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Analysis on Evaluation and Spatial-Temporal Evolution of Port Cluster Eco-Efficiency: Case Study from the Yangtze River Delta in China

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Abstract: The improvement of port cluster eco-efficiency is of great significance to constructing a world-class shipping hub and the high-quality development of regional economy. This study adopts the Super-EBM (Super-efficiency Epsilon-Based Measure) model to evaluate the eco-efficiency of the Yangtze River Delta port cluster in China, and the GML (Global Malmquist-Luenberger) index, spatial hot spot analysis, gravity center migration model, and the Theil index are combined to reveal the spatial-temporal evolution. The results show that the average eco-efficiency of the Yangtze River Delta port cluster is 0.686, with 55.6% of the ports being below the average, which is directly related to the low scale efficiency. Mainly driven by technical efficiency improvement, the overall eco-efficiency has a growth rate of 8.7% from 2010 to 2019. Moreover, considerable spatial divergence has formed in the port cluster, and the eco-efficiency gravity center has always been in the south of Jiangsu. The overall eco-efficiency gap has widened by 19.92%, and the gap within the region, particularly within Zhejiang, is the major source. To improve the overall eco-efficiency of the port cluster, policymakers should strengthen the technological spillover of ecologically efficient ports in clean production and mechanism reform, while optimizing the resource consolidation system of ports with relatively low eco-efficiency.

Keywords: eco-efficiency; the Yangtze River Delta port cluster; Super-EBM; the GML index; spatial-temporal evolution

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1. Introduction

Facing global issues such as resource over-consumption and climate change, all countries have been urged for sustainable transformation. As for China, ecological civilization construction was made a national strategy as early as 2012, and the plenary series that followed highlighted the two main lines of environmental legislation and green development. In particular, the 19th National Congress of CPC combined ecological harmony with modernization, further indicating the practical necessity of ecological protection. Evaluation of the level and evolution of ecological performance, if able to affect the formulation of public policies, can significantly reduce the cost of environmental governance [1]. As resource constraints have been tighter, the need to improve eco-efficiency is more acute in developing countries like China, which show a significant cost gap compared to developed countries [2].

According to the International Energy Agency (IEA), the transportation sector is responsible for 24% of global greenhouse gas emissions, of which maritime transportation is an important source. The international community has recognized the need for strengthening environmental regulation in planning marine logistics systems, and such regulation requires a comprehensive understanding of port operations and ship emissions [3]. In this context, the Ministry of Transport of China has released several major projects, including green port pilot, sustainable development assessment, and port pollution prevention. Despite these efforts, most Chinese ports have not reached the same emission level as the international community [4], and they are still at the stage of ecological underdevelopment [5–7].

Having the most coastal ports and the largest cargo throughput in China, the Yangtze River Delta port cluster exerts a huge impact on the national economy. By the end of 2022, its total exports and imports have reached approximately $1.51 trillion, accounting for 35.8% of China's total foreign trade value. Apart from that, it is also highly competitive among global ports. According to Lloyd's List of Top 100 global container ports in 2022, Shanghai Port and Ningbo-Zhoushan Port, both of which belong to the Yangtze River Delta port cluster, are ranked first and third, respectively, showing considerable advantages in scale. Nevertheless, it must be admitted that ports in the Yangtze River Delta suffer from overlapping hinterlands and homogeneous resource endowments [8]. Large ports occupy most of the market share, while small and medium-sized ports can only divide the remaining part through fierce competition, leading to a severe waste of resources and further aggravating the imbalance within the Yangtze River Delta port cluster.

In recent years, port clusters have played an increasing role in the maritime competition landscape [9], and some studies have found that the coordinated development of port clusters can create the effect of "one is greater than the sum of its parts" [10]. Given that the port cluster is a geographic combination of neighboring ports that share similar economic, political, and social characteristics, comparative analysis in such a homogeneous environment can more effectively identify the weaknesses of specific individual ports [1,11]. Under the trend of regional economic integration and globalization, the Yangtze River Delta port cluster is certainly a good target for eco-efficiency analysis. Unfortunately, there are few studies on port clusters, and the most focused is large-scale ports around the world [12–14], major ports in a country or a region [15–17], and ports along the river or the sea [6,18,19].

Eco-efficiency is an effective tool for sustainability assessment [20–22], and its basic idea is to obtain the maximum economic value with the minimum environmental cost, which is consistent with the goal of port operations. Port cluster eco-efficiency, as a key indicator of the ecological performance of port systems, can be defined as Pareto's optimal solution between economic and ecological development. However, existing research on port efficiency evaluation is mainly based on two perspectives: port operation efficiency and port production efficiency. The former tends to apply several financial indicators, such as cargo profitability [23], business revenue [24], and capital stock [25], while the latter focuses on the performance of equipment and infrastructure, with common indicators including port length [13], number of berths [16], and port throughput [26]. With ship emissions seriously threatening the balance of the entire ecosystem, such undesirable output indicators as NO_x, SO_2, and solid emissions should be included in the evaluation system of port efficiency [27,28]. Apart from that, considering both the higher transportation costs and lower ecological performance in China [3]—with the demand for port business continuing to grow, it is surprising that few studies have been available on port eco-efficiency evaluation.

In terms of the evaluation method of port efficiency, scholars have made a variety of exploration of the evaluation methods of port efficiency, which includes indicator analysis method [29,30], multiple regression analysis [17,31], and stochastic frontier model [32,33]. However, hypotheses of the methods on the production function are difficult to justify, which prevents them from accurately reflecting the real state of port efficiency. Due to the unique advantages of examining the source, direction, and degree of efficiency improvement, DEA (Data Envelope Analysis) has gradually become the frontier of efficiency evaluation [34], which uses the smallest or best-matched convex spherical shell to envelope all the input and output elements, and the corresponding production frontier just right explains the economic connotation of faster and better development.

