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Coupling between Carbon Efficiency and Technology Absorptive Capacity—A Case Study of the Yangtze River Economic Belt

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Abstract: Regional carbon efficiency (CE) improvement is critical to China's "taking concerted efforts to achieve ecological protection" strategy in the Yangtze River Economic Belt (YREB) and their program to build a leading demonstration belt for ecological civilization. This study applied the super efficiency slacks-based measure to calculate the regional differences and evolution characteristics of the YREB's CE from the year of 2006 to 2017. It also constructed a coupling evaluation model to empirically analyze the interactions between CE and technology absorptive capacity (TAC). The results showed that (1) the CE for all YREB provinces followed a "U-shaped" trend. TAC generally increased and incrementally decreased in the sequence of the upper stream, middle stream, and downstream. The gap among the downstream, upper stream, and middle stream increased; (2) coupling between the CE and TAC for the YREB provinces can be characterized as a relatively stable medium to low coupling degree and medium-to-high coordination degree. To improve coupling and achieve balanced, sustainable development in the YREB, this study proposes several measures, including promoting balanced, high-quality economic development, building the YREB talent pool, appropriately guiding foreign capital flows, implementing the strategy of driving economic development through innovation, and launching the network for coordinated technological innovation in YREB.

Keywords: carbon efficiency; technology absorptive capacity; SE-SBM model; degree of coupling and coordination

1. Introduction

Since the industrial revolution, along with the rapid development of global industrialization and urbanization, the extensive economic development model at the cost of consuming a lot of energy has brought serious challenges to the ecological environment, such as global climate change, sea level rise, and other serious ecological environmental problems [1–3]. It has a serious impact on the regional economic and social development of various countries, attracting the attention of governments from various countries. The Yangtze River Economic Belt (YREB) runs across China horizontally, linking the eastern, central, and western regions. In terms of geographic areas, the downstream area covers Shanghai, Jiangsu, Zhejiang, and Anhui; the middle stream area includes Jiangxi, Hubei, and Hunan; and the upper stream area includes Chongqing, Sichuan, Guizhou, and Yunnan. With its population and GDP both accounting for over 40% of the national total quantity, the YREB is an inland river economic belt with global importance. Promoting the YREB development was a critical decision made by the Chinese government, as it is part of a broader strategy for China's development. Implementing the decision on a national level since 2014 has brought rapid economic development in 11 provinces (in this study, they also include municipalities directly under the central government) located in the economic belt, and reform programs such as innovation-driven growth and supply-side reform have been achieved, producing a vibrant economy. In 2019, the YREB GDP was RMB 45.8 trillion Yuan, which represents 46.2% of China's total GDP. Nevertheless, it is challenging to maintain the YREB's development considering the significant threats to the Yangtze River's ecological environment, including deteriorating water quality in areas along the river and heavy pollution from fixed wastes. Therefore, to promote YREB development, the Chinese government must formulate a plan that acts in the interests of future generations and highlights the importance of the restoration of the river's ecological environment. In this plan, to build a superior economic belt while improving its ecosystem, unwavering and concerted efforts are needed to succeed in the substantial undertaking required for ecological protection and to prevent massive development projects. In its "13th Five-Year Plan" for 2016–2020, the government proposed that development should be "innovation-driven, coordinated, green, open, and inclusive" [4]. Specifically, for promoting the YREB's sustainable development, the plan highlighted the key role of technological innovation in economic development, laid out measures that could facilitate assimilation of foreign knowledge and technologies by the YREB provinces, and set higher targets for energy conservation and emission reduction performance. Therefore, for YREB economic development and ecological restoration, a systematic approach is necessary to enhance the synergy and coupling between technological progress and ecological protection. Furthermore, clarifying the relationship between technological innovation and the environmental quality is very important for building a sustainable economic development mode in YREB.

Theoretically, the growth mode of technological innovation should follow the law of ecological economic development. One of the purposes of innovation and development is to guide the mode of economic growth to the resource and energy intensive one, thus energy consumption and environmental pollution would be reduced [5]. Ideally, a higher absorptive capacity level for technological innovation could promote technology spillover and product innovation, improve management efficiency and innovation performance, and optimize industrial structure, thereby having positive effects on CE. In turn, improved CE could provide social and economic activities with a better environment, which could drive and facilitate growth based on technological innovation, thus increasing absorptive capacity for technological innovation [6]. Therefore, in this study, TAC was taken as a separate explanatory variable in the coupling analysis of CE and TAC in the YREB. It is expected that the insights on the interactions between the improvement of CE and TAC in the YREB provinces could provide useful input to the government's decision-making process.

2. Literature Review

Absorptive capacity was first defined by Cohen [7] as an individual, organization, or country's ability to acquire, assimilate, convert, and exploit external knowledge and technology. Studies on technology spillover in different sectors and areas have considered absorptive capacity effects. Li et al. [8] found that the regional difference in agricultural technological efficiency growth and agricultural growth could be satisfactorily explained by the constraints in terms of absorptive capacity. Zahra and George [9] suggested that absorptive capacity is instrumental in developing new products and improving their novelty. Zhu et al. [10] found a non-linear relationship between the absorptive capacity and regional performance in innovation by empirical testing with a panel threshold model. All these studies have demonstrated the lagged effects and constraints of absorptive capacity. They also confirmed that absorptive capacity is an important factor that determines whether innovative technologies could directly lead to product innovation or technology spillover.

