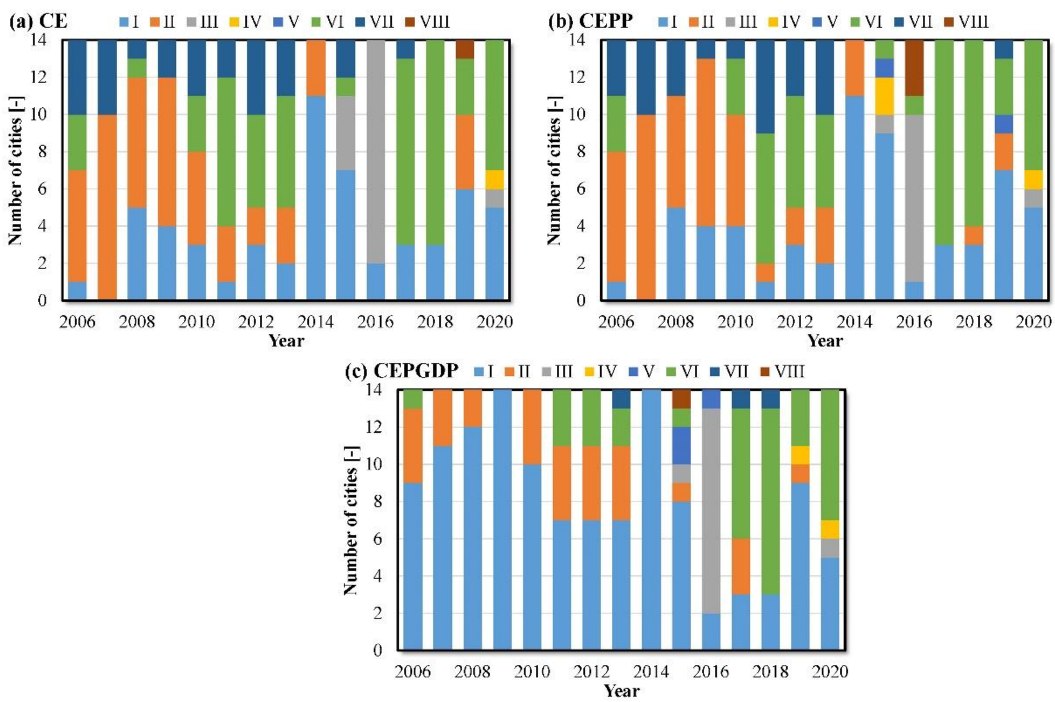

Figure 2. The Number of Cities with Different Levels of Decoupling Between Economic Growth Rate and CE, CEPP, and CEPGDP from 2006 to 2020

Overall, the decoupling state of CEPGDP is best favorable state, CE is the next best, and CEPP has the least favorable decoupling state (Figure 2). For CE, the number of cities in the decoupling state ranges from 2 to 14, with an average of 7.1 cities over the years, and the percentage of decoupling cities is at 51%; while the number of cities in the negative decoupling state ranges from 0 to 11, with an average of 3.9 cities over the years (Figure 2a). Liaoning Province still faces significant challenges in decoupling economic growth rates from CE, mainly due to the long-term high dependence of its economic development on heavy industry and high-energy-consuming industries, which has led to a strong coupling relationship between CO_2 emissions and economic growth. For CEPP, the number of cities in the decoupling state is essentially consistent with CE, but the average number of cities in a state of negative decoupling reaches 4.3 (Figure 2b). For CEPGDP, the average number of cities in a state of decoupling is 10.1, while the average number for weak decoupling is only 2.8 (Figure 2c).

Spatially, Liaoning Province exhibits a significant spatial differences in the decoupling status between the economic growth rate and CE, CEP, and CEPGDP. To analyze the spatial differences, the years 2006, 2013, and 2019 were selected to examine the decoupling levels between economic growth and CO_2 emissions in different cities.

Results revealed that cities experiencing faster or slower economic growth were typically characterized by a state of strong or weak decoupling in relation to CE, CEP, and CEPGDP, while those with more stable economic growth exhibited a general trend of negative decoupling concerning these indicators (Figure 3). As time progresses, the variations in decoupling states among various cities demonstrate notable disparities. For example, some cities (e.g., Shenyang, Tieling, Huludao) has transitioned from a decoupling state to a negative decoupling state, while cities such as Benxi, Jinzhou, etc. show an opposite trend. On the other hand, Fushun, Panjin, and some other cities have consistently remained in a state of negative decoupling. These differences may be caused by a variety of factors, including the industrial structure, energy efficiency, policy enforcement, and the application of green technologies in different regions.

