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# An Efficiency and Coupling Analysis of Chinese Regional Economic and Environmental Sustainability Based on a Super-SBM Model and Coupling Coordination Model

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**Abstract:** This study presents a two-stage framework for analyzing the coupling mechanism between regional sustainable economic development and environmental protection subsystems. We propose a modified super-slack-based measure (SBM) model to evaluate efficiency and apply a coupled coordination model to measure the coordinated development levels of regional economies and environments. Subsequently, we assess the economic and environmental efficiency and coordination levels of 30 Chinese regions from 2011 to 2019. The findings indicate a strong synchronization between regional economic development and environmental protection, whereby regions with better economic development exhibit superior environmental protection measures. Regional technical inefficiency is primarily attributed to scale inefficiency, although the overall developmental trend is predominantly determined by pure technical advancement. While the synchronization between the economy and environment remains highly robust, over time, the coordination level gradually diminishes, transitioning from a state of well-coordinated and orderly development to dysfunctional and disorderly recession. Noticeable regional disparities in efficiency and coordination levels are apparent among the eastern, western, and central regions, with the central region demonstrating exemplary performance across all aspects. To promote sustainable high-quality coordinated development, regions with limited capacity should prioritize economic construction. Conversely, in other regions, the simultaneous promotion of economic development and environmental protection would be more appropriate to achieve a higher level of coordinated regional development.

**Keywords:** coupling coordination; economic development; environmental protection; efficiency evaluation; super-SBM



**Citation:** Liang, N.; Zhao, L. An Efficiency and Coupling Analysis of Chinese Regional Economic and Environmental Sustainability Based on a Super-SBM Model and Coupling Coordination Model. *Sustainability* **2024**, *16*, 3818. https://doi.org/10.3390/su16093818

Academic Editor: Giovanni De Feo

Received: 27 February 2024
Revised: 29 April 2024
Accepted: 30 April 2024
Published: 1 May 2024



## 1. Introduction

In the approximately ten years since the 18th National Congress in China, considerable progress has been made in economic development and the ecological environment, marking a significant achievement in economic and social development and ecological progress. Economic development and ecological and environmental protection complement each other and are dialectically unified, both serving the people's needs for a better life. However, the relationship between economic development and environmental protection has both positive and negative aspects. Particularly, with the rapid growth of the population, the ecological environment faces substantial challenges, leading to increasingly serious environmental pollution and a gradual imbalance between social progress, economic development, and environmental protection [1]. Ensuring the sustainable development of the society, economy, and environment underscores the urgent importance of the governance and protection of the ecological environment. Practices in various regions have demonstrated that strengthening ecological and environmental governance, as well as environmental protection, has become a significant driving force for sustainable regional economic development. However, in the face of downward economic pressure, numerous new situations and problems must be addressed to maintain high-quality development. Thus, questions have been raised regarding how to best implement the regional coordinated development strategy and establish an effective new mechanism for regional coordinated development in line with the requirements of the 19th National Congress. The coordinated promotion of both high-quality economic development and high-level environmental protection has become an urgent issue. Currently, understanding and mastering the level of regional economic development and the ecological environment are fundamental for optimization and coordination, significantly contributing to promoting sustainable and high-quality regional development.

As human beings gradually understand the interaction between economic activities and the environment, especially when a large number of pollutants accompanying economic activities cause serious negative impacts on the environment, the interaction mechanism between economic development and the ecological environment has been further explored by researchers [2,3]. In early studies, economists Grossman and Krueger [4] established that a mutually reinforcing relationship exists between environmental pollution and economic growth. Restrictive rules between resource utilization and environmental protection further strengthen this connection, providing a solid foundation for subsequent investigations into a harmonious development nexus between the economy and the environment. In 1986, Wassily [5] investigated the coupling mechanism between the ecological environment and economic development, finding that, given the prevailing economic development pattern at that time, addressing the issue of ecological deterioration necessitated modifications to environmental and economic policies, as well as alterations to human behavior itself. Their study introduced coupled media from an economic and environmental sustainability perspective, offering valuable insights for subsequent scholars seeking to employ coupled system mechanisms to analyze problems related to economic and environmental coordination. Consequently, this led to further advancements in understanding the coupling mechanism between the economy and environment. For example, Wu and Zhang [6] studied economic and environmental subsystems through the coupled coordination model, selecting an "economic growth and environment" index system composed of 18 indicators and conducting an empirical analysis on the spatiotemporal distribution of the coupled coordinated development of economic growth and environmental protection in 31 provincial regions of China in 1995, 2000, and 2005. After the coupling mechanism, Jin et al. [7] analyzed the coupling and coordinated development of the regional energy, economy, and environment in China, under the dual system of energy and the environment and the ternary system of economic energy and the environment and calculated the coupling and coordinated levels of China's eastern, northeastern, western, and central regions from 1995 to 2014. Li et al. [8] evaluated the eco-economy coupling coordination index at the county level, revealing that coordinating the ecological environment and economic development is the only way to achieve regional sustainability. Of course, the study of applications related to the coupled coordination mechanism is not limited to economic and environmental subsystems. Scholars have conducted relevant analyses and research on regionally diversified and multi-faceted coordination issues, such as economy–society–environment [9], mineral–economic–environment [10], economic–industry–environment [11], economy–environment–health [12], and finance–economy–environment [13], as well as differences in the focus and purpose of the research in the opportunity period.

In the study of the coupling relation between the economy and environment, the entropy weight method is usually applied as an objective weighting method for the comprehensive evaluation of subsystems in the coupling relation. The entropy weighting method is used to assign weights to all the metrics in the system to obtain a comprehensive evaluation metric for each subsystem. However, there are some limitations in the application of the entropy weight method. First, it does not consider the inner workings of the system. Second, the method assumes that all indicators evaluated are independent of each other. Thus, while the level of coupled economic and environmental development can be well analyzed in existing studies, the mechanism of operation between economic development and environmental protection subsystems is not fully explained. Moreover, owing to the independence of the indicators, it is not possible to give concrete proposals to improve the mechanisms of economic development and environmental protection through the relevant indicators. To address this limitation, in the coupling study of the economy and environment, we comprehensively consider the structure of economic development and environmental protection mechanism operation and select systematic evaluation methods and indicators from the perspective of the correlation between operational input and output, in order to provide specific index optimization suggestions for the sustainable and coordinated development of the regional economy and environment after evaluation. The Data Envelopment Analysis (DEA) method is applicable to the objective weighting of multiple indicators and the relative analysis of multiple units [14]. As a method to evaluate the relative efficiency of systems with multiple indicators, it has been widely used in the performance evaluation of different systems, such as the economy, the environment, enterprises, and organizations [15,16]. It is also used to calculate the coupled coordination model [17,18]. Therefore, the DEA method is used in this study to evaluate the relative composite indices of economic development and environmental protection systems.

In the course of long-term development, China's economic development and ecological environment have undergone continuous transformations over time. This study aims to estimate the performance of economic development and environment protection in the current process of sustainable development in most regions of China and to analyze the problem of coordinated development between them. By analyzing the coordinated development state between regional economic development and environmental protection subsystems, such as the state of mutual promotion and coordinated development or the state of mutual inhibition and mutual restriction, we can help the region timely understand the problems existing in the process of regional development. Finally, it provides valuable optimization suggestions for maintaining high-quality coordinated development in the region. Finally, we analyzed the coordinated economic and environmental development of 30 provinces, municipalities, and autonomous regions in China during 2011–2019 (based on data availability) through empirical research. Drawing on an analysis of the interplay between economic development and environmental protection subsystems, this study considers the structure and characteristics of both economic and environmental subsystems to construct an adjusted super-efficiency DEA model. By evaluating the relative index levels (efficiency levels) of the economic development and environmental protection subsystems across 30 regions in China, we objectively assess the coupling and coordination issue among these subsystems. This analysis allows for a comprehensive examination of regional coupling patterns and collaborative development trends, offering differentiated optimization suggestions for regional economic development and environmental protection initiatives.

The remainder of this paper is structured as follows: Section 2 constructs a corresponding SBM-DEA network model to evaluate the efficiency of economic and environmental subsystems, which is based on a two-stage network. Additionally, the coupling coordination model for measuring the coupling degree and coordination level between these subsystems is introduced. Section 3 measures various types of efficiencies and levels of coordination between systems. Subsequently, regional differences in efficiency and coordinated development are analyzed and compared, followed by suggestions for optimization and improvement. Finally, the conclusions are presented in Section 4.

## 2. Super-SBM Model and Coupling Coordination System

Practice and research have consistently demonstrated the interdependent relationship between economic development and ecological environmental protection. Figure 1 illustrates the network structure of the economy and environment, highlighting relevant inputs and outputs in the economic development and environmental protection processes. National and regional economic development relies on various inputs such as human, material, and financial resources, including non-energy resources like humans and capital, as well as energy resources such as coal, natural gas, and crude oil. The output is intuitively expressed through the gross domestic product (GDP) [16]. Furthermore, energy consumption processes often lead to pollution. To address environmental concerns, each region invests resources to control and mitigate pollution, thus forming a regional environmental protection subsystem.