Concerning the relationship between technological progress and ecological protection, most recent studies argued that technology spillover from foreign direct investment (FDI) has positive effects on carbon emission reduction or incorporated absorptive capacity as a factor or condition for explaining the technology spillover effects on domestic technological progress. For example, Li [11] indicated that FDI could have positive effects on an industry's carbon emission performance through horizontal, vertical, and backward technology spillover. While investigating the effects of FDI technology spillover on energy efficiency, Fan et al. [12] found that in the study regions, the effects are lagged, implying that those regions could not fully absorb advanced foreign production technologies to improve energy efficiency. Abdoulaye [13] and Tian [14] suggested that absorptive capacity is a key determinant of the technology spillover effects. More recently, Yu [15] proposed that absorptive capacity could be used to predict the strength of the technology spillover effects. All of these studies are indicative of the absorptive capacity role in determining how technology spillover could affect carbon emission. Shangguan [16] established a direct relationship between foreign technology spillover and domestic technological progress without considering the intermediate role of absorptive capacity, meaning the inflow of advanced foreign technologies would definitely lead to technological progress. However, such an argument could be misleading and cause the government to make policies only for technology spillover without considering absorption. By employing a regression model, Zhou [17] found that foreign technology spillover from FDI and exporting businesses inhibited rather than promoted carbon productivity improvement, further highlighting the importance of absorption.

In terms of methodologies, coupling analysis has been widely applied in the carbon emissions area to measure the interactions between multiple systems related to carbon emissions. For instance, Lu et al. [18] constructed a coupling model that incorporated three systems, energy, economy, and environment, for measuring the coupling and coordination levels among the three systems for four major regions in China from 1995–2014. The results showed that the coupling level among the three systems continued increasing albeit with a lower absolute value. Regional differences were also noticeable and the general pattern was high in the east and low in the west. Cao et al. [19] investigated the coupling between industrial structure and carbon dioxide emissions and found an intermediate level of coupling and consistency between the two. In other words, the industrial structural adjustment movement and the results of controlling carbon dioxide emissions were consistent to an intermediate degree; therefore, by building a coupling model, it is possible to capture the relationship between CE changes and absorptive capacity, thereby revealing the inner driving forces in economic development and industrial structural adjustment.

Based on the existing domestic and foreign literatures, it is found that research generally did not take the technology absorption capacity as an independent explanatory variable, ignoring the possibility of improving energy conservation and emission reduction from the perspective of technology absorption capacity. In this study, the coupling between carbon efficiency (CE) and technology absorptive capacity (TAC) in the YREB from the year of 2006 to 2017 was examined. The goal of this study was to identify ways to facilitate coordination between economic development and ecological protection and relevant recommendations were proposed for policy making to realize the strategic goal of green and sustainable development in the YREB.

3. Methodology and Materials

3.1. Methodology

3.1.1. The Method for Evaluating CE in the YREB

CE is one of several key indicators that measure an area's performance in low-carbon development, where "carbon" generally refers to carbon dioxide from energy consumption. In China, industrial energy consumption is a major carbon emission source. In the related research of CE, there are two main research methods: One is single-factor evaluation, the other is total-factor evaluation. The single-factor evaluation mainly measures CE by the carbon productivity indicator, which is simple and easy to apply [20–23]; however, it cannot capture the comprehensive factors affecting carbon emissions and its characteristics, such as capital and labor that act in conjunction with energy consumption. In contrast, the total-factor evaluation considers the joint actions of multiple factors, for example, capital and labor, and is used more widely in investigating CE because it accounts for the comprehensive characteristics of carbon emission in a specific area [24,25].

Data envelopment analysis (DEA) is an important tool in the total factor evaluation; however, conventional DEA models have several defects. First, measurement errors may be introduced due to radial and angular selections because input and output slackness is not considered. Second, based on the perspective of the desirable output, carbon dioxide emission is included as an input in the object functions, contrary to the fact that carbon dioxide is an undesirable output in regional development. Third, because the maximum efficiency value is one, which it is the case for multiple efficient decision-making units (DMUs), it is impossible to compare a combination of multiple efficient DMUs. Tone [26] developed the slacks-based measure (SBM) for non-radial and non-angular efficiency measurement. Slack variable direction inclusion into the object function could avoid the measurement errors caused by differences in the radial and angular selections. Tone and Sahoo [27] later incorporated undesirable outputs into an SBM model, which could better describe that, in reality, carbon dioxide emission is an undesirable output. For addressing the first conventional model defect, Andersen and Petersen [28] proposed a super efficiency model, which could accurately rank the combination of multiple efficient DMUs (i.e., the maximum efficiency value could exceed 1) on the production frontier.

In this study, the super efficiency model and SBM are combined to build the super efficiency SBM (SE-SBM) [29–31]. In contrast to DEA models we have mentioned, the SE-SBM can appropriately handle undesirable outputs, consider input and output slackness issues, and further distinguish among the efficient DMUs [31–33]. Thus, a better measure of the carbon super efficiency in the YREB can be determined. In the. SE-SBM model, it assumes that the production system has n decision-making units, and each decision-making unit contains m inputs (x), s_1 expected outputs (y^g), and s_2 unexpected outputs (y^b). The matrix X, Y^g, and Y^b are defined as $X = [x_1, x_2, \ldots, x_n]$, $Y^g = [y_1^g, y_2^g, \ldots, y_n^g]$, $Y^b = [y_1^b, y_2^b, \ldots, y_n^b]$, where these input and output variables are greater than 0. In line with Ding et al. [30], the SE-SBM model is constructed as follows:

$$\min\rho = \frac{1 + \frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{ik}}}{1 - \frac{1}{q_1+q_2}\left(\sum_{r=1}^{q_1}\frac{s_r^{g+}}{y_{rk}^g} + \sum_{r=1}^{q_2}\frac{s_t^{b-}}{y_{rk}^b}\right)}$$

s.t.

$$\begin{aligned}
&\sum_{j=1,j\neq k}^{n} x_{ij}\lambda_j - s_i^- \le x_{ik}\\
&\sum_{j=1,j\neq k}^{n} y_{rj}^g\lambda_j + s_r^b \ge y_{rk}^g\\
&\sum_{j=1,j\neq k}^{n} y_{tj}^b\lambda_j - s_t^b \le y_{tk}^b\\
&1 - \frac{1}{q_1+q_2}\left(\sum_{r=1}^{q_1}\frac{s_r^g}{y_{rk}^g} + \sum_{r=1}^{q_2}\frac{s_r^b}{y_{rk}^b}\right) > 0\\
&s^-, s^g, s^b, \lambda \ge 0;\\
&i = 1,2,\cdots,m; r = 1,2,\cdots,q;\\
&j = 1,2,\cdots n(j \neq k)
\end{aligned} \tag{1}$$

This model, x_{ij} is the ith input of jth DMU, and y_{rj} is the rth output of jth DMU. s is slack variable of input resources and output product. λ is the weight vector, ρ is the objective functions of three varizbles s^-, s^b, and s^g. The value of s^-, s^b, and s^g is between 0 and 1.