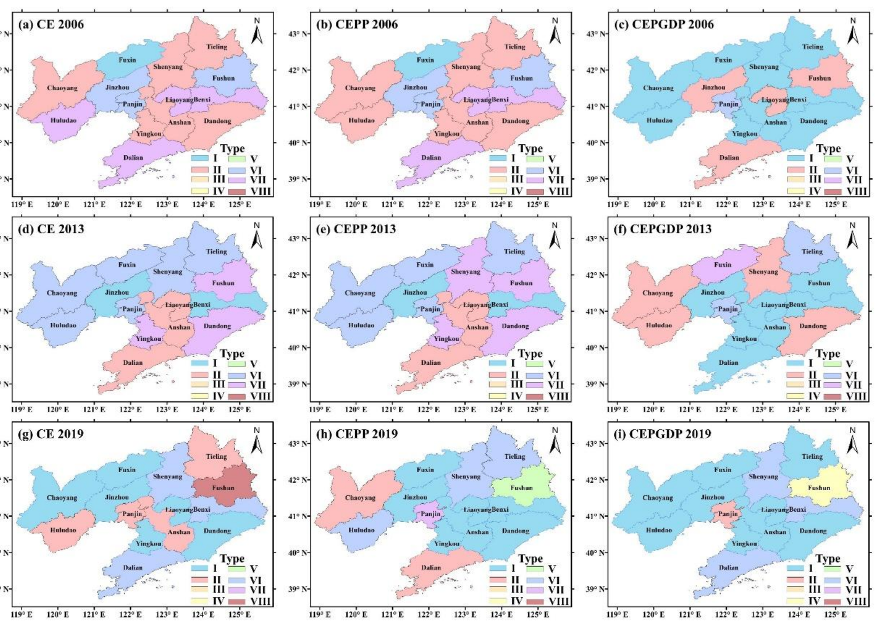

Figure 3. The Level of Decoupling between Economic Growth Rates and CE, CEPP, CEPGDP in Various Cities of Liaoning Province from 2006 to 2020

4.2 Regional Economic Growth and CO_2 Emissions Reduction Targets

Based on the regional economic growth and CO_2 emissions reduction target model, this study selects 2020 as the current period to analyze the CE, CEPP, and CEPGDP reduction targets for achieving strong and weak decoupling between regional economic growth and CO_2 emissions. The CE, CEPP, and CEPGDP reduction targets for achieving strong and weak decoupling in various cities of Liaoning Province are shown in Table 2. Overall, Liaoning Province needs to reduce CE by 5659.33 10^7 Kg or 5397.80 10^7 Kg to achieve strong or weak decoupling between economic growth rate and CO_2 emissions. Compared to the current period, achieving strong decoupling and weak decoupling requires a reduction in CE by 11.66% and 11.11%, respectively.

The cities in Liaoning Province continue to face significant challenges in decoupling their economic growth rates from CO_2 emissions. Out of 14 cities in Liaoning Province, 8 cities have not achieved strong or weak decoupling (Figures 4 and 5). Among them, cities such as Anshan, Yingkou, Chaoyang, and Benxi face the greatest challenges. In contrast to the current period, Anshan, Yingkou, Chaoyang, and Benxi need to reduce their CE by 35.46%, 34.89%, 27.82% , and 25.72% respectively; and CEPP by 45.44%, 41.77%, 33.97%, 55.18% respectively; and CEPGDP by 22.17%, 19.94%, 17.33%, and 16.62% respectively (Figure 4). Cities such Liaoyang and Dandong face the second greatest challenges, Liaoyang, Jinzhou and Dandong need to reduce their CE by 7.06%, 6.89% and 6.53, respectively; and CEPP by 23.03%, 16.90% and 17.28%, respectively; and CEPGDP by 4.80%, 3.75% and 4.46%, respectively (Figure 4). Fushun City faces relatively minor challenges, requiring a reduction in its CE, CEPP, and CEPGDP by less than 10%. The challenges faced by the aforementioned cities in achieving weak decoupling between economic growth rates and CE, CEPP, and CEPGDP are similar to those for strong decoupling, and thus will not be further elaborated upon (Figure 5). Overall, the economic growth rate in Liaoning Province still largely depends on resource consumption.