The traditional DEA models, such as CCR (Charnes-Cooper-Rhodes) [35] and BCC (Banker-Charnes-Cooper) [36], do not take slackness into account. When assessing the effects of environmental pollutants, they usually convert the undesirable output into desirable output or input, which is thought to have a strong subjective preference [5,16]. The SBM (Slack-Based Measure) model [37] maps the undesirable output directly onto the collection of production possibilities, providing a more reliable solution. Nevertheless, the SBM model only works for the non-radial and non-angular estimation, and the efficiency will be underestimated when the input and output variables are diverse [38]. For this reason, Tone and Tsutsui [39] improved SBM to EBM, which is a mixed-distance model that can not only calculate the optimal distance radially, but also measure the slack variables. To further identify the difference between the effective DMU (Decision-making Unit), the EBM model can be further combined with the super-efficiency DEA [40] with a maximum efficiency value greater than 1. In recent years, the Super EBM model has received increasing attention for the broader applicability and stronger comparability [38,41], which can more accurately reflect the actual characteristic of efficiency.

In fact, the single DEA can only compare the relative effectiveness of DMU over the same period [42]. Once the factor of time is incorporated into the model, the production frontier may change, and different baselines in multi-period comparison will lead to measurement errors. On this basis, the Malmquist index was first proposed to measure dynamic efficiency, but it can only calculate the radial distance functions. Chung [43] proposed the ML (Malmquist-Luenberger) index, which is capable to examine the change in efficiency containing undesirable outputs. To further reveal the long-term trend of efficiency, Pastor and Lovell [44] built a global production frontier covering input and output variables in all periods. Oh [45] combined global production index with the directional distance function and proposed the GML index, which is regarded as a useful tool for inter-period analysis, ensuring the cyclic accumulation and comparability of efficiency evaluation from a dynamic perspective.

In summary, existing studies have clarified the necessity to improve the ecological environment of ports. However, the selected objects are too dispersed to examine the efficiency characteristics of regional port system. In addition, little literature combines port ecological performance with the concept of efficiency, and fails to reflect the actual situation of port operation and ship emissions. Moreover, there is a lack of appliance of improved DEA models in port efficiency evaluation, and the study in dynamic efficiency changes should be further supplemented. Based on this, this paper takes the Yangtze River Delta port cluster as the research object, which is representative of the world. Introducing the concept of eco-efficiency to port management, this paper constructs a new evaluation system of port efficiency, which can effectively quantify the coordination between port resource input, economic output, and ecological impact. Improved DEA combination methods are also adopted in assessing port efficiency, filling the gap of insufficient attention on comparability and continuity.

In this paper, first, we employ the Super-EBM model with undesirable outputs to assess the eco-efficiency of the Yangtze River Delta port cluster, with discussions of the reason for inefficiency. Then, we apply the GML index to examine the temporal trend of port cluster eco-efficiency from 2010 to 2019, and the internal factors affecting the eco-efficiency changes are also deeply analyzed. Finally, we use spatial hot spot analysis, gravity center migration model, and the Theil index to further explore the spatial evolution and regional difference of the eco-efficiency of the Yangtze River Delta port cluster, which can help optimize the layout of port resources and narrow the regional differences in ecological development. As it turns out, our study is of great importance to promote the ecological coordination of the Yangtze River Delta, and can also provide referential experience on methods for efficiency evaluation and temporal-spatial evolution analysis.

2. Materials and Methods

2.1. Models

2.1.1. Super-EBM Model

For the production system of the Yangtze River Delta port cluster, there are 18 port DMUs to be dealt with, and each contains m inputs, s desirable outputs, and q undesirable outputs. x_{ik}, y_{rk}, and z_{pk} respectively refer to the k-th (k = 1,..., 18) input, desirable output, and undesirable output. s_i^-, s_r^+, and s_p^- represent slack variables of x_{ik}, y_{rk}, and z_{pk}, respectively. With reference to Tone and Tsutsui [39], this paper constructs a Super-EBM considering undesirable outputs, and the following principle defines how the model works.

$$TE = \min \frac{\theta - \varepsilon^- \sum_{i=1}^{m} \frac{w_i^- s_i^-}{x_{ik}}}{\phi + \varepsilon^+ \left(\sum_{r=1}^{s} \frac{w_r^+ s_r^+}{y_{rk}} + \sum_{p=1}^{q} \frac{w_p^- s_p^-}{z_{pk}} \right)}$$
$$s.t. \begin{cases} \sum_{j=1, j \neq k}^{n} \lambda_j x_{ij} + s_i^- \leq \theta x_{ik}, i = 1, 2, \ldots, m \\ \sum_{j=1, j \neq k}^{n} \lambda_j y_{rj} - s_r^+ \geq \phi y_{rk}, r = 1, 2, \ldots, s \\ \sum_{j=1, j \neq k}^{n} \lambda_j z_{pj} + s_p^- \geq \phi z_{pk}, p = 1, 2, \ldots, q \\ \lambda_j \geq 0, s_i^-, s_r^+, s_p^- \geq 0 \end{cases} \quad (1)$$

In Equation (1), TE represents the eco-efficiency value of each port. When TE is more than 1, it means that the port eco-efficiency is at the effective level, and when TE is less than 1, it indicates that there is room to reach the production frontier.