3.1.2. Method for Evaluating TAC in the YREB

The absorptive capacity is comprehensive in its coverage of a multitude of fields. According to Zhao et al.'s [34] comprehensive indicator evaluation, this study utilized the entropy method to measure the TAC level in the YREB. Specifically, the entropy is calculated by the following steps:

1. In order to avoid the case in which data for the entropy do not exist, a data shift is applied to the original indicator value X_{ij} of the jth indicator in the ith plan [35]. For positive indicators:

$$X'_{ij} = \frac{X_{ij} - min(X_{1j}, X_{2j}, \cdots, X_{nj})}{max(X_{1j}, X_{2j}, \cdots, X_{nj}) - min(X_{1j}, X_{2j}, \cdots, X_{nj})} + 1,\ (i = 1, 2, \cdots, n; j = 1, 2, \cdots m) \tag{2}$$

For negative indicators:

$$X'_{ij} = \frac{max(X_{1j}, X_{2j}, \cdots, X_{nj}) - X_{ij}}{max(X_{1j}, X_{2j}, \cdots, X_{nj}) - min(X_{1j}, X_{2j}, \cdots, X_{nj})} + 1,\ (i = 1, 2, \cdots, n; j = 1, 2, \cdots m) \tag{3}$$

2. The ratio of the jth indicator in the ith plan to the sum of the jth indicator is calculated as:

$$P_{ij} = \frac{X'_{ij}}{\sum_{i=1}^{n} X'_{ij}},\ (j = 1, 2, \cdots m) \tag{4}$$

3. The entropy of the jth indicator is calculated as:

$$e_j = -k \sum_{i=1}^{n} P_{ij} \ln(P_{ij})$$

where

$$k > 0,\ k = 1/\ln(m),\ e_j \geq 0 \tag{5}$$

4. The coefficient of variation of the jth indicator is calculated as:

$$g_j = \frac{1 - e_j}{m - E_j}$$

where

$$E_j = \sum\nolimits_{j=1}^{m} e_j,\ 0 \leq g_i \leq 1,\ \sum\nolimits_{j=1}^{m} g_j = 1 \tag{6}$$

5. The weight of each coefficient of variation is determined by the following equation:

$$\omega_j = \frac{g_j}{\sum_{j=1}^{m} g_j},\ (j = 1, 2, \cdots m) \tag{7}$$

6. The development level of each variable is:

$$S_i = \sum\nolimits_{j=1}^{m} \omega_j * P_{ij}, (i = 1, 2, \cdots n) \tag{8}$$

3.1.3. Method for Coupling Evaluation

"Coupling" is a concept in physics for capturing the interactions of multiple systems. TAC and CE are coupled due to their interactions; therefore, based on the TAC and CE evaluations, it is possible to construct a dual coupling model to investigate their interactions as follows:

$$C = \left(\frac{E(x)I(y)}{(E(x) + I(y))^2} \right)^{1/2} \tag{9}$$

where C denotes the coupling degree, $E(x)$ represents the CE value, $I(y)$ is the TAC value, and the value range of the coupling degree, C, is 0–1. Mathematically, it can be found that high coupling degree occurs not only when the two systems are at high levels, but also when both systems are at low levels. The coupling degree only represents interaction strength rather than the comprehensive effect and the synergies among the systems [19]; therefore, to describe the coupling between CE and TAC further, a coordination model was introduced. The coordination model not only captures the coordinating degree, but also the development level of the systems. A high coordinating degree indicates that CE and absorptive capacity are generally strongly correlated and developed rather consistently. The coordinating degree index, R, can be expressed as:

$$R = \sqrt{C \times (\alpha * E(x) + \beta * I(y))} \tag{10}$$

where C is the coupling degree; $E(x)$ and $I(y)$ represent CE and TAC value, respectively; and α and β are the weights for CE and TAC, respectively. According to Cao et al. [19] and Guan et al. [36], TAC and CE are equally important in the system; therefore, the weights for $E(x)$ and $I(y)$ are both assigned a value of 0.5, and R is in the range of 0–1.

3.2. Materials

3.2.1. Selection of Indicators

Selection of Indicators for End Point CE in the YREB

In the CE measurement model, the inputs selected usually include capital stock, labor force, and energy consumption [24]. For the selection of capital stock and labor force indicators, consideration is given to quality differences between new and old capital and different labor forces. Drawing on the indicator selection method of Tian et al. [37], and based on the perpetual inventory method, the capital stock indicator, which accounts for capital age in years, is used as the indicator for the system's capital stock input. Furthermore, the labor force indicator, which accounts for years of education per person, is used as the indicator for the system's labor force input. The energy consumption is represented by the total annual energy consumption of each province. In terms of indicators for system outputs, regional GDP and carbon dioxide emission are used for the system's desirable and undesirable outputs, respectively [38,39]. Thus, the specific indicators selected are shown in Table 1 as follows:

Table 1. Indicators selections for regional carbon efficiency (CE) in the Yangtze River Economic Belt (YREB).