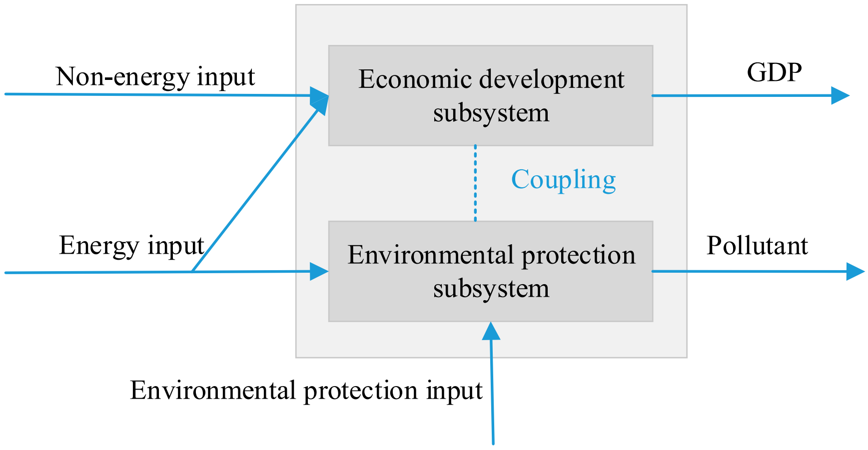


**Figure 1.** Economic subsystem and environmental subsystem.

The performance of economic development and environmental protection subsystems can be evaluated based on the input–output relationship. Subsequently, considering the coupling correlation structure, the coupling coordination model can further evaluate the correlation degree and coordination development among subsystems. The corresponding model construction is detailed below.

*2.1. Super-SBM Model*

Evaluating the performance of economic development and environmental protection subsystems involves a multi-index system evaluation problem. The weighting of each metric significantly impacts the results and is a focal point of multi-index evaluations. The DEA method effectively addresses the subjective issue of index weighting in multi-index evaluations and has been extensively utilized in systematic evaluation studies. Moreover, the DEA method can be tailored to suit specific evaluation systems by modifying it according to research objectives, index variance, and system structure. For an evaluation system with a network structure, two-stage and multi-stage DEA models have been constructed and applied [19,20]. The dynamic DEA model was constructed to consider the influence of time [15,21], and the super-DEA model was built to improve the identification of the DEA method [22]. Additionally, the SBM model [23] was constructed to deeply analyze the "crowding" or "relaxation" of each input or output. Therefore, to evaluate the performance of economic development and environmental protection subsystems in greater detail, we construct a super-efficient SBM model with stronger discriminative power.

Consider $n$ independent decision-making units (DMUs), denoted as $\mathrm{DMU_j}(j = 1, \ldots, n)$. Figure 1 illustrates a typical development system comprising two subsystems within each DMU. In the economic development subsystem, each DMU consumes energy $\mathrm{x_{ij}^{E}}(\mathrm{i} = 1, \ldots, \mathrm{I^E})$ and non-energy inputs $\mathrm{x_{ij}^{NE}}(\mathrm{i} = 1, \ldots, \mathrm{I^{NE}})$ to produce desired outputs $\mathrm{y_{rj}}(\mathrm{r} = 1, \ldots, \mathrm{R})$. In the environmental protection subsystem, each DMU consumes inputs $\mathrm{x_{ij}^{EP}}(\mathrm{i} = 1, \ldots, I^{EP})$ to reduce undesirable outputs $\mathrm{p_{kj}}(\mathrm{k} = 1, \ldots, \mathrm{K})$, which result from the consumption of energy inputs $\mathrm{x_{ij}^{E}}(\mathrm{i} = 1, \ldots, \mathrm{I^E})$.

The super-DEA method, with enhanced discernment, comprises two steps. The first step is to calculate the efficiency of all DMUs using the traditional DEA model. In the second step, the super-DEA model is used to re-evaluate the DMU with an efficiency of 1 obtained in the first step, and their super-efficiency value can be calculated [24]. An input-oriented super-DEA model is constructed in this study, as the management of inputs generally offers greater convenience compared to that of outputs in system operation. Meanwhile, the SBM model can easily define and evaluate subsystem efficiency through the slack variables in the efficiency evaluation of complex multisystem structures. Finally, we construct an input-oriented SBM model as the first step in evaluating the efficiency of all DMUs. The model is expressed as follows:

$$\max \sum_{i=1}^{I^E} \frac{s_{io}^E}{x_{io}^E} + \sum_{i=1}^{I^{NE}} \frac{s_{io}^{NE}}{x_{io}^{NE}} + \sum_{i=1}^{I^{EP}} \frac{s_{io}^{EP}}{x_{io}^{EP}} \tag{1}$$

$$s.t. \sum_{j=1}^{n} \lambda_j x_{ij}^{E} = x_{io}^{E} - s_{io}^{E}, i = 1, \ldots, I^{E}$$

$$\sum_{j=1}^{n} \lambda_j x_{ij}^{NE} = x_{io}^{NE} - s_{io}^{NE}, i = 1, \ldots, I^{NE}$$

$$\sum_{j=1}^{n} \lambda_j x_{ij}^{EP} = x_{io}^{EP} - s_{io}^{EP}, i = 1, \ldots, I^{EP}$$

$$\sum_{j=1}^{n} \lambda_j y_{rj} \geq y_{ro}, r = 1, \ldots, R$$

$$\sum_{j=1}^{n} \lambda_j p_{kj} \leq p_{ko}, k = 1, \ldots, K$$

$$\sum_{j=1}^{n} \lambda_j = 1$$

$$\lambda_j, s_{io}^{NE}, s_{io}^{E}, s_{io}^{EP} \geq 0, \forall j, i, r, k.$$

In Model (1), $s_{io}^E$, $s_{io}^{NE}$, and $s_{io}^{EP}$ are slack variables denoting energy input excess, non-energy input excess, and environment protection input excess. $\lambda_j (j = 1, \ldots, n)$ is the intensity vector. Note that Model (1) is an input-oriented SBM model under the variable returns to scale (VRS) assumption, which evaluates the pure technical efficiency (PTE) of the system.

If the influence of scale is not considered, the constraint $\sum_{j=1}^{n} \lambda_j = 1$ can be omitted. The model then becomes an input-oriented SBM model under the constant returns to scale (CRS) assumption, which can evaluate technical efficiency (TE). TE is the product of PTE and scale efficiency (SE). Then, the TE, PTE, and SE of the system can be obtained and decomposed by adjusting the constraint $\sum_{j=1}^{n} \lambda_j = 1$. The effective and ineffective problems of technology and scale can then be analyzed.

The objective function calculates the maximum slack variables for all inputs. $s_{io}^E$, $s_{io}^{NE}$, and $s_{io}^{EP}$ represent the slacks in the energy, non-energy, and environmental protection inputs, respectively. Constraint $\sum_{j=1}^{n} \lambda_j p_{kj} \leq p_{ko} (k = 1, \ldots, K)$ indicates that an undesirable output is treated in terms of as few variables as possible. Existing studies have posited that if pollution can be controlled, then it can be regarded as somewhat controllable to a certain extent [15]. Therefore, the efficiency of the economic development and environmental protection subsystems corresponding to Model (1) can be defined as follows:

$$e_o^{eco} = 1 - \frac{1}{I^E + I^{NE}} \left( \sum_{i=1}^{I^E} \frac{s_{io}^E}{x_{io}^E} + \sum_{i=1}^{I^{NE}} \frac{s_{io}^{NE}}{x_{io}^{NE}} \right) \tag{2}$$

$$e_o^{env} = 1 - \frac{1}{I^E + I^{EP}} \left( \sum_{i=1}^{I^E} \frac{s_{io}^E}{x_{io}^E} + \sum_{i=1}^{I^{EP}} \frac{s_{io}^{EP}}{x_{io}^{EP}} \right) \tag{3}$$

Formulas (2) and (3) correspond to the efficiency of economic development ($e_o^{eco}$) and environmental protection ($e_o^{env}$) subsystems, respectively, and are defined according to the input structure. $e_o^{eco}$ is composed of slacks in energy and non-energy inputs. $e_o^{env}$ is composed of slacks in energy and pollution control inputs. The energy input plays a role in both subsystems and is similar to the shared input in related studies [25–27]. However, the function of the energy input in this study differs from that of the shared input. In the traditional system, as part of the shared input is consumed in one subsystem, the remainder is consumed in the other. Then, the shared inputs should be suitably allocated to all subsystems for the efficiency evaluation. However, in this study, energy acts on both subsystems simultaneously, rather than partially on one. All the energy used to develop the economy, together with the production of pollutants, must be controlled in a timely manner for environmental protection. Thus, we do not allocate energy inputs to the two subsystems, and slacks in energy inputs are an essential element of efficiency in both subsystems.