2.1.2. GML Index

This paper takes the Super-EBM model as the directional distance function, and then establishes the GML index at the same level of production technology. To further investigate the internal influencing factors of port eco-efficiency changes, the GML index can be decomposed into the Global Technical Efficiency change index (GEC) and the Global Technological Progress change index (GTC).

$$\begin{aligned} & GML^{t,t+1}\left(x^t, y^t, b^t, x^{t+1}, y^{t+1}, b^{t+1}\right) = \frac{D^G\left(x^{t+1}, y^{t+1}, b^{t+1}\right)}{D^G\left(x^t, y^t, b^t\right)} \\ & = \frac{D^{t+1}\left(x^{t+1}, y^{t+1}, b^{t+1}\right)}{D^t\left(x^t, y^t, b^t\right)} \times \left[\frac{D^G\left(x^{t+1}, y^{t+1}, b^{t+1}\right)}{D^{t+1}\left(x^{t+1}, y^{t+1}, b^{t+1}\right)} \frac{D^t\left(x^t, y^t, b^t\right)}{D^G\left(x^t, y^t, b^t\right)} \right] \\ & = GEC^{t,t+1} \times GTC^{t,t+1} \end{aligned} \quad (2)$$

In Equation (2), x_t, y_t, and b_t are the input, desirable output, and undesirable output in the t-th period, respectively. $GML_{t,t+1}$ indicates the eco-efficiency changes during the adjacent two periods. When the target GML is more than 1, it indicates an increase in eco-efficiency, and when the target GML is less than 1, it indicates a decrease in eco-efficiency. $GEC_{t,t+1}$ measures the changes in port cluster management, while $GTC_{t,t+1}$ measures the change in port cluster technology.

2.1.3. Theil Index

The Theil index is a special format of the generalized entropy indicator system. It was initially for measuring the differences in a data group and then was widely used in fairness evaluation, such as regional economy, household income and consumption structure. Compared with other index systems, the Theil index can decompose the overall eco-efficiency gap into between-group and within-group gaps, which can effectively analyze the source and structure of differences. On this basis, this paper divides the 18 major ports of the Yangtze River Delta port cluster into four regions: Shanghai, Jiangsu, Zhejiang, and Anhui. The calculation equation is as follows.

$$T = T_W + T_B = \frac{1}{18}\sum_{i=1}^{18} \frac{e_i}{\bar{e}} \ln\frac{e_i}{\bar{e}} \tag{3}$$

$$T_W = \sum_{p=1}^{4} \left(\frac{n_p}{18} \frac{\bar{e}_p}{\bar{e}} \right) T_p \tag{4}$$

$$T_B = \sum_{p=1}^{4} \frac{n_p}{18} \left(\frac{\bar{e}_p}{\bar{e}} \right) \ln\left(\frac{\bar{e}_p}{\bar{e}} \right) \tag{5}$$

In the Equations (3)–(5), T, T_W, and T_B represent the overall gap, the gap between regions, and the gap within the region, respectively. The value of Thiel index is in the range of [0, 1], and the larger the value, the larger the eco-efficiency gap.

2.2. Evaluation Indicators System

Port eco-efficiency can be viewed as the ratio between inputs and outputs. In this paper, inputs refer to the resources consumed by port production, and outputs refer to the economic value generated by the port products and services, as well as the pollutant emitted in the production process. With reference to the related research shown in Table 1, this paper further combines the characteristics of port operations, and the following indicators are finally selected.

1. Input indicators: Berths and piers are important infrastructures representing the port's operation and service capacity. Transferring goods from ships to the coast through the piers fundamentally affects port efficiency, which is also critical to shaping the competitive advantages of ports. Therefore, this paper takes the number of berths and pier lengths as the input indicators.
2. Desirable output indicators: The throughput of all ports in the Yangtze River Delta has increased significantly in recent years [14]. Considering that stable cargo flow is a fundamental guarantee for efficient port production, the desirable output is assessed by cargo throughput and container throughput in most cases.
3. Undesirable output indicators: The main pollutants emitted by ships are NO_x and SO_2, which account for 15% and 7% of the global total NO_x and SO_2 emissions, respectively [46]. For a more comprehensive measurement of the negative externalities of port production, this paper adds up the indicator of solid waste and finally uses NO_x, SO_2, and solid waste as the undesirable output.

Table 1. Related research on the evaluation indicator system of port efficiency.

Reference	Research Object	Input	Desirable Output	Undesirable Output
Ye et al. [1]	Port Efficiency	The number of berths, Pier lengths, Channel depth	Cargo throughput, Container throughput	/
Song and Liu [8]	Total Factor Productivity of Port Enterprise	The number of berths, Pier lengths	Cargo throughput, Container throughput	/
Huang et al. [18]	Port Operation Efficiency	The number of berths, Pier lengths, Gantry cranes	Container throughput	/
Gao and Sun [24]	Port Operation Efficiency	Staff number, Fixed assets	Operating cost, Net profit, Cargo throughput	NO_x

Table 1. *Cont.*

Reference	Research Object	Input	Desirable Output	Undesirable Output
Wanke [26]	Shipment Consolidation Efficiency	The number of berths, The warehousing area, The yard area	Cargo throughput, Container throughput	/
Chin and Low [27]	Port Production Efficiency	Frequency of shipping, Capacity flow	Container capacity, flows	NO_x, SO_2, CO_2, Particulate matter
Lee et al. [28]	Port Environmental Efficiency	Labor population	Container throughput, GDP	NO_x, SO_2, CO_2, Solid waste
Dong et al. [47]	Environmental Efficiency of Port	The number of berths, Pier lengths, Quay cranes	Container throughput	CO_2

2.3. Research Area and Data Sources

According to the latest Outline of the Yangtze River Delta Regional Integration Development Plan, the Yangtze River Delta incorporates Shanghai, Jiangsu, Zhejiang, and Anhui. Based on the directory of major ports released by the Ministry of Transport of China, as well as taking into account the availability of data, this paper takes the panel data of 18 representative ports in the Yangtze River Delta port cluster from 2010–2019, which includes Shanghai, Ningbo-Zhoushan, Hangzhou, Wenzhou, Taizhou-Z (Zhejiang Province), Huzhou, Nanjing, Suzhou, Zhenjiang, Nantong, Wuxi, Lianyungang, Taizhou-J (Jiangsu Province), Changzhou, Yangzhou, Ma'anshan, Anqing, and Wuhu ports. Data are collected from the China Ports Yearbook, China Statistical Yearbook on Environment, and statistical yearbooks of cities in the Yangtze River Delta.