	System Layer	Indicator Layer
Carbon efficiency	System inputs	Capital stock considering capital age in years (billion yuan)
		Labor force considering years of education (persons)
		Total annual energy consumption of each province (10,000 t)
	System outputs	Regional GDP (billion yuan)
		Carbon dioxide emission (10,000 t)

Selection of Indicators for TAC in the YREB

Researchers have proposed many evaluation indicators for absorptive capacity in different dimensions. In the micro dimension, Chen et al. [40] suggested that a firm's absorptive capacity of knowledge could be measured in terms of its knowledge base, research and development (R&D) activities, management capabilities, knowledge environment, and capital. In the macro dimension, the system of the evaluation indicators for absorptive capacity is more complex and there is still no widely accepted system. Su and Li [41] suggested that absorptive capacity mainly includes human capital, institutions, R&D expenditure ratios, urbanization rate, trade openness, technological gap, and comprehensive variables. Huang et al. [42] investigated the absorptive capacity from three dimensions including level of human capital, government expenditure, and financial development in the host country. Zhang [43] suggested that the absorptive capacity could be examined from dimensions such as technological R&D, human capital, trade openness, marketization level, institutions, financial market efficiency, and intellectual property rights protection. In summary of these studies, the absorptive capacity can be classified into three categories. The first category is the absorptive capacity based on R&D activities, which reflects a region's R&D capabilities and knowledge base for absorbing new knowledge and technologies. Investment in R&D could improve an industry's capabilities in imitating and innovation. Therefore, investment plays a key role in determining how much technology spillover will be absorbed. The second category relates to the macro environment in a region, including economic development level, trade openness, institutions, and intellectual property rights protection. Changes in the environment also affect the absorbing technology spillover results. The third category is regarding human capital, as affluent human capital is instrumental in improving technology spillover absorption [43]; therefore, as shown in Table 2, this study constructed a comprehensive evaluation system for TAC in the YREB based on the four dimensions of R&D investment level, economic development level, human capital, and economic openness.

Table 2. A comprehensive evaluation system for technology absorptive capacity (TAC).

	Dimensions	**Indicators**
Technology absorptive capacity	R&D investment level	Ratio of R&D expenditure over GDP (%)
	Economic development level	Regional per capita GDP (Yuan/person)
	Human capital	Labor force considering years of education (persons)
	Economic openness	FDI (million USD)

3.2.2. Data Sources

Considering the access of the data, the panel data were collected from 11 YREB provinces from 2006 to 2017. The underlying data for the input and output indicators, as well as the TAC evaluation indicators, are from the "statistical yearbooks" for the provinces and the "China energy statistical yearbooks" for the corresponding years. As one of the input indicators, the energy consumption for each province is the annual energy consumption in standard coal derived by multiplying the standard coal coefficients and the consumption of their corresponding energy types, including raw and cleaned coal, coke, gas, liquefied petroleum and natural gas, crude oil, gasoline, kerosene, diesel and fuel oil, heat, and electricity. Among the system output indicators, the GDP of each province from 2006 to 2017 was converted into the constant price in 2006, and the carbon dioxide emissions are the total gas emissions of all the energy consumption end points in each province [44].

4. Results and Discussion

4.1. Results and Discussion of CE in the YREB

CE of the 11 YREB provinces was calculated by MAXDEA6.6 PRO, and the results are presented in Table 3. According to the SE-SBM principle, CE is classified into three levels: Fully efficient (greater than 1), weakly efficient (between 0.5 and 1), and inefficient (less than 0.5).

Table 3. Super efficiency slacks-based measure (SE-SBM) index for CE in the YREB (2006–2017).

Province	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Mean
Shanghai	1.155	0.898	0.850	0.854	0.829	0.812	0.805	0.798	0.795	0.884	0.938	1.821	0.953
Jiangsu	1.030	0.807	0.757	0.748	0.761	0.738	0.728	0.714	0.725	0.782	0.953	1.040	0.815
Zhejiang	1.069	0.861	0.769	0.743	0.736	0.716	0.694	0.669	0.667	0.707	0.767	1.012	0.784
Anhui	0.716	0.542	0.518	0.504	0.515	0.521	0.502	0.463	0.449	0.462	0.481	0.511	0.516
Jiangxi	0.623	0.521	0.503	0.465	0.528	0.530	0.523	0.497	0.490	0.502	0.524	0.542	0.521
Hubei	0.921	0.563	0.522	0.501	0.503	0.497	0.505	0.524	0.514	0.553	0.580	0.601	0.565
Hunan	1.022	0.593	0.547	0.527	0.577	0.587	0.592	0.576	0.566	0.580	0.559	1.000	0.644
Chongqing	0.574	0.527	0.456	0.464	0.475	0.478	0.480	0.510	0.506	0.554	0.602	1.010	0.553
Sichuan	0.754	0.588	0.529	0.488	0.489	0.517	0.514	0.484	0.473	0.497	0.525	0.561	0.535
Guizhou	0.350	0.309	0.311	0.300	0.319	0.329	0.338	0.340	0.345	0.359	0.389	0.431	0.343
Yunnan	0.424	0.371	0.356	0.339	0.357	0.361	0.365	0.368	0.362	0.399	0.461	0.421	0.382
Aggregate	0.691	0.606	0.569	0.556	0.588	0.583	0.566	0.554	0.550	0.584	0.617	0.666	0.594

As shown in Figure 1, in terms of temporal changes, the figures for the 11 provinces all were basically followed a "U-shaped" trend. As shown in Table 2, between 2006 and 2017, the CE of all provinces peaked in 2006 or 2017, with four provinces (Shanghai, 1.155; Jiangsu, 1.030; Zhejiang, 1.069; and Hunan, 1.022) achieving full efficiency in 2006, and five provinces (Shanghai, 1.821; Jiangsu, 1.040; Zhejiang, 1.012; Hunan, 1.000; and Chongqing, 1.010) reaching full efficiency in 2017. Over 81.8% of the provinces had a mean value larger than 0.5, which was in the weak efficient range. Only Guizhou (0.343) and Yunnan (0.382) had values below 0.5, and were therefore classified as inefficient in terms of carbon emission. In the study horizon, CE followed a decreasing trend and then rebounds (mainly in 2015), indicating that the national strategy for promoting sustainable economic development measures in the YREB were starting to be effective. These measures included increasing local government investments in science and technology, promoting economic recovery and development, ascribing significant importance to ecological environmental protection, and enhancing regulations for environmental protection. The YREB was abandoning its traditional energy-extensive and inefficient growth model that relied on large-scale investment at the expense of ecological and environmental benefits and was instead adopting a sustainable and intensive economic development model that emphasizes industrial structure optimization and ecological environmental protection.