The efficiencies of $e_o^{eco}$ and $e_o^{env}$ are equal to 1 when the slacks $s_{io}^{E}$, $s_{io}^{NE}$, and $s_{io}^{EP}$ in Model (1) are equal to zero. At this point, a further comparison is made between effective units, namely, DMUs with an efficiency of 1, and the corresponding super-SBM model is as follows:

$$\min \sum_{i=1}^{I^E} \frac{\delta_{io}^{E}}{x_{io}^{E}} + \sum_{i=1}^{I^{NE}} \frac{\delta_{io}^{NE}}{x_{io}^{NE}} + \sum_{i=1}^{I^{EP}} \frac{\delta_{io}^{EP}}{x_{io}^{EP}} \tag{4}$$

$$s.t. \sum_{j=1,j\neq o}^{n} \lambda_j x_{ij}^{E} \le x_{io}^{E} + \delta_{io}^{E}, i = 1,\ldots,I^{E}$$

$$\sum_{j=1,j\neq o}^{n} \lambda_j x_{ij}^{NE} \le x_{io}^{NE} + \delta_{io}^{NE}, i = 1,\ldots,I^{NE}$$

$$\sum_{j=1,j\neq o}^{n} \lambda_j x_{ij}^{EP} \le x_{io}^{EP} + \delta_{io}^{EP}, i = 1,\ldots,I^{EP}$$

$$\sum_{j=1,j\neq o}^{n} \lambda_j y_{rj} \ge y_{ro}, r = 1,\ldots,R$$

$$\sum_{j=1,j\neq o}^{n} \lambda_j p_{kj} \le p_{ko}, k = 1,\ldots,K$$

$$\sum_{j=1,j\neq o}^{n} \lambda_j = 1$$

$$\lambda_j, \delta_{io}^{NE}, \delta_{io}^{E}, \delta_{io}^{EP} \ge 0, \forall j,i,r,k.$$

$\delta_{io}^{E}$, $\delta_{io}^{NE}$, and $\delta_{io}^{EP}$ in Model (4) are slack variables denoting the energy input shortfall, non-energy input shortfall, and environment protection input shortfall of the DMU, at or beyond the frontier. Model (4) is the super-SBM model under the VRS assumption. However, the super-efficiency model under the VRS constraint [28] or with undesirable production variables faces infeasibility problems [29]. Model (4) must be adjusted and modified to solve the problem of a lack of feasibility. Therefore, the modified super-SBM model is constructed as follows:

$$\min \sum_{i=1}^{I^E} \frac{\delta_{io}^{E}}{x_{io}^{E}} + \sum_{i=1}^{I^{NE}} \frac{\delta_{io}^{NE}}{x_{io}^{NE}} + \sum_{i=1}^{I^{EP}} \frac{\delta_{io}^{EP}}{x_{io}^{EP}} + +M\sum_{k=1}^{K} \frac{\delta_{ko}^{y}}{p_{ko}} + M\sum_{k=1}^{K} \frac{\delta_{ko}^{p}}{p_{ko}} \tag{5}$$

$$s.t. \sum_{j=1,j\neq o}^{n} \lambda_j x_{ij}^{E} \le x_{io}^{E} + \delta_{io}^{E}, i = 1,\ldots,I^{E}$$

$$\sum_{j=1,j\neq o}^{n} \lambda_j x_{ij}^{NE} \leq x_{io}^{NE} + \delta_{io}^{NE}, i = 1, \ldots, I^{NE}$$

$$\sum_{j=1,j\neq o}^{n} \lambda_j x_{ij}^{EP} \leq x_{io}^{EP} + \delta_{io}^{EP}, i = 1, \ldots, I^{EP}$$

$$\sum_{j=1,j\neq o}^{n} \lambda_j y_{rj} \geq y_{ro} - \delta_{ko}^{y}, r = 1, \ldots, R$$

$$\sum_{j=1,j\neq o}^{n} \lambda_j p_{kj} \leq p_{ko} + \delta_{ko}^{p}, k = 1, \ldots, K$$

$$\sum_{j=1,j\neq o}^{n} \lambda_j = 1$$

$$\lambda_j, \delta_{io}^{NE}, \delta_{io}^{E}, \delta_{io}^{EP}, \delta_{ko}^{y}, \delta_{ko}^{p} \geq 0, \forall j, i, r, k.$$

$\delta_{io}^{E}$, $\delta_{io}^{NE}$, $\delta_{io}^{EP}$, $\delta_{ko}^{y}$, and $\delta_{ko}^{p}$ in Model (5) are slack variables denoting the energy input shortfall, non-energy input shortfall, environment protection input shortfall, desirable output excess, and undesirable output shortfall of the DMU, at or beyond the frontier, respectively. The main difference between the modified super-SBM Model (5) and super-SBM Model (4) lies in three parts: constraints $\sum_{j=1,j\neq o}^{n} \lambda_j y_{rj} \geq y_{ro} - \delta_{ko}^{y}$ $(r = 1, \ldots, R)$ and $\sum_{j=1,j\neq o}^{n} \lambda_j p_{kj} \leq p_{ko} + \delta_{ko}^{p}(k = 1, \ldots, K)$ and the objective function. The slack $\delta_{ko}^{y}$ represents the allowable reduction in the desirable output, and $\delta_{ko}^{p}$ allows for an increase in the undesirable output. The coefficients of $\delta_{ko}^{y}$ and $\delta_{ko}^{p}$ in the objective function are $M$, which represents the maximum value (i.e., take $M = 10^6$). Meanwhile, the objective minimization means that DMUs beyond the frontier are prioritized to reach the frontier by increasing energy, non-energy, and environmental inputs. The method of increasing desirable outputs or decreasing undesirable outputs is considered only when the frontier can be reached by increasing the inputs. Finally, only the inputs are considered in the efficiency definition based on the input orientation. The corresponding super-efficiency of the two subsystems is defined as follows:

$$e_o^{eco} = 1 + \frac{1}{I^E + I^{NE}} \left( \sum_{i=1}^{I^E} \frac{\delta_{io}^{E}}{x_{io}^{E}} + \sum_{i=1}^{I^{NE}} \frac{\delta_{io}^{NE}}{x_{io}^{NE}} \right) \tag{6}$$

$$e_o^{env} = 1 + \frac{1}{I^E + I^{EP}} \left( \sum_{i=1}^{I^E} \frac{\delta_{io}^{E}}{x_{io}^{E}} + \sum_{i=1}^{I^{EP}} \frac{\delta_{io}^{EP}}{x_{io}^{EP}} \right) \tag{7}$$

Therefore, we first obtain the efficiency value of the invalid DMU using Model (1) and Formulas (2) and (3). The super-efficiency value of the effective DMU in Model (1) can then be obtained using Model (5) and Formulas (6) and (7). Finally, the efficiency values of all DMUs are determined.

### 2.2. Coupling Coordination Model

Coupling coordination involves coordinating and monitoring multiple systems or subsystems within a complex system. Interdependence and interaction occur between different subsystems. Thus, the degree of coupling coordination can be used to analyze and guarantee the normal operation and high performance of the entire system. Economic and environmental issues coexist within the complex system of social development. Analyzing the degree of dependence and coordination between economic development and environmental protection can facilitate a further understanding and optimization of regional coordinated development. Referring to existing studies [6,7], the coupling coordination model of the economy and environment can be constructed as follows:

$$C = \left( \frac{ECO \times ENV}{\left( \frac{ECO+ENV}{2} \right)^2} \right)^2 \quad (8)$$

where ECO and ENV represent the comprehensive indices of the economic development and environmental protection subsystems, respectively, with values ranging from 0 to 1. The degree of coupling (C) represents the level of interdependence among subsystems. Table 1 illustrates the different levels of coupling. The larger C is, the higher the coupling level, which means that the higher the degree of intersystem correlation and synchronization, the better or worse the economy and environment perform simultaneously. The smaller C is, the lower the coupling level, indicating a lower degree of correlation and synchronization between systems and reflecting the opposing performance of the economy and environment.

**Table 1.** Coupling degree classification.

| C | Degree | C | Degree |
|---|---|---|---|
| $0 < C \leq 0.3$ | Low-level coupling stage | $0.6 < C \leq 0.8$ | Run-in stage |
| $0.3 < C \leq 0.5$ | Antagonistic stage | $0.8 < C \leq 1$ | High-level coupling stage |

C reflects the degree of correlation and synchronization between systems but cannot reflect whether subsystems maintain a healthy interaction and development state. The coupling coordination level can be used to analyze the coordination state between the economic and environmental subsystems; therefore, the coordination level is further calculated according to Formulas (9) and (10) as follows:

$$T = \alpha \cdot ECO + \beta \cdot ENV \quad (9)$$

$$D = \sqrt{C \cdot T} \quad (10)$$

where $T$ is the comprehensive weighted evaluation index for the two subsystems, and $\alpha$ and $\beta$ represent the weights of the two subsystems, respectively. Generally, the economy and environment are considered equally important (i.e., $\alpha = \beta = 1/2$). D is the coupling coordination level, which reflects whether the subsystems maintain a good interaction and healthy development state.

Table 2 lists the coordination types corresponding to different coupling coordination levels. $D > 0.5$ indicates the system is in a state of coordinated development, in which the two subsystems promote each other and develop healthily. The larger D is, the more coordinated the system development and the more conducive it is to joint optimization. In contrast, $D < 0.5$ indicates that the system is in a state of dysfunctional recession, in which the development between the two subsystems is unbalanced. The smaller D is, the more unbalanced the regional development and the more unfavorable the conditions are to the sustainable development of the region.

In calculating C and D, we use economic and environmental efficiencies ($e_o^{eco}$ and $e_o^{env}$) to represent their comprehensive index. However, owing to the super-efficiency being greater than 1, the efficiency value cannot be directly calculated in coupling coordination Models (8)–(10). The efficiency must be normalized to ensure a value between 0 and 1. Accordingly, simple Formulas (11) and (12) are used to treat the efficiency value as a comprehensive index of economic development and environmental protection as follows:

$$ECO_o = \frac{e_o^{eco}}{\max\left\{ e_j^{eco}, j = 1, \ldots, n \right\}} \quad (11)$$

$$ENV_o = \frac{e_o^{env}}{\max\left\{e_j^{env}, j = 1, \ldots, n\right\}} \quad (12)$$

Finally, the coupling and coordination level of the regional economy and environment subsystems can be calculated and analyzed by introducing the comprehensive index from the efficiency value adjustment into the coupling formulas.