3. Empirical Results

3.1. Static Evaluation of Eco-Efficiency

Based on the evaluation indicator system of port eco-efficiency, the Super-EBM model is adopted to assess the static eco-efficiency of the Yangtze River Delta port cluster using MaxDEA ultra 8. Drawing on the criteria of the existing research [20,22,48], the eco-efficiency can be divided into five grades: Grade I ($0 \leq$ eco-efficiency < 0.4) is the optimal eco-efficiency, Grade II ($0.4 \leq$ eco-efficiency < 0.6) is the high-level eco-efficiency, Grade III ($0.6 \leq$ eco-efficiency < 0.8) is the moderate eco-efficiency, Grade IV ($0.8 \leq$ eco-efficiency < 1) is the low-level eco-efficiency, and Grade VI (eco-efficiency ≥ 1) is the poor eco-efficiency. The eco-efficiency score of ports in the Yangtze River Delta port cluster are displayed in Table 2 below.

Table 2. The overall eco-efficiency of the Yangtze River Delta port cluster from 2010 to 2019.

DMU	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Mean
Shanghai	0.367	0.321	0.274	0.354	0.414	0.363	1.011	1.027	1.032	1.033	0.620
Ningbo-Zhoushan	0.316	0.272	0.248	0.330	0.429	0.380	0.584	0.708	0.780	0.915	0.496
Hangzhou	0.565	1.000	1.000	1.106	1.039	1.002	1.092	1.075	1.088	1.057	1.002
Wenzhou	0.218	0.210	0.237	0.192	0.138	0.189	0.252	0.327	0.330	0.229	0.232
Taizhou-Z	0.370	0.343	0.388	0.307	0.331	0.320	0.377	0.360	0.318	0.134	0.325
Huzhou	1.000	1.050	1.044	1.027	0.435	0.703	0.323	0.280	0.263	0.157	0.628
Nanjing	0.185	0.197	0.212	0.126	0.162	0.156	0.349	0.481	0.567	0.538	0.297
Suzhou	1.202	1.190	1.193	1.147	1.170	1.174	1.056	1.189	1.178	1.114	1.161
Zhenjiang	1.053	1.039	1.046	1.057	1.059	1.050	1.056	1.056	1.055	1.086	1.056
Nantong	1.022	1.025	0.671	1.021	1.016	1.015	1.036	1.027	1.030	1.028	0.989
Wuxi	0.087	1.008	1.010	0.420	1.056	1.008	0.436	0.318	0.308	0.313	0.597
Lianyungang	0.632	0.639	0.559	0.754	1.002	0.676	1.121	1.105	1.107	1.106	0.870

Table 2. *Cont.*

DMU	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Mean
Taizhou-J	1.039	1.044	1.050	1.040	1.046	1.050	1.035	1.032	1.036	1.017	1.039
Changzhou	1.052	1.045	1.028	1.024	1.008	1.015	1.008	1.002	0.323	0.107	0.861
Yangzhou	0.234	0.219	0.354	0.291	0.376	0.276	0.519	0.640	0.709	0.388	0.401
Ma'anshan	1.012	1.014	1.006	1.025	0.661	0.703	1.008	1.011	0.861	0.598	0.890
Anqing	0.668	0.579	0.473	0.299	0.217	0.285	0.173	0.210	0.268	0.193	0.337
Wuhu	0.614	0.581	0.552	0.441	0.495	0.501	0.548	0.571	0.619	0.514	0.543
Mean	0.646	0.710	0.686	0.665	0.670	0.659	0.721	0.746	0.715	0.640	0.686

From 2010 to 2019, the average port cluster eco-efficiency equals 0.686, which is at the moderate eco-efficiency level, indicating that the challenges to environmental governance have not been fundamentally overcome in the past ten years. The eco-efficiency value of Suzhou, Zhenjiang, Taizhou-J, and Hangzhou ports exceeds 1, reflecting that they attach great importance to clean production and have advanced knowledge of green transition. In terms of continuous performance, Suzhou and Zhenjiang ports maintain the optimal eco-efficiency level, which have beautiful natural scenery and are led mainly by light industry, thus with less pressure of emission reduction. Nantong, Lianyungang, Changzhou, and Ma'anshan ports get high-level eco-efficiency. As the relatively late-developing ports, the transportation demand and trade scale are relatively stable, which has slowed down the discharge of environmental pollutants [31]. Unlike other ports, Lianyungang port is far away from the center of the Yangtze River Delta, which has a strategic role in the development of the Maritime Silk Road, avoiding the homogeneous competition within the port cluster to some extent. In addition, Ma'anshan port is an important steel base in China and has a heavy task for pollution control. Under the strategy of revitalizing the city with the port, the ecology state has been greatly improved.

With eco-efficiency scores of 0.620 and 0.628, respectively, Shanghai and Huzhou ports have moderate eco-efficiency performance, which is somewhat distant from the production frontier. The average eco-efficiency of Yangzhou, Ningbo-Zhoushan, and Wuhu ports is 0.401, 0.496, and 0.543, respectively, belonging to the low level, which indicates that there may be a potential conflict between economic growth and ecological protection. It is surprising that Ningbo-Zhoushan and Shanghai ports lead the world in terms of total throughput, while the eco-efficiency scores are not ideal. Tracking to the cause, when the production scale has expanded to a certain level, the internal cost of organization, information, and management will rise rapidly, which in turn shows a significant diseconomy effect of scale [49]. In general, ports with low-level and poor eco-efficiency account for 44.4% of the total sample, among which the eco-efficiency of Anqing, Taizhou-Z, Nanjing, and Wenzhou ports is lower than 0.4 and at the poor eco-efficiency level. As for the reason, Anqing port is relatively backward in the port infrastructure, and the environmental investment will take up the expenditure for economic construction, thus leading to low enthusiasm for equipment renewal and technology upgrading. Although Nanjing port is surrounded by many high eco-efficient ports, the conditions for ecological transition are very limited as it is inland, reflecting the spillover effect of the neighboring ports has not been fully played [50]. As for Taizhou-Z and Wenzhou ports, it is difficult for them to obtain the prioritized resources and policy opportunities under the squeeze of Ningbo-Zhoushan port, and they have long suffered from unclear positioning and scattered layout of Zhejiang.