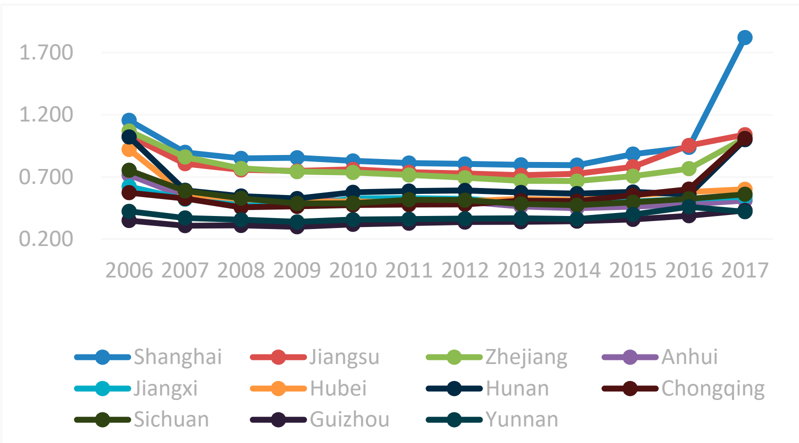

Figure 1. CE of the YREB provinces in 2006–2017.

In terms of spatial distribution, the regional difference in CE for the YREB provinces was obvious, with the value decreasing gradually from the downstream area to the upper stream areas. The average CE of Shanghai (0.953), Jiangsu (0.815), and Zhejiang (0.784) in the downstream area was higher and had an overall average efficiency of 0.767, while the middle and upper stream areas had a substantially lower efficiency. The mean for Jiangxi (0.521), Hubei (0.565), Hunan (0.644), Chongqing (0.553), and Sichuan (0.535) were in the range between weak efficient and inefficient, while those of Guizhou (0.343) and Yunnan (0.382) were in the inefficient range. The differences in CE could mainly be explained by the economic development level, industrial structure, and technology spillover effects. In the downstream area, the economic development model and technological development level were discernibly better than those in the middle and upper stream areas. In addition, the spread of economic and technological development from the downstream weakened with increased distance, resulting in an uneven CE distribution along the YREB.

4.2. Results and Discussion of TAC in the YREB

Table 4 shows the evaluation results of the YREB's TAC calculated by the entropy weight method. For a more intuitive presentation of the TAC's development level, TAC was allocated into five sections based on mean values as follows: Section I (equal to or larger than 0.726), Section II (between 0.526 and 0.725), Section III (between 0.326 and 0.525), Section IV (between 0.126 and 0.325), and Section V (between 0 and 0.125) [45].

Table 4. YREB's TAC evaluation results (2006–2017).

Province	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Mean
Shanghai	0.673	0.668	0.676	0.673	0.667	0.664	0.665	0.671	0.686	0.711	0.708	0.745	0.684
Jiangsu	0.777	0.802	0.797	0.802	0.819	0.822	0.839	0.845	0.848	0.851	0.852	0.856	0.826
Zhejiang	0.475	0.495	0.516	0.517	0.532	0.529	0.545	0.549	0.544	0.553	0.557	0.581	0.533
Anhui	0.314	0.311	0.270	0.288	0.293	0.296	0.318	0.330	0.325	0.346	0.333	0.364	0.316
Jiangxi	0.124	0.129	0.167	0.167	0.165	0.155	0.158	0.162	0.148	0.151	0.155	0.214	0.158
Hubei	0.325	0.317	0.328	0.354	0.361	0.355	0.359	0.359	0.357	0.358	0.354	0.385	0.351
Hunan	0.266	0.261	0.292	0.305	0.309	0.306	0.315	0.313	0.307	0.307	0.304	0.360	0.304
Chongqing	0.136	0.150	0.135	0.149	0.161	0.166	0.181	0.178	0.165	0.182	0.187	0.186	0.165
Sichuan	0.400	0.383	0.358	0.371	0.376	0.350	0.352	0.351	0.348	0.353	0.354	0.375	0.364
Guizhou	0.061	0.048	0.047	0.055	0.018	0.014	0.014	0.015	0.000	0.006	0.008	0.043	0.027
Yunnan	0.096	0.089	0.090	0.089	0.090	0.095	0.099	0.099	0.081	0.090	0.093	0.111	0.094
Aggregate	0.332	0.332	0.334	0.343	0.345	0.341	0.350	0.352	0.346	0.355	0.355	0.384	0.347

Generally, from 2006 to 2017, the YREB's TAC had increased, but the regional disparity was considerable and expanding, as shown in Figures 2 and 3. In 2006, Jiangsu, Zhejiang, Shanghai, and Anhui were in Sections I, III, II, and IV, respectively. In 2017, except for Jiangsu that maintained a high level of I, Zhejiang, Shanghai and Anhui made a breakthrough to Sections II, I, and III, respectively. Due to their openness, commitment to the development of high-quality and new technologies, and large talent pool, Jiangsu, Zhejiang, and Shanghai, were not only very innovative, but also better positioned to absorb advanced foreign technologies. In 2006, the TACs of Jiangxi, Hubei, and Hunan were in Sections V, IV, and IV, respectively. In 2017, the TAC levels of Jiangxi, Hubei and Hunan increased to Sections IV, III and III, respectively. For Chongqing, Sichuan, Guizhou, and Yunnan, from 2006 to 2017 TAC changed minimally and remained in Sections IV, III, V and V, respectively. In addition, their TACs were the lowest among the YREB provinces. Meanwhile, the sum of the TACs for Jiangsu, Zhejiang, and Shanghai was higher than that of all the other provinces.