**Table 2.** Coupled coordination level and state type.

| D | Type | D | Type |
|---|---|---|---|
| 0 < D ≤ 0.1 | Hyper Dysfunctional recession | 0.5 < D ≤ 0.6 | Grudgingly coordinated development |
| 0.1 < D ≤ 0.2 | Severe Dysfunctional recession | 0.6 < D ≤ 0.7 | Primary coordinated development |
| 0.2 < D ≤ 0.3 | Moderate Dysfunctional recession | 0.7 < D ≤ 0.8 | Moderate coordinated development |
| 0.3 < D ≤ 0.4 | Mild Dysfunctional recession | 0.8 < D ≤ 0.9 | Sound coordinated development |
| 0.4 < D ≤ 0.5 | Borderline Dysfunctional recession | 0.9 < D ≤ 1 | High-quality coordinated development |

## 3. Efficiency and Coupling Analysis

In this section, we apply the modified super-SBM-DEA model and coupling coordination model to evaluate the efficiency and coupling of regional economic development and environmental protection in China. In the process of data processing, we mainly use MATLAB 2014 software to calculate various efficiency values of the economic subsystem and environmental subsystem and then use IBM SPSS statistics 21 software to conduct a statistical analysis of part of the content.

### *3.1. Regions, Variables, and Data*

Considering the availability of the data, not all pollution data from four provinces (Tibet, Macau, Hong Kong, and Taiwan) can be obtained; therefore, this study evaluates and analyzes 30 Chinese provinces from 2011 to 2019. Based on geographical location, the 30 provinces are divided into three areas: eastern, central, and western.

As discussed in previous studies [16,30,31], indicators of fixed assets, labor, and energy consumption are generally used as input in regional efficiency evaluations. This study considers the fixed asset investment, number of employees, and energy consumption as inputs for the regional economic subsystem. Energy consumption includes all types of energy inputs, such as coal, petroleum, and gas. Notably, these energy inputs are also those of the environmental subsystem, as environmental pollution is produced during the energy consumption process. Investment in pollution control (IPC) for environmental protection is another input of the environmental subsystem. The GDP is the final desirable output produced in the economy subsystem. The pollution outputs of the environment subsystem are mainly wastewater and waste gas. After statistically analyzing the correlations between pollution indicators, chemical oxygen demand (COD), sulfur dioxide ($SO_2$) emissions, nitric oxide (NOx), and dust were selected as undesirable outputs of the environmental subsystem. Due to the limitations of fresh data, we collected data on regional sectors between 2011 and 2019 from the China Statistical Yearbook and Easy Professional Superior (EPS) data platform. The descriptive statistics for the data are summarized in Table 3.

**Table 3.** The descriptive statistics of the data.

| **Variables** | | **2011** | **2012** | **2013** | **2014** |
|---|---|---|---|---|---|
| Non-energy input [a] | Fixed asset investment | 10.18 (6.41) [f] | 12.26 (7.47) | 14.66 (8.8) | 16.82 (10.16) |
| | Employee | 4.8 (2.84) | 5.07 (2.99) | 6.03 (4.18) | 6.08 (4.27) |
| Energy consumption [b] | Coal | 143 (101.03) | 145.48 (102.92) | 144.07 (101.65) | 143.91 (103.99) |
| | Petroleum | 3.56 (2.7) | 3.87 (2.87) | 3.8 (2.62) | 3.98 (2.73) |
| | Gas | 43.97 (34.39) | 50.06 (36.06) | 54.94 (38.14) | 60.84 (43.59) |
| Pollution control input [c] | IPC | 221.74 (157.2) | 264.1 (181.22) | 298.55 (196.31) | 303.56 (203.11) |
| Economy output [d] | GDP | 1.64 (1.26) | 1.81 (1.36) | 1.99 (1.49) | 2.16 (1.62) |
| Pollution [e] | COD | 83.24 (51.49) | 80.7 (49.54) | 78.34 (47.75) | 76.39 (46.29) |
| | SO2 | 73.92 (43.52) | 70.57 (41.16) | 68.12 (39.53) | 65.8 (37.88) |
| | NOx | 80.01 (47.64) | 77.78 (46.36) | 74.1 (43.46) | 69.11 (40.34) |
| | Dust | 42.39 (29.5) | 41.17 (28.86) | 42.46 (29.23) | 57.98 (41.36) |
| | 2015 | 2016 | 2017 | 2018 | 2019 |
| Fixed asset investment | 18.51 (11.39) | 19.98 (12.84) | 21.13 (14.25) | 21.98 (15.54) | 22.99 (16.14) |
| Employee | 6.01 (4.19) | 5.95 (4.16) | 5.87 (4.15) | 5.74 (4.11) | 5.71 (4.06) |
| Coal | 141.83 (105.72) | 141.65 (105.47) | 145.07 (109.75) | 150.12 (123.11) | 154.09 (129.67) |
| Petroleum | 4.41 (2.88) | 4.75 (3.18) | 4.99 (3.25) | 5.07 (3.24) | 5.18 (3.31) |
| Gas | 64.91 (46.69) | 69.46 (49.74) | 78.14 (57.69) | 89.26 (66.02) | 96.38 (70.74) |
| IPC | 285.43 (197.35) | 305.91 (210.97) | 316.95 (221.43) | 316.96 (221.43) | 303.61 (185.67) |
| GDP | 2.31 (1.79) | 2.5 (1.95) | 2.77 (2.17) | 3.04 (2.36) | 3.27 (2.52) |
| COD | 74.02 (45.17) | 34.79 (21.79) | 71.2 (46.37) | 19.42 (14.46) | 18.85 (14.3) |
| SO2 | 61.95 (35.72) | 36.75 (24.23) | 21.77 (13.47) | 17.19 (10.96) | 15.23 (9.31) |
| NOx | 61.53 (35.76) | 46.29 (29.17) | 55.84 (35.08) | 42.82 (28.2) | 40.99 (26.44) |
| Dust | 51.11 (37.29) | 33.54 (25.93) | 26.52 (17.99) | 37.56 (22.29) | 35.83 (22.27) |

Notes: [a] The units for this category are CNY 100 billion and one million people; [b] one million tons; [c] CNY one billion; [d] CNY one trillion; [e] 10,000 tons. [f] The values outside of the brackets are the mean value and inside are the standard deviation, $n$ = 30.

### 3.2. *Efficiency Analysis*

This section focuses on the TE, PTE, and SE of the economy and environment in 30 provinces from 2011 to 2019. TE can be obtained under CRS constraints using Models (1) and (4), and PTE can be obtained under VRS constraints. SE is the ratio of TE to PTE. The efficiency analysis encompasses two main phases. First, we conduct a comparative analysis of TE, PTE, and SE to identify disparities in the allocation, management, and scale of economic and environmental resources across regions. Second, we examine the strength of regional economic development and environmental protection by comparing variations in one type of economic or environmental efficiency (TE, PTE, or SE) among different regions.

Table 4 lists the mean TE, PTE, and SE of the economy and environment for 30 provinces from 2011 to 2019. In Table 4, PTEeco, TEeco, and SEeco refer to the pure technical efficiency, technical efficiency, and scale efficiency of the economic development subsystem, respectively. PTEenv, TEenv, and SEenv correspond to the related efficiency of the environmental protection subsystem. We can find that approximately one-third of the provinces display efficient or super-efficient TE in economic and environmental subsystems. Super-efficient TE means that these provinces have performed well in terms of economic and environmental resource allocation and utilization. In the economic subsystem, 14 provinces have efficient or super-efficient PTE and 6 have efficient or super-efficient SE. The six provinces with efficient or super-efficient SE all have efficient or super-efficient PTE and are Beijing, Shandong, Guangdong, Henan, Hubei, and Yunnan. For the environmental subsystem, these six provinces are also efficient or super-efficient in terms of PTE and SE. Further observation would also reveal that provinces with inefficient PTE are also inefficient in terms of SE. Notably, owing to the existence of super-efficiency, when both PTE and SE are inefficient, TE is inefficient and smaller than PTE and SE, such as in Sichuan and Anhui.

Conversely, when both PTE and SE are super-efficient, TE is super-efficient and greater than PTE and SE, such as in Beijing and Shandong.