In order to investigate the reason why the overall ecological performance of the Yangtze River Delta port cluster is inefficient, this paper further decomposes the static eco-efficiency to PTE (Pure Technical Efficiency) and SE (Scale Efficiency) [51]. According to the static decomposition results shown in Table 3, the PTE is effective and significantly higher than SE, reflecting that the low SE of the Yangtze River Delta port cluster directly pulls down the overall eco-efficiency, which is closely related to the non-intensive utilization of resources and the homogeneous competition. Besides, the overall SE of each region in the Yangtze River Delta is relatively low as well, with Shanghai and Anhui even below 0.6, further indicating that the spatial layout of the Yangtze River Delta port cluster needs to be optimized. Due to the scarcity of land and shoreline resources, it is difficult and costly for Shanghai port to continue the building and expansion, but the efforts in the collection-distribution system and port-city linkage have recently improved the operation efficiency. In contrast, the SE of ports in Anhui dropped from 0.697 to 0.454. The ports of Anhui are relatively small and poorly organized, and the financial assistance has also been long-delayed, putting them at a disadvantage in the maritime market.

Table 3. The static decomposition results of the port cluster eco-efficiency.

Time	Port Cluster		Shanghai		Zhejiang		Jiangsu		Anhui	
	PTE	SE	PTE	SE	PTE	SE	PTE	SE	PTE	SE
2010	0.981	0.672	1.061	0.346	0.797	0.629	1.030	0.725	1.115	0.697
2011	0.983	0.748	1.062	0.302	0.793	0.713	0.983	0.864	1.274	0.609
2012	1.021	0.695	1.053	0.261	0.854	0.660	1.090	0.775	1.084	0.663
2013	0.974	0.661	1.051	0.337	0.873	0.639	0.998	0.735	1.050	0.588
2014	1.084	0.608	1.047	0.396	0.916	0.484	1.192	0.753	1.054	0.456
2015	1.036	0.637	1.046	0.347	0.887	0.559	1.087	0.766	1.133	0.481
2016	1.112	0.671	1.044	0.969	1.019	0.504	1.162	0.765	1.146	0.573
2017	1.015	0.765	1.040	0.987	0.776	0.694	1.112	0.827	1.119	0.627
2018	1.618	0.711	1.039	0.993	3.146	0.550	1.021	0.801	1.060	0.616
2019	0.946	0.691	1.038	0.996	0.715	0.590	0.975	0.793	1.214	0.454
Mean	1.077	0.686	1.048	0.593	1.078	0.602	1.065	0.780	1.125	0.576

3.2. Temporal Trend of Eco-Efficiency

Table 4 gives the dynamic assessment results of the eco-efficiency of the Yangtze River Delta port cluster. From the whole point of view, the average of GML, GEC, and GTC indexes equals 1.087, 1.090, and 1.062, respectively, showing that the overall eco-efficiency has a growth rate of 8.7%, and the GEC and GTC indexes have increased by 9% and 6.2%, respectively. In other words, the increase in the port cluster eco-efficiency is attributed to technical efficiency improvement and technological progress, and technical efficiency improvement is the main driving force. It can be inferred that port enterprises in the Yangtze River Delta pay more attention to optimizing the management pattern and the resource allocation institution along with technological innovation, and with the joint efforts of these two factors, the port cluster eco-efficiency has been greatly elevated.

Table 4. The dynamic assessment results of eco-efficiency in the Yangtze River Delta port cluster.

Time	2010–2011	2011–2012	2012–2013	2013–2014	2014–2015
GML	1.265	0.978	1.077	1.220	0.929
GEC	1.603	1.000	0.968	1.086	1.021
GTC	0.977	0.982	1.131	1.005	0.934
Time	**2015–2016**	**2016–2017**	**2017–2018**	**2018–2019**	**Mean**
GML	1.112	1.061	1.029	1.110	1.087
GEC	1.258	1.057	0.986	0.828	1.090
GTC	1.021	1.020	1.134	1.352	1.062

From the perspective of local trend, the chronological evolution of eco-efficiency in the Yangtze River Delta port cluster can be divided into two stages based on the correlation of index changes, and Figure 1 shows the dynamic trend of the GML and the decomposition indexes from 2010 to 2019. 2010–2017 was divided as the first development stage, which is driven by technical efficiency, and the GEC index has generally maintained a high level. In 2010, the State Council formally approved the integration of the Yangtze River Delta, leading to a profound leap in the professional and orderly operation of the ports. As the positive effect of technical efficiency was not enough to compensate for the negative impact of technological regression [52], a short-term decline in eco-efficiency occurred in 2011–2012 and 2014–2015. It reflects that technological progress at this stage relied mainly on technology introduction, which will not only lead to rapid loss of advantage due to competitors' imitation, but also cause blind layout and repetitive construction [53]. China's work on the integration of ports across the country began in 2015, and by reducing the undesirable outputs at the end of the production chain, environmental regulation has exerted a positive impact on the GML index, thus releasing a strong marginal effect of office investment during 2015–2017.