Table 2. The CE, CEPP, and CEPGDP Reduction Targets for Regional Economic Growth in Various Cities of Liaoning Province Aim to Achieve Strong and Weak Decoupling from CO2 Emissions

Cities	Strong decoupling			Weak decoupling		
	CE (10^7 Kg)	CEPP (10^3 Kg per Capita)	CEPGDP (10^3 Kg per 10^4 Yuan)	CE(10^7 Kg)	CEPP(10^3 Kg per Capita)	CEPGDP (10^3 Kg per 10^4 Yuan)
Shenyang	0.00	0.00	0.00	0.00	0.00	0.00
Dalian	0.00	0.00	0.00	0.00	0.00	0.00
Anshan	2144.20	7.87	0.65	2125.00	7.81	0.64
Fushun	0.00	1.88	0.17	0.91	1.39	0.08
Benxi	1169.60	16.24	1.05	1080.00	15.71	0.97
Dandong	87.86	0.97	0.08	82.76	0.95	0.08
Jinzhou	162.84	1.30	0.11	161.32	1.30	0.11

Yingkou	1277.44	6.38	0.70	1206.90	6.09	0.65
Fuxin	0.00	0.00	0.00	0.00	0.00	0.00
Liaoyang	176.01	3.18	0.16	160.92	3.09	0.14
Panjin	0.00	0.00	0.00	0.00	0.00	0.00
Tieling	0.00	0.00	0.00	0.00	0.00	0.00
Chaoyang	641.38	2.39	0.76	580.00	2.18	0.68
Huludao	0.00	0.00	0.00	0.00	0.00	0.00

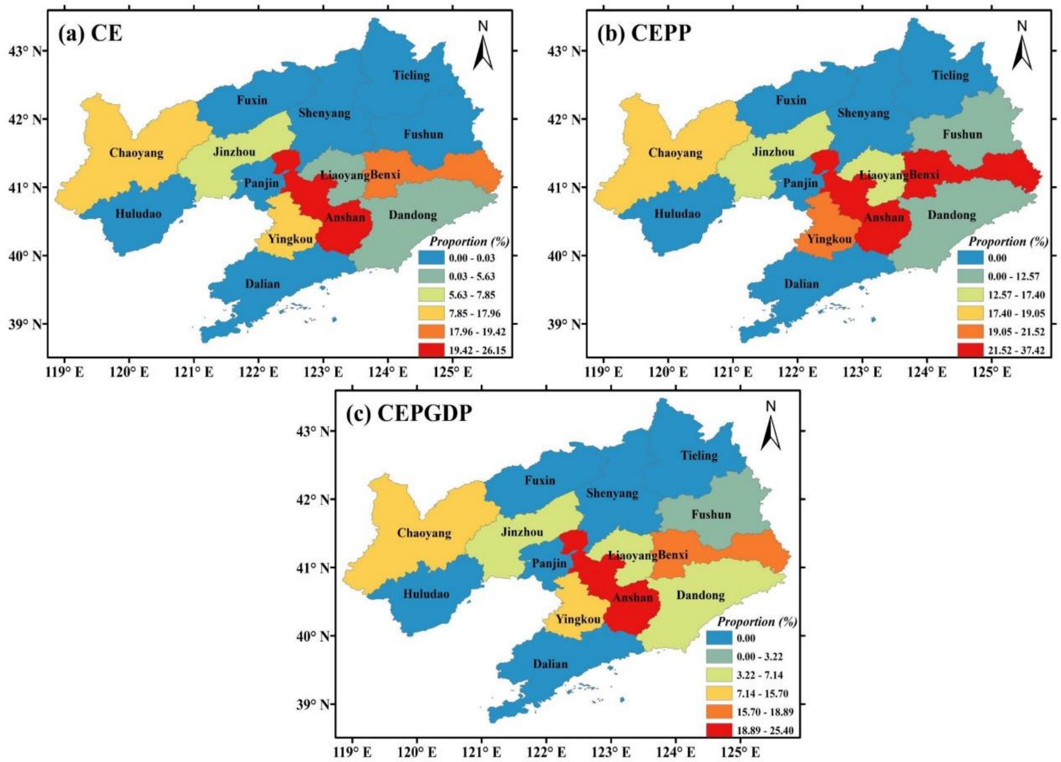

Figure 4. The Reduction Ratios for Liaoning Province's Cities to Achieve Strong Decoupling Between Economic Growth Rates and CE (a), ECPP (b), CEPGDP (c), Respectively