In summary, TAC's regional disparity in the YREB was substantial. TAC distribution incrementally decreased in the sequence of the downstream, middle stream, and upper stream. The gap among the downstream, middle, and upper stream was expanding. One plausible explanation for the above results was that after opening up to the outside world, China adopted a strategy to develop its economy progressively from east to west. The development in the middle and upper stream of the YREB lagged behind the downstream, particularly with regard to the level of economic development and openness, R&D investment, and talent attraction. Moreover, the TAC spread substantially weakened as the distance increases. The upper stream provinces gained little benefit from the downstream provinces; therefore, there was little motivation to increase their development.

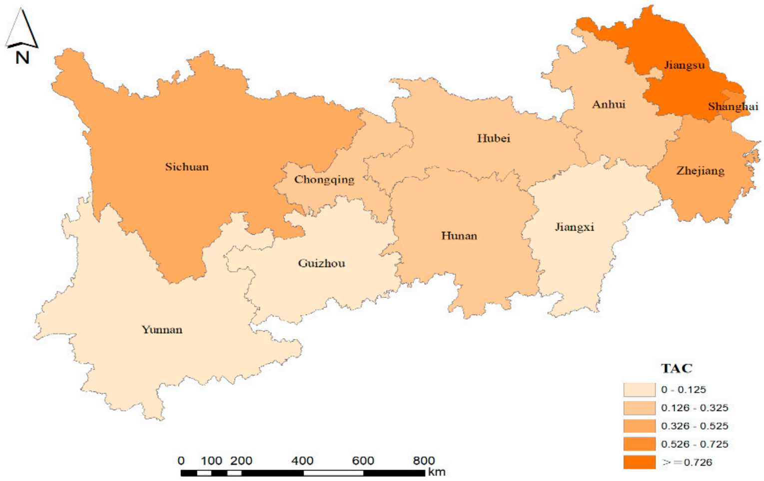

Figure 2. TAC of the YREB provinces in 2006.

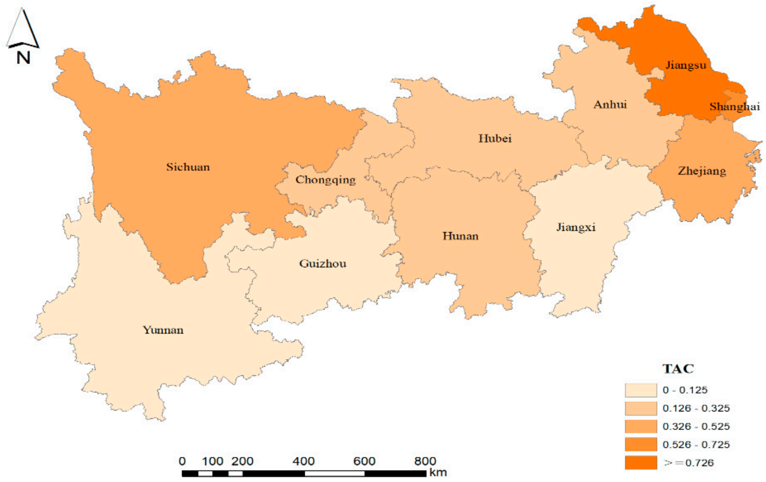

Figure 3. TAC of the YREB provinces in 2017.

4.3. Results and Discussion of Coupling in the YREB

The coupling and coordinating degrees can be divided into several sections according to their mean values [16,44]. Section $0 \leq C < 0.3$ indicates that CE and TAC are weakly coupled and the correlation is very low, section $0.3 \leq C < 0.6$ suggests that CE and TAC are partly coupled, section $0.6 \leq C < 0.8$ suggests that CE and TAC are coupled together and are in the break-in stage, and section $0.8 \leq C < 1.0$ suggests that CE and TAC are highly coupled and they are very highly correlated. Similarly, the coordinating degree is classified as low coordination ($0 \leq R < 0.3$), medium coordination ($0.3 \leq R < 0.6$), high coordination ($0.6 \leq R < 0.8$), and extreme coordination ($0.8 \leq R < 1.0$), representing an incremental increase in the coordinating degree.

Figure 4 and Table 5 summarized the coupling and coordination degrees between CE and TAC for the individual YREB provinces and the aggregated values of CE and TAC from 2006 to 2017. The YREB's overall coupling degree increased from 0.430 in 2006 to 0.441 in 2017, which was always within the partly coupled stage ($0.3 \leq C < 0.6$). The overall coordinating degree increased from 0.483 in 2006 to 0.502 in 2017, which was always within medium coordination stage ($0.3 \leq R < 0.6$). The degree of coupling and coordination fluctuated minimally during the study period, meaning it was stable and without a substantial increase.

(**a**) (**b**)

Figure 4. Coupling and coordination between the CE and TAC for the YREB provinces in 2006–2017. (**a**) Chart for the relative positions of coupling degree. (**b**) Chart for the relative positions of coordinating degree.

Table 5. Degree of coupling and coordination between CE and TAC for the YREB provinces from 2006 to 2017.