**Table 4.** Descriptive statistics of economic and environmental efficiency of each region in China during 2011–2019.

| Regions | | Economy | | | Environment | | |
|---|---|---|---|---|---|---|---|
| | | **TEeco** | **PTEeco** | **SEeco** | **PTEenv** | **PTEenv** | **SEenv** |
| East | Beijing | 2.229 (1.363) [a] | 1.271 (0.332) | 1.639 (0.514) | 2.687 (1.75) | 1.338 (0.415) | 1.745 (0.563) |
| | Tianjing | 0.64 (0.144) | 0.969 (0.093) | 0.665 (0.151) | 0.618 (0.178) | 0.975 (0.092) | 0.631 (0.148) |
| | Hebei | 0.775 (0.151) | 0.814 (0.151) | 0.952 (0.056) | 0.704 (0.205) | 0.741 (0.203) | 0.943 (0.078) |
| | Liaoning | 0.544 (0.05) | 0.638 (0.056) | 0.853 (0.022) | 0.43 (0.049) | 0.558 (0.05) | 0.786 (0.06) |
| | Shanghai | 0.549 (0.046) | 0.715 (0.166) | 0.792 (0.129) | 0.391 (0.033) | 0.58 (0.243) | 0.737 (0.197) |
| | Jiangsu | 0.557 (0.073) | 0.688 (0.186) | 0.834 (0.114) | 0.471 (0.094) | 0.615 (0.226) | 0.816 (0.18) |
| | Zhejiang | 0.616 (0.032) | 0.978 (0.067) | 0.633 (0.049) | 0.635 (0.052) | 0.979 (0.064) | 0.633 (0.049) |
| | Fujian | 0.496 (0.046) | 0.67 (0.04) | 0.741 (0.065) | 0.447 (0.029) | 0.623 (0.039) | 0.723 (0.064) |
| | Shandong | 1.292 (0.054) | 1.242 (0.075) | 1.043 (0.073) | 1.754 (0.303) | 1.601 (0.208) | 1.058 (0.104) |
| | Guangdong | 1.098 (0.052) | 1.098 (0.052) | 1 (0) | 1.057 (0.017) | 1.056 (0.017) | 1 (0) |
| | Hainan | 1.042 (0.093) | 1.061 (0.051) | 0.981 (0.057) | 1.037 (0.11) | 1.074 (0.067) | 0.978 (0.067) |
| Central | Shanxi | 0.903 (0.138) | 0.919 (0.125) | 0.981 (0.02) | 0.807 (0.192) | 0.86 (0.192) | 0.974 (0.029) |
| | Inner Mongolia | 1.019 (0.091) | 1.046 (0.05) | 0.973 (0.055) | 1.047 (0.077) | 1.052 (0.059) | 0.971 (0.062) |
| | Jilin | 0.996 (0.086) | 1.027 (0.041) | 0.969 (0.062) | 0.963 (0.123) | 1.032 (0.046) | 0.949 (0.102) |
| | Heilongjiang | 0.998 (0.097) | 1.035 (0.032) | 0.963 (0.074) | 1.015 (0.116) | 1.042 (0.039) | 0.94 (0.118) |
| | Anhui | 0.835 (0.162) | 0.848 (0.152) | 0.983 (0.027) | 0.803 (0.171) | 0.851 (0.179) | 0.98 (0.039) |
| | Jiangxi | 0.948 (0.089) | 0.956 (0.081) | 0.992 (0.011) | 0.924 (0.115) | 0.916 (0.113) | 0.985 (0.02) |
| | He'nan | 1.167 (0.025) | 1.167 (0.025) | 1 (0) | 1.181 (0.075) | 1.192 (0.077) | 1 (0) |
| | Hubei | 1.086 (0.054) | 1.086 (0.054) | 1 (0) | 1.25 (0.163) | 1.231 (0.163) | 1 (0) |
| | Hu'nan | 1.088 (0.156) | 1.107 (0.129) | 0.981 (0.056) | 1.074 (0.16) | 1.134 (0.161) | 0.979 (0.062) |
| West | Guangxi | 0.637 (0.141) | 1 (0) | 0.637 (0.141) | 0.605 (0.189) | 1.002 (0.006) | 0.61 (0.173) |
| | Chongqing | 0.991 (0.138) | 0.999 (0.116) | 0.989 (0.033) | 0.989 (0.165) | 1.001 (0.127) | 0.986 (0.042) |
| | Sichuan | 0.625 (0.035) | 0.642 (0.034) | 0.973 (0.045) | 0.593 (0.056) | 0.646 (0.042) | 0.928 (0.062) |
| | Guizhou | 0.676 (0.053) | 0.954 (0.092) | 0.713 (0.069) | 0.607 (0.11) | 0.926 (0.148) | 0.671 (0.109) |
| | Yunnan | 1.281 (0.14) | 1.281 (0.14) | 1 (0) | 1.381 (0.163) | 1.353 (0.174) | 1 (0) |
| | Shaanxi | 0.665 (0.095) | 0.771 (0.109) | 0.87 (0.111) | 0.656 (0.088) | 0.759 (0.103) | 0.858 (0.12) |
| | Gansu | 0.568 (0.189) | 0.932 (0.086) | 0.607 (0.173) | 0.509 (0.206) | 0.931 (0.087) | 0.574 (0.191) |
| | Qinghai | 0.427 (0.034) | 1 (0) | 0.427 (0.034) | 0.369 (0.054) | 1 (0) | 0.379 (0.06) |
| | Ningxia | 1.021 (0.189) | 1.071 (0.072) | 0.95 (0.15) | 1.028 (0.258) | 1.089 (0.09) | 0.936 (0.193) |
| | Xinjiang | 0.42 (0.043) | 0.53 (0.052) | 0.793 (0.018) | 0.297 (0.046) | 0.41 (0.07) | 0.763 (0.055) |
| No. of efficient and super-efficient regions | | 10 | 14 | 6 | 11 | 15 | 6 |

Notes: [a] The values outside of the brackets are the mean value and inside are the standard deviations, $n = 9$.

TE is influenced by both PTE and SE. When PTE and SE are inefficient, TE is most likely also inefficient, such as in Tianjin, Shanxi, and Jilin. When TE and SE are efficient or super-efficient, TE is efficient or super-efficient, such as in Beijing and Shandong. However, when either PTE or SE is inefficient and the other is super-efficient, whether regional TE is efficient is uncertain. For example, in Hunan and Hainan, PTE is super-efficient, SE is inefficient, and the corresponding TE is super-efficient. However, in Jilin and Heilongjiang, PTE is super-efficient, SE is inefficient, and the corresponding TE is inefficient. This demonstrates that the comprehensive performance of the regional economy and environment is affected by both the TE of resource management and SE of resource scale, and the degree of impact is observably different. To ensure regional sustainable development, each region should formulate appropriate reform and optimization strategies according to its PTE and SE performance.

Figure 2 depicts the overall trend in economic and environmental efficiency. From the efficiency point of view, the efficiency values and development trends of economic TE (or PTE) and environmental TE (or PTE) are similar in different periods. Only the SE trend before 2013 is different, which, to some extent, indicates a strong correlation between regional economies and the environment. Table 5 shows the paired-sample T-test results for various efficiencies over the 9-year period for 30 different regions. Correlation data verify a strong correlation between the economy and environment. In Figure 2, in the economic development and environmental protection subsystem, the fluctuation trend of TE is closer to PTE, indicating that the development direction of TE is mainly affected by PTE. However, due to the more serious ineffectiveness of SE, TE is affected by it, and its efficiency value is lower than PTE. Therefore, for TE, the "drag" situations of inefficient SE are more serious. The paired-sample T-test in Table 5 also verifies the correlations and differences among the various efficiencies. First, the efficiency value of TE under the influence of SE is lower than that of PTE in all periods, regardless of the economy or the environment. Thus, although TE and PTE have the same development trend, there are significant differences between them. Simultaneously, there are significant differences between PTE and SE. Then, comparative data on the economy and environment further confirm some synchronization between regional economic and environmental development, especially in TE and PTE. However, there is a significant difference between the economy and environment in terms of scale efficiency, with the economy outperforming the environment in this regard.

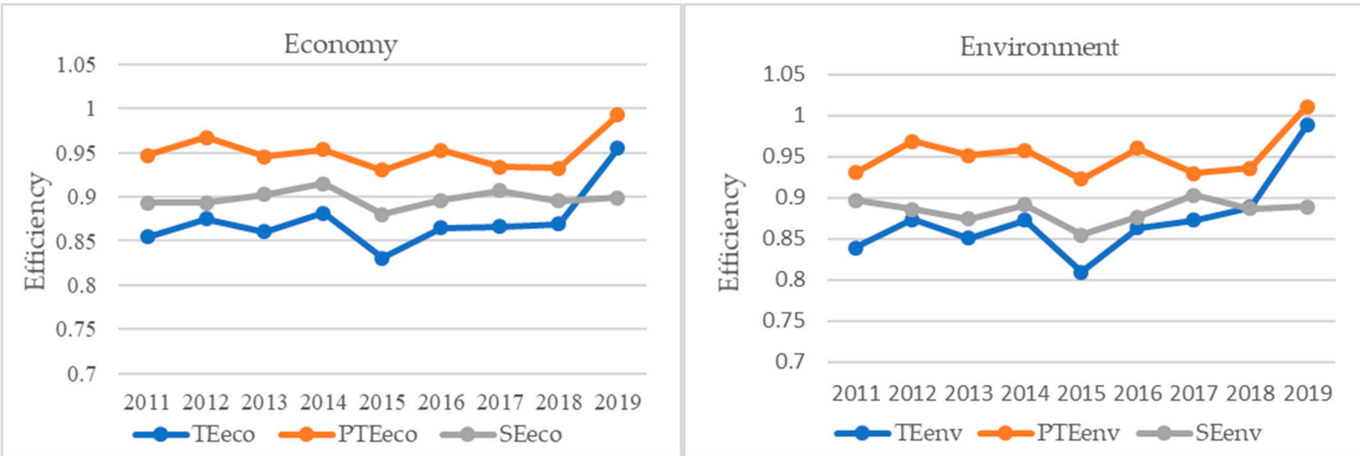


**Figure 2.** Three kinds of efficiencies in economy and environment during 2011–2019.

**Table 5.** Paired-samples T-test for all efficiencies during 2011–2019.

| | **Pairs** | **N** | **Correlation** | **Paired Difference [a]** | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | **Mean** | **Std.** | **Lower** | **Upper** | **sig.** |
| Economy | TEeco–PTEeco | 270 | 0.749 | −0.077 ** | 0.311 | −0.115 | −0.040 | 0 |
| | TEeco–SEeco | 270 | 0.868 | −0.025 | 0.262 | −0.056 | 0.007 | 0.122 |
| | PTEeco–SEeco | 270 | 0.383 | 0.053 ** | 0.253 | 0.022 | 0.083 | 0.001 |
| Environment | TEenv–PTEenv | 270 | 0.773 | −0.079 ** | 0.375 | −0.124 | −0.034 | 0.001 |
| | TEenv–SEenv | 270 | 0.85 | −0.011 | 0.354 | −0.054 | 0.031 | 0.604 |
| | PTEenv–SEenv | 270 | 0.4 | 0.068 ** | 0.307 | 0.031 | 0.105 | 0 |
| Economy–Environment | TEeco–TEenv | 270 | 0.984 | 0 | 0.143 | −0.017 | 0.017 | 0.983 |
| | PTEeco–PTEenv | 270 | 0.957 | −0.002 | 0.104 | −0.014 | 0.011 | 0.791 |
| | SEeco–SEenv | 270 | 0.983 | 0.013 ** | 0.055 | 0.007 | 0.020 | 0 |

Notes: [a] Lower and Upper correspond to the 95% Confidence Interval of the difference. ** The mean difference is significant at the 0.05 level.