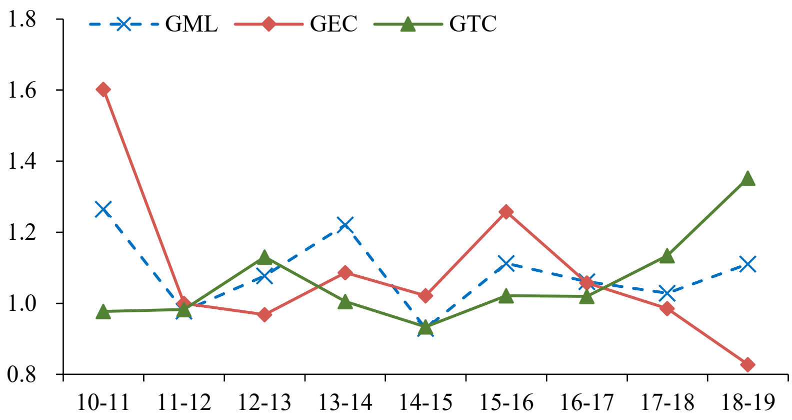

Figure 1. The changes of the GML and the decomposition indexes from 2010 to 2019.

The second stage lasted from 2017 to 2019, when the GML and GTC indexes both exhibited an upward trend, and technological progress became the leading factor. With the problems of insufficient inter-linkage and unclear division of labor becoming increasingly prominent [54], the management mechanism gradually lagged the requirements of port modernized transition, which also reflects that while gathering advantageous resources for ecological improvement, the long-term intervention of administrative forces also inhibits the free flow and allocation of resources to a certain extent [55], making the port management mechanism more closed and decentralized. Coupled with the supply-side structural reform in China, the calls for structural adjustment and reduced capacity have posed challenges to port business, leading to a further decline in the GEC index. However, global commerce has been back on the rails since mid-2016, and the cyclical upturn of the world economy has created a favourable opportunity for talent introduction and knowledge innovation. With the diversity of demand in the port industry, a variety of cleaner production equipment and pollution control technologies have been fully applied, effectively improving the port environment. As a result, the GTC index has been greater than the GEC index after 2017, and technological progress has since become the primary driver of the eco-efficiency improvements of the Yangtze River Delta port cluster.

3.3. Spatial Evolution of Eco-Efficiency

Figure 2 depicts the distribution of cold and hot spots of eco-efficiency in the Yangtze River Delta port cluster, which was visualized by ArcGIS 10.2. Hotspots are primarily located in the central-east of the Yangtze River Delta. Benefiting from the abundant waterways and advanced infrastructures, most cities there have already completed the pilot construction of green ports, showing a high-level agglomeration in the near and mid-term. Instead, cold spots are mainly the southeast coastal ports and central inland ports. Most of these ports are directly influenced by ports with high eco-efficiency, but with smaller logistics capacity and longer duration of transportation, they cannot obtain a competitive market share.

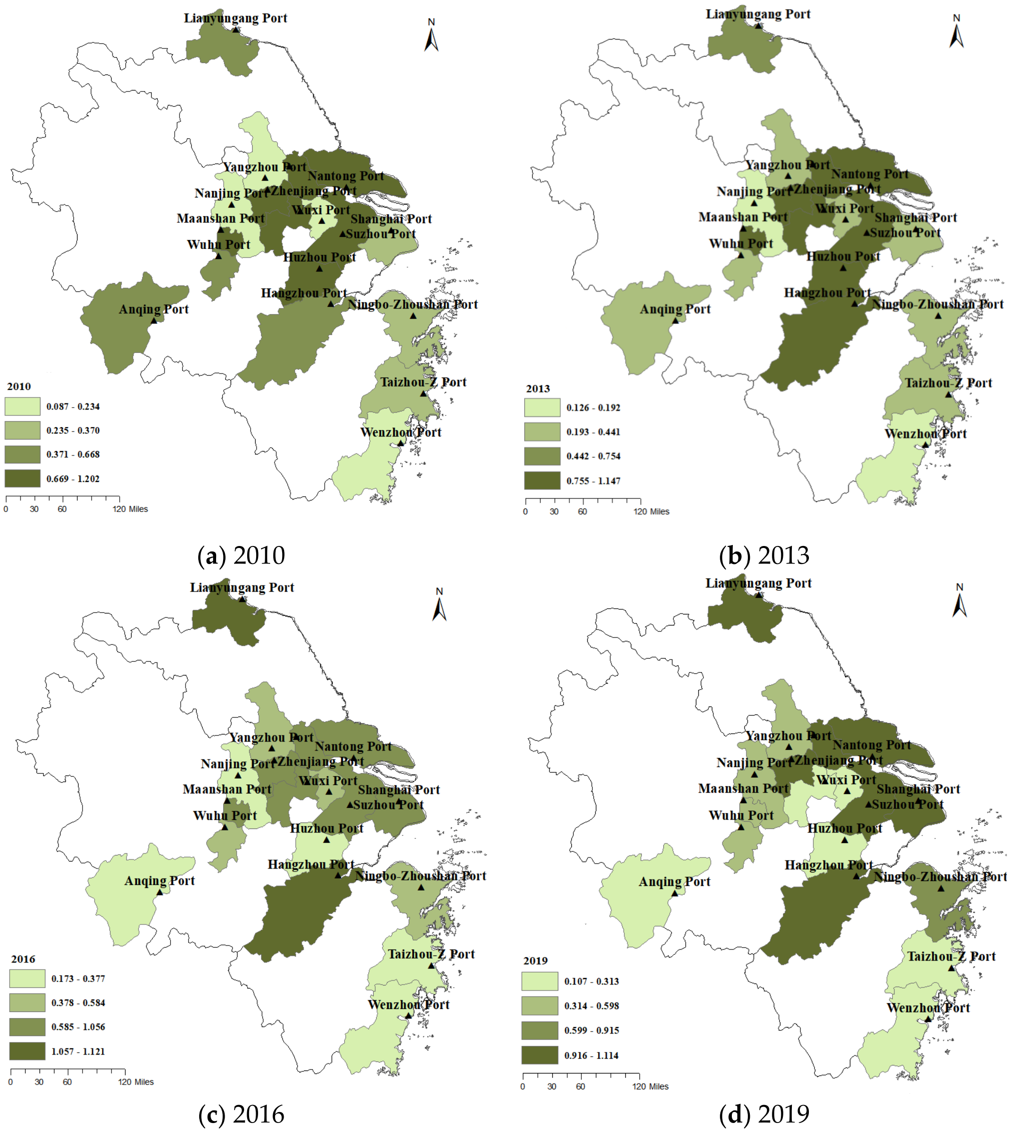

Figure 2. Spatial distribution of eco-efficiency in the Yangtze River Delta from 2010 to 2019.