	2006		**2007**		**2008**		**2009**		**2010**		**2011**	
	C	**R**	**C**	**R**	**C**	**R**	**C**	**R**	**C**	**R**	**C**	**R**
Shanghai	0.482	0.664	0.495	0.622	0.497	0.616	0.496	0.616	0.497	0.610	0.497	0.606
Jiangsu	0.495	0.669	0.500	0.634	0.500	0.623	0.500	0.622	0.500	0.628	0.499	0.624
Zhejiang	0.462	0.597	0.482	0.571	0.490	0.561	0.492	0.557	0.494	0.559	0.494	0.555
Anhui	0.460	0.487	0.481	0.453	0.475	0.432	0.481	0.437	0.481	0.441	0.481	0.443
Jiangxi	0.372	0.373	0.399	0.360	0.433	0.381	0.441	0.373	0.426	0.384	0.418	0.378
Hubei	0.439	0.523	0.480	0.459	0.487	0.455	0.493	0.459	0.493	0.462	0.493	0.458
Hunan	0.405	0.511	0.461	0.443	0.476	0.447	0.482	0.448	0.477	0.459	0.475	0.460
Chongqing	0.393	0.374	0.416	0.375	0.420	0.353	0.429	0.363	0.435	0.372	0.438	0.376
Sichuan	0.476	0.524	0.489	0.487	0.491	0.467	0.495	0.461	0.496	0.463	0.491	0.461
Guizhou	0.355	0.270	0.342	0.247	0.337	0.246	0.361	0.253	0.223	0.194	0.198	0.184
Yunnan	0.388	0.317	0.395	0.302	0.401	0.299	0.405	0.295	0.401	0.300	0.406	0.304
Aggregate	0.430	0.483	0.449	0.450	0.455	0.444	0.461	0.444	0.447	0.443	0.444	0.441
	2012		**2013**		**2014**		**2015**		**2016**		**2017**	
	C	**R**	**C**	**R**	**C**	**R**	**C**	**R**	**C**	**R**	**C**	**R**
Shanghai	0.498	0.605	0.498	0.605	0.499	0.608	0.497	0.630	0.495	0.638	0.454	0.763
Jiangsu	0.499	0.625	0.498	0.623	0.498	0.626	0.500	0.639	0.499	0.671	0.498	0.687
Zhejiang	0.496	0.555	0.498	0.550	0.497	0.549	0.496	0.559	0.494	0.572	0.481	0.619
Anhui	0.487	0.447	0.493	0.442	0.494	0.437	0.495	0.447	0.492	0.447	0.493	0.465
Jiangxi	0.422	0.379	0.430	0.377	0.422	0.367	0.422	0.371	0.420	0.377	0.451	0.413
Hubei	0.493	0.461	0.491	0.466	0.492	0.463	0.488	0.472	0.485	0.476	0.488	0.491
Hunan	0.476	0.465	0.478	0.461	0.478	0.457	0.476	0.459	0.478	0.454	0.441	0.548
Chongqing	0.446	0.384	0.438	0.388	0.430	0.380	0.432	0.399	0.425	0.410	0.362	0.465
Sichuan	0.491	0.461	0.494	0.454	0.494	0.451	0.493	0.457	0.490	0.464	0.490	0.479
Guizhou	0.198	0.187	0.201	0.189	0.000	0.000	0.122	0.149	0.139	0.166	0.288	0.261
Yunnan	0.410	0.308	0.408	0.309	0.387	0.293	0.387	0.307	0.374	0.322	0.407	0.329
Aggregate	0.447	0.443	0.448	0.442	0.426	0.421	0.437	0.445	0.435	0.454	0.441	0.502

From 2006 to 2017, the degree of coupling and coordination between the CE and TAC for the YREB provinces was within the ranges of 0–0.5 and 0–0.8, respectively. The coupling degree for all the provinces, which was below 0.5, was not satisfactory. However, except for Guizhou when the coupling degree decreased from 0.355 in 2006 to 0.288 in 2017 or when the partly coupled stage ($0.3 \leq C < 0.6$) dropped to the disengaged stage ($0 \leq C < 0.3$), all the other provinces maintained their coupling degree in the partly coupled stage ($0.3 \leq C < 0.6$). During this period, except for Shanghai, Chongqing, and Guizhou, where the coupling degree decreased from 0.482 to 0.454, 0.393 to 0.362, and 0.355 to 0.288, respectively, the coupling degree increased in all the other provinces, albeit minimally. In terms of the coordinating degree, in 2006 and 2017, Shanghai and Jiangsu were always in the high coordination stage ($0.6 \leq R < 0.8$); the Zhejiang province upgraded from medium-to-high coordination; Anhui, Jiangxi, Hunan, Chongqing, Sichuan, and Yunnan maintained the medium coordination stage ($0.3 \leq C < 0.6$); and Guizhou remained in the low coordination stage ($0 \leq R < 0.3$). Compared with 2006, the degree of coupling and coordination in 2017 increased moderately for all the provinces except for Anhui, Hubei, Sichuan, and Guizhou.

In summary, the relationship between the CE and TAC for the YREB provinces in the study period could be mainly characterized as a relatively stable medium to low degree of coupling and medium-to-high degree of coordination, with notable regional disparity in terms of the interaction between TAC and CE. The medium coupling and high coordination between the TAC and CE in the downstream area of the YREB were more beneficial and could be attributed to the fact that they began reformation and economic transformation earlier, they had high technology industry clusters, and a high-quality talent pool. However, in the middle and upper stream provinces, the coupling between the TAC and CE was not satisfactory and the results could be explained by their varied degree of success and time receiving industrial transfer and economic spillover effects from the downstream areas. In addition, these provinces did not have sufficient human resources. At the same time, because the coupling degree changed minimally over the study period in these provinces, it was obvious that TAC improvement from increased investments in innovation resources and environmental improvement for economic development failed to bring a significant increase in management efficacy and innovation performance, or considerable optimization of the industrial structure. This issue was alarming with regard to large-scale resource investment and the introduction of foreign capital.

5. Conclusions and Recommendations

5.1. Conclusions

Based on SE-SBM model and the coupling models, this study measured the coupling relationship between carbon emission efficiency and technology absorption capacity of the Yangtze River economic belt from 2006 to 2017, and explored the methods and paths for the coordinated development of economic development and ecological protection, which was of great significance to realize the strategic goal of green and sustainable development in YREB. The main results are presented as follows.