Figure 3 further compares and analyzes the economic and environmental efficiency of the eastern, central, and western areas of China. TE, PTE, and SE in the central area ranked first in both economic and environmental aspects, with PTE in the area being super-effective. The eastern and western areas ranked second and third, respectively.

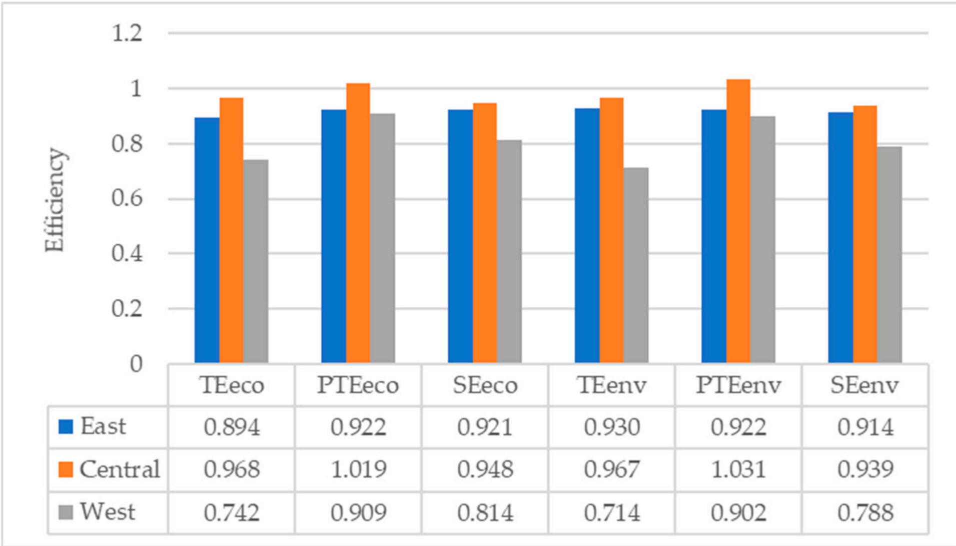


**Figure 3.** All efficiencies of eastern, central, and western areas.

Figure 4 depicts the trends in the three types of economic and environmental efficiency changes in the eastern, central, and western areas. The figure indicates that the trend of one region's economic TE and environmental TE (or PTE or SE) is fundamentally the same. This reflects the consistency between the regional economy and environment to some extent. For example, the TE trends of the economy and environment in the eastern area are consistent and changed from 2011 to 2015, with a significant growth trend after 2015. The TE changes in the economy and environment in the central area are similar, with slight fluctuations in the early period, a gradual decline in the middle period, and an upward trend in the late period. Similarly, the economic and environmental PTE in the central area is consistent, decreasing significantly in the first two periods but generally not fluctuating in the later periods. The consistent trends of economic and environmental development indicate that economic development and environmental protection are mutually reinforcing, which partially confirms the view in relevant studies that regions with a higher GDP have higher ecological efficiency [32].

By additionally observing the differences in efficiency across regions, obvious regional differences can be noted in the development trends of the three types of efficiency, especially TE. As economic and environmental trends are the same, we take economic efficiency as an example. Figure 4 demonstrates that TE differs in the three regions before 2015, but the trend is relatively stable. Post-2015, the three regions display a clear "divergence". Between 2015 and 2018, the TE of the central and western regions gradually declined, whereas that in the eastern region showed a more pronounced growth trend. TE improved in all three areas in 2019. A further analysis of the development trends of PTE and SE in the three areas shows that the growth trend of TE is basically consistent with that of PTE in all areas, indicating that the TE of the regional economy and environment is mainly affected by technology. The results of the T-test in Table 6 further verify the differences in the various efficiencies in the three regions. For example, there is a significant difference in efficiency between the central and western regions. Moreover, there are significant differences in economic and environmental TE between the west and east and west and central but no significant differences between the east and central.

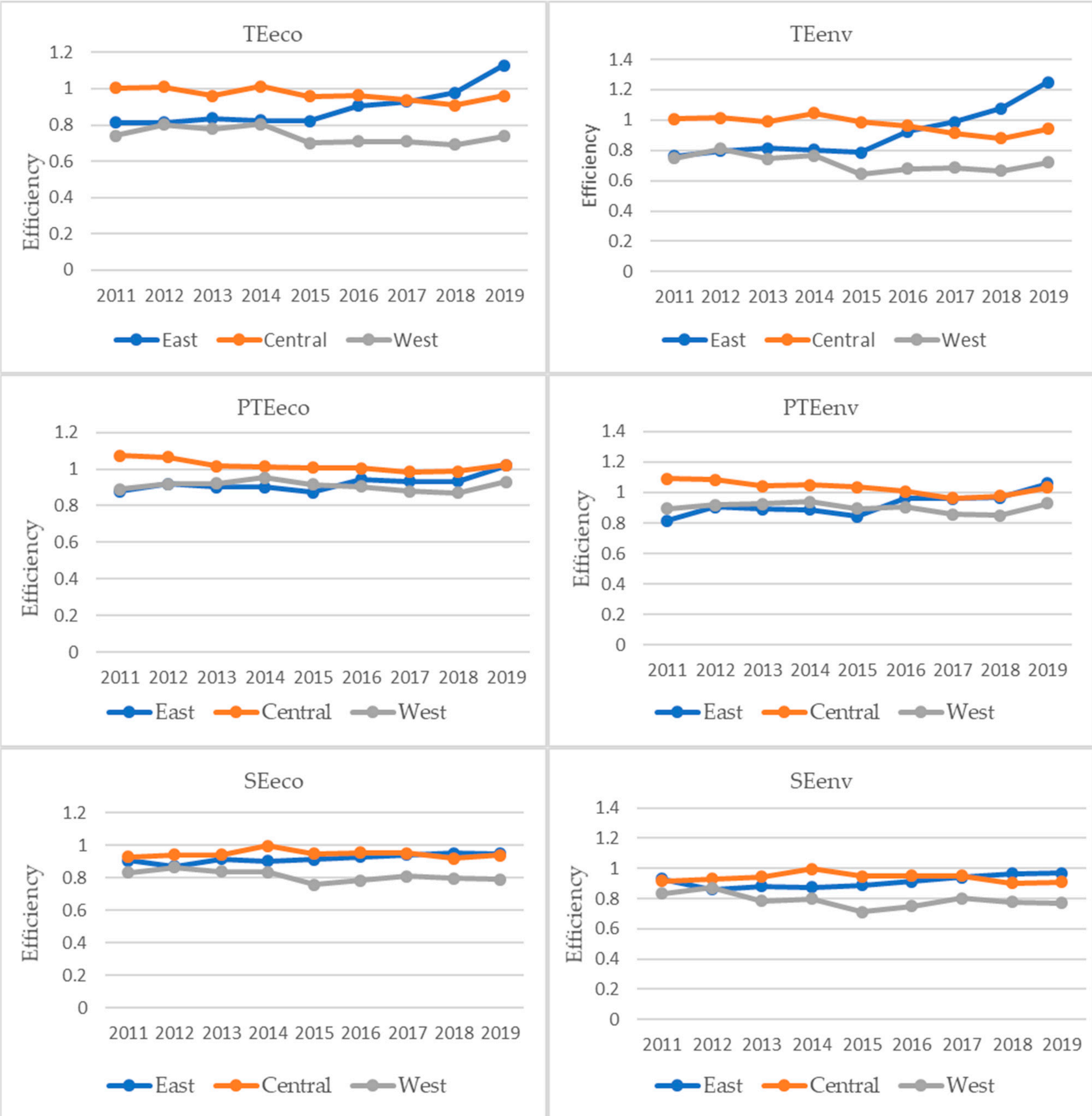


**Figure 4.** Mean efficiency trends of eastern, central, and western areas from 2011 to 2019.

**Table 6.** Tamhane's Test of all efficiency differences between three areas.

| I(area)_J(area) | Economy TEeco | Economy PTEeco | Economy SEeco | Environment TEenv | Environment PTEenv | Environment SEenv |
|---|---|---|---|---|---|---|
| East_Central | −0.073 | −0.097 ** | −0.027 | −0.060 | −0.109 ** | −0.025 |
| East_West | 0.153 ** | 0.013 | 0.107 ** | 0.193 ** | 0.020 | 0.125 ** |
| Central_West | 0.226 ** | 0.110 ** | 0.134 ** | 0.254 ** | 0.130 ** | 0.150 ** |

Notes: ** The mean difference is significant at the 0.05 level.

### *3.3. Coupling Analysis*

In the preceding section, we examined the disparities in efficiency (TE, PTE, and SE) between the two subsystems of the economy and environment across each region in China from 2011 to 2019. The analysis reveals a consistent and synchronized relationship between regional economic development and environmental protection. However, the extent of the harmony between the economic and environmental systems and level of coordinated development within a region remains uncertain. More relevant information could help in making optimization decisions for specific regional economic environments. Therefore, in this study, we conduct a coupling and coordination analysis of the subsystems of economic development and environmental protection in each region. We analyze the coupling and coordination status of each region's economy and environment by calculating the coupling and coordination degrees based on efficiency. Then, by considering two cases (whether the scale difference problem is excluded in calculating the coupling and coordination degrees), the impact of the scale problem on the coupling coordination evaluation is analyzed. Case 1: The coupling degree C (TE) and coordination degree D (TE) obtained based on TE are analyzed; that is, the coordinated development of the regional economy and environment is analyzed when the impact of scale difference is not excluded. Case 2: The coupling degree C (PTE) and coordination degree D (PTE), obtained based on PTE, are analyzed; that is, the coordinated development of the regional economy and environment is analyzed when the impact of scale difference is excluded.