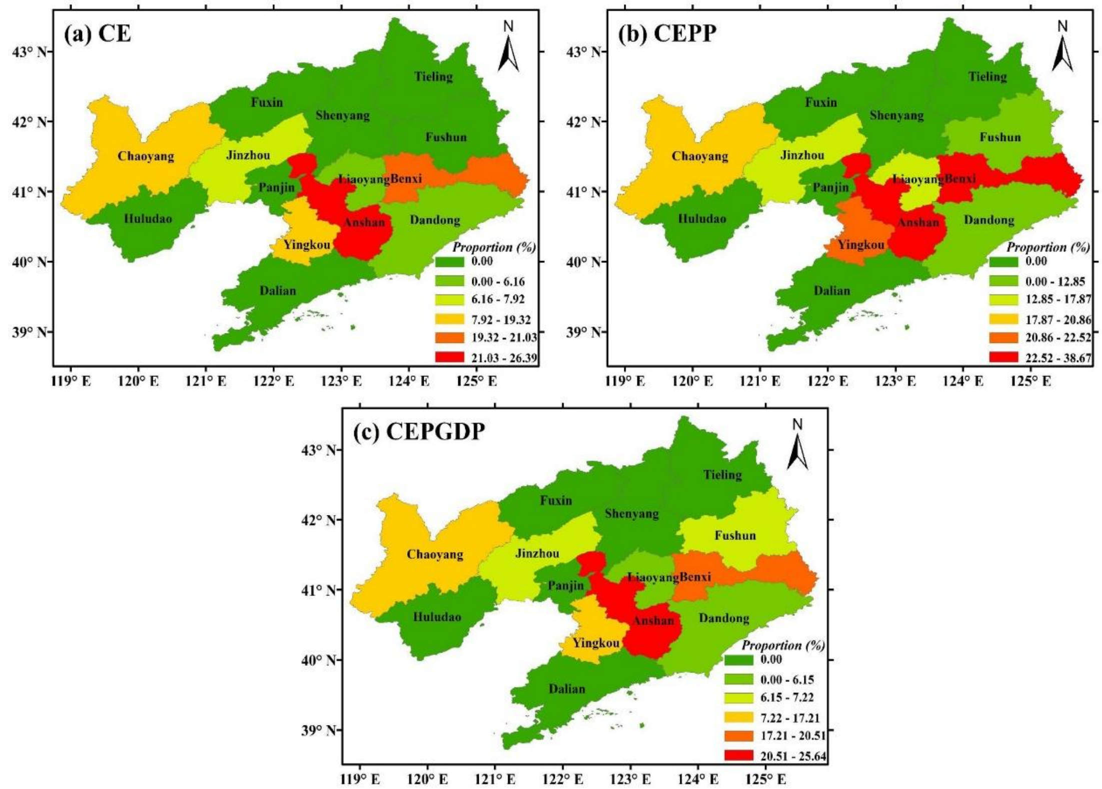

Figure 5. Similar to Figure 4 but for Weak Decoupling

5. Conclusions

This study utilizes the economic growth, CE, CEPP, and CEPGDP data across 14 cities in Liaoning Province, spanning the period from 2005 to 2020. Utilizing the Tapio Decoupling Model, it examines the decoupling relationships between economic growth and CE, CEPP, and CEPGDP, respectively. And leveraging the established Regional Economic Growth and CO2 Emissions Reduction Target Model, the study determines the specific CO_2 reduction targets required for each city to attain strong and weak decoupling states. The following conclusions are drawn:

(1) Although the majority of cities demonstrated a state of strong or weak decoupling from 2005 to 2020, the decoupling performance in specific years was not satisfactory. Particularly between 2017 and 2020, the proportion of negative decoupling increased, indicating that while economic growth slowed, CO_2 emissions remained high.

(2) The decoupling status of CEPGDP is the most favorable, followed by CE, while the decoupling status for CEPP is the least optimistic. In terms of CE, on average, 7.1 cities showed a state of decoupling (i.e., strong and weak decoupling), accounting for 51%; while the average number of cities in a state of negative decoupling is 3.9. The number of cities in a decoupling state for CEPP is essentially consistent with that of CE, but the average number of cities in a state of negative decoupling reaches 4.3. Regarding CEPGDP, an average of 10.1 cities achieved a state of decoupling, and the average number of cities in a weak decoupling state is only 2.8.

(3) To achieve strong or weak decoupling between economic growth rates and CE, Liaoning Province

needs to reduce its CE by 5659.33 10^7 Kg or 5397.80 10^7 Kg, respectively. Compared to the current level, this translates to a reduction of 11.66% for strong decoupling and 11.11% for weak decoupling.

(4) Overall, the cities in Liaoning Province continue to face significant challenges in decoupling their economic growth rates from CO_2 emissions. Among the 14 cities, 8 cities have not achieved strong or weak decoupling. Among them, cities such as Anshan, Yingkou, Chaoyang, and Benxi face the greatest challenges, with a minimum required reduction of 25.72% in CE, 41.77% in CEPP, and 16.62% in CEPGDP. The economic growth of Liaoning Province still largely depends on resource consumption.

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