First, from the year of 2006 to 2017, the regional disparity in the YREB's CE was substantial, indicating that there was still significant reduction potential for emissions, particularly for the provinces in the middle and upper stream. In terms of temporal changes, the CE followed a "U-shaped" trend, suggesting significant potential for energy conservation and emission reduction in the YREB.

Second, in general, the YREB's TAC had increased slowly, but regional disparity was obvious, with an incremental distribution in the sequence of the upper, middle, and downstream. The regional disparity in terms of TAC was expanding. Development in the middle and upper stream of the YREB lagged behind that in the downstream, particularly in terms of the level of economic development, openness, R&D investment, and talent attraction. Moreover, TAC spread weakened substantially as distance increased and because upper stream provinces gain minimal benefits from the downstream provinces, there was little motivation to increase their development.

Third, from 2006 to 2017, the degree of coupling and coordination between CE and TAC for the YREB generally increased; however, the changes for individual provinces were less evident. The relationship between CE and TAC for the YREB provinces in the study period could be characterized mainly as a relatively stable medium to low degree of coupling and medium-to-high coordination, with notable regional disparity in terms of the interaction between TAC and CE. The medium coupling and high coordination between the TAC and CE in the downstream area of the YREB were more beneficial and could be attributed to the fact that they began reformation and economic transformation earlier, had high technology industry clusters, and a high-quality talent pool. However, in the middle and upper stream provinces, the coupling between TAC and CE was not satisfactory and the results could be explained by their varied degree of success and time receiving industrial transfer and economic spillover effects from the downstream areas. In addition, these provinces did not have sufficient human resources. It should be noted that increased innovation resource investments and environmental improvements for economic development failed to improve the coupling between TAC and CE significantly for the YREB. This issue was alarming with regard to large-scale resource investment and the introduction of foreign capital.

5.2. Recommendations

A good ecosystem is indispensable for sustainable development. For the strategic target of "putting concerted efforts to the grand undertaking in ecological protection and building a demonstration area for ecological civilization," improving coupling between TAC and CE and high-quality, balanced development in the YREB is critical. In order to achieve this, it is necessary to promote high-quality economic development, appropriately allocate technological innovation resources, implement innovation-driven and coordinated development in the YREB, and promote the development of smart, green, and information-based industries in the YREB and individual provinces. Therefore, the recommendations of this study are discussed in sections below.

First, the gap of economic development level will lead to significant differences in the quantity and quality of regional resources and environment, resulting in the disparity of carbon emission efficiency in different regions. Therefore, in the critical stage of comprehensively building the YREB, for regions that are still in the extensive development stage, industrial optimization and transformation need to be completed as soon as possible to achieve intensive development based on regional advantages. For well-developed provinces, relevant measures should be adopted to expedite industry upgrades, develop new powerhouses for economic development, and build a social system that is resource and environmentally friendly for high-quality development. At the same time, developed provinces should play an active role in promoting coordinated economic development across regions to narrow the gaps in social and economic development, particularly among the upper stream, middle stream, and downstream. Numerous types of economic cooperation could be enhanced to promote regional economic integration. The development of conglomerates that leverage resources and technological advantages across regions should be encouraged. We should also develop cross regional group alliances in the form of capital and technology participation and establish regional joint financial organizations as well as development and construction companies, so as to promote and drive regional economic development and integration.

Second, in order to absorb the technology spillover effectively brought by foreign capital and improve the efficiency of carbon emission, the provinces in YREB must have the corresponding human capital stock and quality. Such a talent pool is not only attractive to investments and cooperation from entities with more advanced technology at home and abroad but is also instrumental in absorbing and accepting external technology spillover, so as to provide effective support for regional technological innovation. Therefore, it is necessary to make full use of the existing resources of colleges and universities in the YREB, create an excellent talent pool, and formulate relevant policies for enticing and recruiting new talents. In particular, more preferential policies should be given to the introduction of talents in the middle stream and upper stream, so as to realize regional linkage and human resource sharing.

Third, the substantial regional disparity in the YREB's TAC could partly be explained by the uneven distribution of foreign investment businesses, which in turn could explain the regional distribution of the degree of coupling and coordination between the regional TAC and CE. Therefore, policies for introducing foreign investments should be adjusted to improve openness to foreign investments in the upper stream by inter-regional exchange and cooperation. Nevertheless, attention should be paid to the structure and quality of the foreign investments. While high-quality foreign investments and major projects are encouraged, technologies that are excessively high or low should be avoided. Meanwhile, channeling foreign investments to green and smart manufacturing and modern service industries could fully exploit and release their technology spillover effects for improving regional TAC and realize maximum resource utilization as well as high-quality economic development.

Forth, technological innovation can not only improve resource utilization efficiency and promote economic and social development, but also generate environmental benefits. Therefore, promoting innovation-driven strategy could guide and support high-quality economic development. Specifically, increasing R&D investments, appropriately allocating technological innovation resources, and optimizing investment structure are needed to maximize the positive investment effects on TAC. The network for coordinated technological innovation in the YREB in the form of the "Internet+" and the program of "business go cloud" could be implemented and promoted to connect social resources as well as to share local services and capabilities through the internet and cloud computing. Thus, we could upgrade conventional industries and promote smart, green, and information-based industries in the YREB and individual provinces, thereby, the overall competitiveness and level of development of the YREB could be improved.

There are some limitations in this study. First, the internal conduction mechanism between TAC and CE cannot be well analyzed in the section of empirical analysis, which is restricted by the coupling model we have selected. Second, due to the limitation of data availability, this study period is from 2006 to 2017, which will lead to the deviation of the actual significance of the recommendations in this paper. Therefore, more appropriate and comprehensive index selection, or alternative models to express the relationship of TAC and CE, will become a breakthrough problem in our future research.

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