In terms of the evolution trend of cold and hot spots, around 2010, the port eco-efficiency of Anhui was relatively high, but in 2013, Anqing and Wuhu ports took the lead in decreasing, and in 2019, Ma'anshan port was also transformed into low eco-efficient port, showing a general cooling trend. The distribution of port eco-efficiency in Jiangsu is stable, with only Lianyungang Port realizing the transformation from moderate eco-efficiency to high eco-efficiency in the past decade. In addition, the port eco-efficiency of Shanghai maintained a high level after the improvement from 2013 to 2016, and that of Zhejiang shows a fluctuating trend, with a higher proportion of ports with low eco-efficiency. In summary, the port cluster eco-efficiency has significant spatial transmission characteristics from 2010–2019, showing a changing trend of heating-cooling-reheating. The hot spots gradually spread to the southwest and northeast directions from 2010 to 2016, and then assembled to the mid-east as a whole after 2016, while the spatial range of the cold spots had a trend of contraction followed by expansion.

Figure 3 shows the migration path of the eco-efficiency gravity center from 2010 to 2019. As far as the position of gravity center is concerned, the ports of Jiangsu have always reached the peak of eco-efficiency, reflecting superior performance than other regions in the Yangtze River Delta. Additionally, it is logical to conclude that a certain coordination mechanism in port ecological development may have formed there [3,54].

During the research period, the gravity center shows a trend of moving to the northeast, and the eastward distance is longer than the northward distance, which indicates that the eastern ports have the most positive trend of ecological benefits. Especially in recent years, Changzhou port takes building into a logistics hub as the core task and seeks growth through various policy opportunities such as the free trade areas and the Belt and Road Initiative. As a result, the eco-efficiency gravity center entered Changzhou between 2013 and 2014, during which it experienced the longest movement throughout the research period, reflecting that the efforts of Changzhou port on environmental management have produced remarkable achievements. After 2015, the gravity center began to fluctuate around the boundary between southwest Wuxi and southeast Changzhou, and it gradually moved northeastward and finally fell into Changzhou again after 2018. It can be inferred that the waterway with Wuxi and Changzhou ports as the axis will become a critical zone for eco-efficiency expansion, so the resource integration and intensive planning of this area should be strengthened in the future. As can be seen from the trajectory of changes, the gravity center moves from slowly to strongly and then slowly again, and the strongest directional shift occurred from 2014 to 2017, generally showing an inverted N-shaped trajectory. It indicates that the uncertainty of port business has increased with the fragile recovery of the global economy and weakening demand for foreign trade [56], thus resulting in the unstable development of the port cluster eco-efficiency.

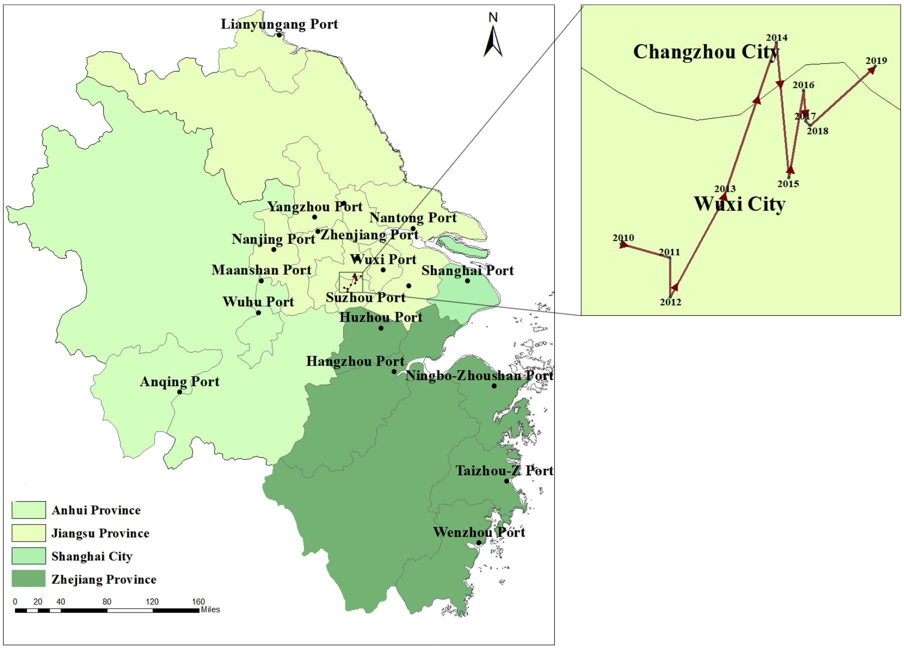

Figure 3. The migration path of gravity center of eco-efficiency.

According to the result of the Theil index shown in Table 5, the eco-efficiency gap in the Yangtze River Delta port cluster generally expands, with the Theil index increasing by 19.92% from 2010 to 2019. Although most ports have gradually recognized the negative effects of uncontrolled development, some still have not changed their traditional crude pattern of production, which ultimately aggravates the heterogeneity of ecological development in the Yangtze River Delta. The imbalance of ecological port construction became increasingly obvious after 2017. As the expansion of port business has produced a more extensive environmental impact, more and more ports fail to form the scale effect of resource utilization, gradually resulting in a polarization in ecological governance capacity [10]. The constitution of the overall gap is comparatively stable, and the gap within the region contributes to a large extent to the overall gap. Additionally, the point at which changes in the within-regional gap occurs and the specific trends in changes are highly consistent with the overall gap. As a consequence, whether the gap within the region can be narrowed is the key factor in supporting the ecologically coordinated development of the Yangtze River Delta port cluster.