First, the C and D of two subsystems in different regions from 2011 to 2019 are determined from the relevant formulas (Formulas (6)–(10)). Figure 5 depicts the development trend of the coupling and coordination level under two cases over the past nine years.

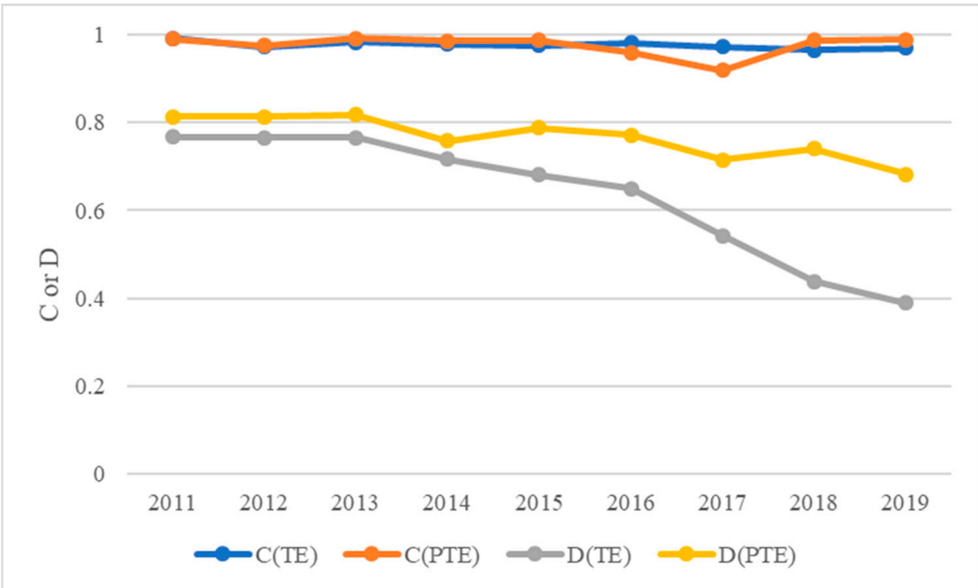


**Figure 5.** Evolution trend of C and D in two cases.

Figure 5 shows that the coupling degree (C(TE) and C(PTE)) between the economy and environment in both two cases has maintained a high value over an extended period; that is, it has been in a high-level coupling stage. However, the degree of coordination (D(TE) and D(PTE)) has gradually decreased over time, and the economy and environment have transitioned from a coordinated and orderly development state to a state of recession and disorder in the later stage. For example, C(TE) and C(PTE) remained relatively stable until 2015 and then decreased slightly. Thus, both seed systems show a high-level coupled state with strong interdependence, synchronization, and interaction. D(TE) in case 1 displays a downward trend, which has increased since 2015. By 2019, the coordination degree of each region was approximately 0.4, indicating a state of dysfunctional recession. At this time, although the economic development and environmental protection subsystems were still in a stage of high-level coupling and high synchronization, the state had already shifted from coordinated development to dysfunctional recession. In case 2, after eliminating the impact of scale, although the coupling degree C(PTE) varied over time, it remained high during the study period. However, the decrease in the coordination degree D(PTE) slowed after 2015 and remained at a moderate level of coordinated development by 2019.

Comparing the coupling degree and coordination level in cases 1 and 2, it can be seen in Figure 5 that scale has little influence on the coupling degree. In both cases, the coupling degree was only slightly different in 2017. However, scale has a significant impact on the measurement of the coordination degree of the subsystems. In case 2, the coordination level improves by excluding the scale impact of the regional economy and environment. Thus, the problem of increased difficulty in coordinated development among subsystems owing to the difference in scale between the regional economy and environment is identified. The economic and environmental subsystems have a lower coordination level when considering the scale, and the coordination is more difficult. Conversely, coordinating development is easier when only technical management is considered.

Table 7 provides the statistical results for the efficiency and coupling coordination levels in the economic and environmental subsystems. Both the economy and environment are shown to significantly affect regional coordination. In terms of correlation, the environmental subsystem exerts a slightly stronger influence on the degree of coupling (0.424 > 0.395, 0.483 > 0.443), whereas the economic subsystem demonstrates a marginally greater impact on the degree of coordination (0.603 > 0.590, 0.891 > 0.886). Therefore, in optimizing and reforming regional development issues, regions must prioritize improving and protecting environmental concerns to achieve simultaneous economic and environmental development. However, if prioritizing coordinated development, the emphasis should lean toward economic advancement. Economic development is fundamental; however, with the passage of time, China and its people have become increasingly concerned about environmental protection. Investment in environmental protection is gradually increasing in China, and regional sustainable development is not only a matter of synchronous development but also of coordinated development at a high level. Only by simultaneously improving economic and environmental efficiency can a region achieve a synchronized high level of coordinated development and avoid a synchronized low level of unbalanced or unsynchronized development. As shown in Figure 5, the economy and environment shared a synchronized and coordinated relationship in 2011. However, by 2019, although synchronization remained high, it was accompanied by dysfunctional recessionary development.

**Table 7.** Correlation and significant statistical testing of efficiency and coupling coordination levels.

| | C(TE) | D(TE) | C(PTE) | D(PTE) |
|---|---|---|---|---|
| TEeco | 0.395 *** | 0.603 *** | 0.443 *** | 0.891 *** |
| TEenv | 0.422 *** | 0.590 *** | 0.483 *** | 0.886 *** |

Notes: *** denotes 1% significance levels.

Figure 6 plots the coupling and coordination levels of all regions in the three areas studied during the individual years. It can be found that the coupling degree of all regions is close to the level of the outer circle 1, which is the high-level coupling phase. High coupling means that the economy and environment of a region have been developing in sync over the past few years. The economy and environment are developing better or at the same time, developing worse. However, apart from Beijing, the coordination level in most regions consistently remained within the “outer circle” above 0.6 in 2011 but transitioned to the “inner circle” below 0.4 in 2019. This shift indicates a transformation from a state of coordinated development between economic growth and environmental protection systems to a state of recession over time, posing significant challenges to regional sustainable development. Meanwhile, as Figure 6 illustrates, the development trends of the eastern, central, and western areas exhibit a high degree of similarity. Figure 7 demonstrates the specific development trends across these three areas.

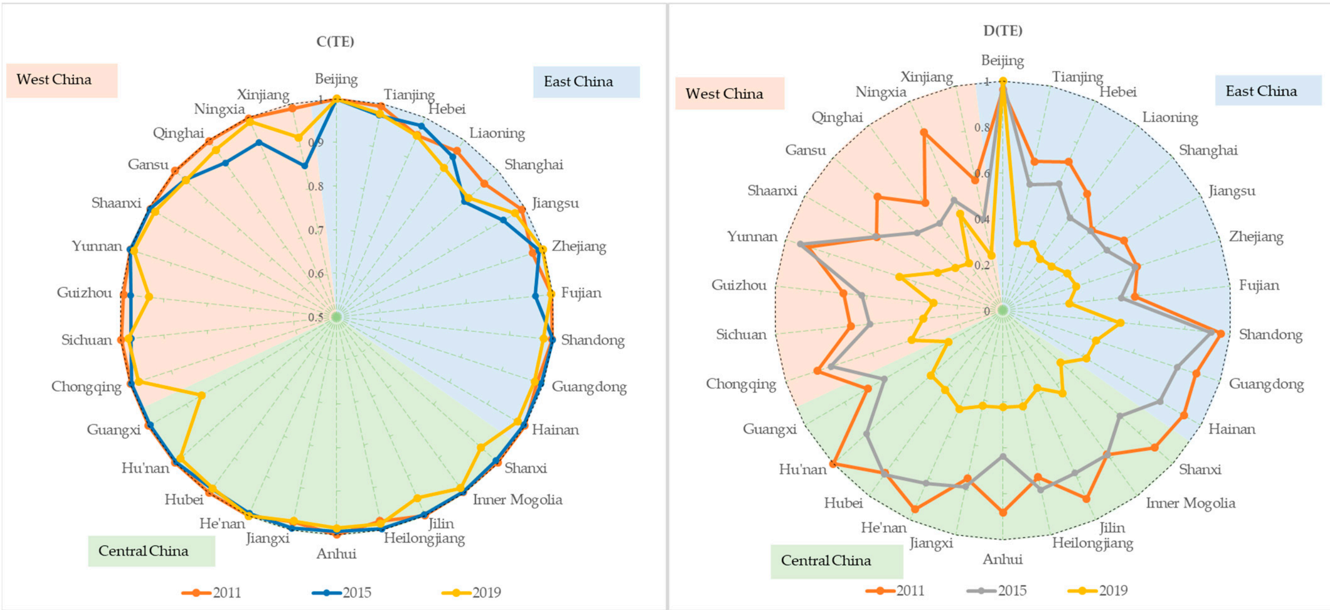


**Figure 6.** The C and D of all regions in 2011, 2015, and 2019.

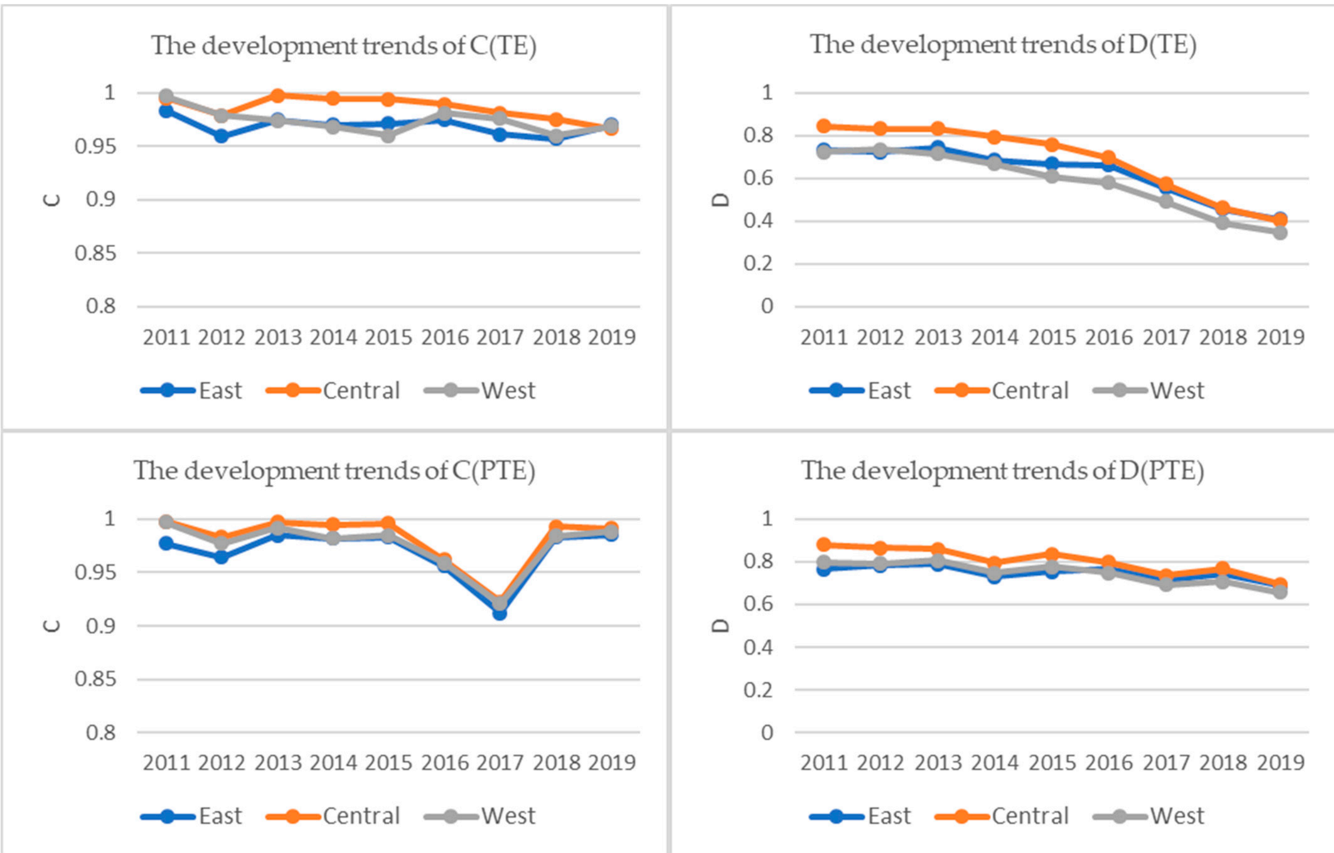


**Figure 7.** Development trends of C and D in eastern, central, and western areas.

Figure 7 illustrates the evolutionary trends in the coupling degree and coordination level in the three areas over the past nine years for both cases. The eastern, central, and western areas are clearly fundamentally moving in the same direction. In terms of the coupling degree, the three areas have been in strong economic and environmental synchronization for nine years. However, the coordination level began to deteriorate over time, eventually entering a state of dysfunctional recession. The changes in the three areas are the same as the overall evolution trend depicted in Figure 4. However, as shown in Figure 7, the central area is primarily situated above the western and eastern areas. Statistical analysis can verify the presence of relatively pronounced regional differences among the regions, as demonstrated by the detection results in Table 8 which presents the significance levels for intergroup coupling and coordination, as well as pairwise comparisons. A significant difference is evident between the eastern and central areas, with the central area clearly outperforming the eastern, regardless of coupling or coordination levels and irrespective of excluding scale effects. No significant differences are observed between the eastern and western areas. The coupling and coordination levels are significantly different in the central and western areas; however, there is no significant difference in the coupling degree after excluding scale effects.

**Table 8.** Tamhane's Test of C and D difference between three areas.

| I (Area) | J (Area) | Mean Difference (I–J) C(TE) | D(TE) | C(PTE) | D(PTE) |
|---|---|---|---|---|---|
| East | Central | −0.0168 *** | −0.0623 ** | −0.0125 ** | −0.0553 *** |
| | West | −0.0047 | 0.0417 | −0.0066 | 0.0008 |
| Central | West | 0.0121 ** | 0.1040 *** | 0.0059 | 0.0561 * |

Notes: * and ** and *** denote the 10%, 5%, and 1% significance levels, respectively.

## 4. Conclusions

This study aims to assess the relative efficiency and coordinated development levels of regional economic development and environmental protection systems. An adjusted input-oriented super-SBM model is constructed based on the synergistic development mechanism and structure between the regional economic development and environmental protection subsystems. We analyze the TE, PTE, and SE of the regional economy and environment under VRS and CRS constraints. The coupling coordination level of the regional economy and environment is then measured using a coupled coordination model. The effects of scale difference on the coordination level are also compared. Finally, the efficiencies and coordinated development levels of the economic and environmental subsystems in 30 Chinese regions from 2011 to 2019 are analyzed. Suggestions for appropriate improvements are made to help each region enhance and optimize its economy and environment in a timely manner. The main findings are discussed below.

In the efficiency analysis stage, the directions of economic construction and environmental protection in each region are fundamentally the same but change synchronously. Thus, regions with excellent economic development exhibit improved environmental protection. Conversely, regions with poor economic development demonstrate relatively poor environmental protection. This validates existing research showing that regions with a higher GDP have better ecological effects. Next, we find that low SE is the main cause of low TE in the regional economy and environment during the study period. Therefore, the difference in scale is the main reason for "dragging down" regional economic development and environmental protection construction. However, the trends in regional economic and environmental TE are more consistent with those of PTE. Thus, technology primarily determines the direction of regional development. Finally, comparing the three areas, we find clear regional differences in efficiency across these areas. The central area is economically and environmentally superior to the eastern and western areas. In particular, PTE is super-efficient in the central area. The western area is found to have the worst economic and environmental efficiency.

The study also revealed strong synchronization between economic development and environmental protection in the coupling analysis stage. However, although the coupling between the economy and environment has remained strong, the level of coordination has gradually declined. From 2011 to 2019, regional economies and environments transitioned from a state of coordinated development to one characterized by disorderly recession, deviating from the original intention of promoting harmonized high-quality regional development. Therefore, most regions must enhance their coordinated economic and environmental development. This study also found that scale differences in the economy and environment pose challenges to coordinating development. Technical management could more effectively facilitate coordination. Coordinated development levels are influenced by both economic and environmental efficiency, with the statistical analysis showing economic development to have a slightly higher impact. Given the limited development capacity in some regions, prioritizing economic development is a reasonable approach. However, as environmental protection awareness and regional development abilities gradually strengthen, simultaneous economic and environmental progress will be pursued to achieve coordinated, high-level regional development at a faster pace. Moreover, similar to efficiency, coupling coordination exhibits distinct regional characteristics within the ground domain. The central area shows significantly higher levels of coupling and coordination than the eastern and western areas. Moreover, excluding scale differences, no significant differences in coupling are observed between the eastern and western areas.

In this paper, we focus on the most representative subsystems of economic development and environmental protection in the process of regional development and construction. Based on the coupling and interaction structure between them, the SBM model and the coupling coordination model are used together to investigate the performance of each subsystem and the intersystem coordination problem. This paper not only expands the application of the DEA method but also analyzes the economic development and environmental protection systems of various regions in China to help various regions find the problems in the process of the coordinated development of the economy and environment and provides certain suggestions for the planning and optimization of regional sustainable development policies. Finally, as regional comprehensive, sustainable, and coordinated development deepens, the methods of this paper can be further extended to analyze the performance of multiple subsystems such as the economy, environment, society, and ecology and the multi-level and multi-angle coordinated development of these subsystems. Therefore, in our research, we comprehensively analyze and forecast the performance problems of subsystems and the coordinated development among systems in the process of regional sustainable development from multiple perspectives, such as the economy, society, environment, and transportation, amongst others. Finally, relevant research will assist each region in formulating appropriate regional coordinated development strategies to help the sustainable development of the region.

**Author Contributions:** N.L.: conceptualization, methodology, data collection, result analysis, original draft preparation, and editing. L.Z.: reviewing. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work is sponsored by the National Natural Science Fundation of China (No. 71801132, No. 71701102) and the Natural Science Fund for Colleges and Universities in Jiangsu Province (No. 18KJD120003).

**Data Availability Statement:** The raw data that support the findings of this article are openly available from the China Statistical Yearbook and Easy Professional Superior (EPS) data platform.

**Acknowledgments:** The authors would like to thank the journal editors and anonymous reviewers for their helpful comments.

**Conflicts of Interest:** No potential conflicts of interest were reported by the authors.

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