Table 5. Theil index and the decomposition of the overall gap in eco-efficiency.

Time	Overall Gap	Gap between Regions		Gap within the Region		Proportion of Each Region		
		Value	Proportion	Value	Proportion	Jiangsu	Zhejiang	Anhui
2010	0.173	0.021	0.123	0.152	0.877	0.550	0.382	0.068
2011	0.143	0.022	0.151	0.121	0.849	0.326	0.569	0.105
2012	0.135	0.022	0.160	0.114	0.840	0.289	0.548	0.163
2013	0.168	0.015	0.088	0.153	0.912	0.282	0.442	0.276
2014	0.157	0.049	0.309	0.109	0.691	0.256	0.507	0.237
2015	0.148	0.034	0.230	0.114	0.770	0.344	0.473	0.184
2016	0.122	0.026	0.216	0.096	0.784	0.169	0.366	0.465
2017	0.112	0.024	0.213	0.088	0.787	0.177	0.386	0.438
2018	0.118	0.020	0.168	0.099	0.831	0.259	0.467	0.274
2019	0.204	0.033	0.160	0.172	0.840	0.271	0.570	0.159
Mean	0.173	0.021	0.123	0.152	0.877	0.292	0.471	0.237

Analyzing the source of the gap within the region, the contribution rate of Zhejiang is at the highest, with an average value of 47.11%, which shows that the layout of ports in Zhejiang is relatively scattered, and there is significant heterogeneity in the ecological development within it. Ningbo-Zhoushan port ranks among the world's top in terms of scale, with first-moving advantages of the waterway depth, shoreline resources, and terrestrial support. However, the rest of the ports in Zhejiang are distributed in multi-point [14], whose maritime industry is still in the initial stage, so it is challenging to upgrade the service function to meet the development demand of modern ports [57]. Jiangsu ranks second in the contribution to the gap within the region, but the rate has shrunk over time, indicating that the integration of Jiangsu into the shipping network of the Yangtze River Delta has promoted internal interaction. In addition, the contribution rate of Anhui is low, but it has got a nearly twofold increase during the research period, which is mainly due to the huge fall in the eco-efficiency of Anqing.

4. Discussion and Conclusions

4.1. Discussion

As the green renovation cycle of port infrastructure is lengthy and many environmental plans are relatively advanced in time, most ports in the Yangtze River Delta are still in the early stages of planning and piloting, and even the large-scale ports have failed to improve the port environment comprehensively in a short period, which is consistent with the findings of Shen et al. [58]. In order to enhance the overall eco-efficiency of the port cluster, local authorities should facilitate the cooperation between highly eco-efficient ports in technological innovation, multi-modal transportation, and intelligent dispatching, of which the central-eastern ports may become the new hotspots to attract more private capital and foreign investment and help drive the development of neighboring ports. As for the ports with relatively and low eco-efficiency, the first step is to reduce the input redundancy and accelerate the withdrawal of scattered wharves [59,60], which can minimize construction costs and promote the centralized utilization of advantageous resources.

In this paper, we provide insights into the characteristics and evolution of port eco-efficiency, in order to empower the green upgrading of the Yangtze River Delta port cluster. Nevertheless, there are several limitations to this study. First, due to the limitations in available data at the municipal level, we did not use labor, capital, and energy as input indicators. In addition, when evaluating the environmental cost of port operation, only NO_x, SO_2, and solid emissions were considered as undesirable outputs, and the data on other types of particulate matter and water pollution emitted by ports could be further collected. Second, the performance of port eco-efficiency is vulnerable to such factors as trade situation, industrial policy, and environmental regulation [56,61,62]. Given that the context for different DMUs is diverse and dynamic, it may be biased to compare them at the same production frontier. Some scholars have introduced these exogenous variables into the Dynamic-DEA model [63,64], so as to identify the influence of key external factors that may impact the heterogeneity and tendency of port eco-efficiency, and how to select the carry-over variable and quantify the influence through efficiency models may be important directions for future research.

4.2. Conclusions

This paper focuses on the eco-efficiency of the Yangtze River Delta port cluster, and the application of the Super-EBM model enhances the accuracy of evaluation. We also use the GML index to reveal the temporal trend from 2010–2019, and the spatial evolution is further monitored, including the distribution of hot and cold spots, migration of the eco-efficiency gravity center, and regional differences. The conclusions are as follows:

First, the eco-efficiency level of the Yangtze River Delta port cluster is moderate, with the value of PTE and SE being 1.077 and 0.686, respectively, indicating that the scale inefficiency restricts the ecological development of the port cluster. Suzhou and Zhenjiang ports maintain a score of more than 1, while the ecological performance of 55.6% of ports was lower than the average, and Anqing, Taizhou-Z, Nanjing and Wenzhou ports have poor eco-efficiency.

Second, the port cluster eco-efficiency shows an increasing trend, with the GEC and GTC indexes rising by 9% and 6.2%, respectively. Technical efficiency has exerted a greater influence by the large, while the GTC index surpassed the GEC index st 2017, and the growing effect of technological progress has since continued to drive the eco-efficiency improvement of the Yangtze River Delta port cluster.

Third, eco-efficient ports are mainly located in the central east, while the inefficient are southeast coast and central inland ports. Southern Jiangsu is the stable gravity center of the port cluster, and the area between Wuxi and Changzhou should become the focus of future ecological development. In addition, the imbalance within the port cluster became increasingly significant, with the contribution of the within-regional gap being up to 87%, which is most related to the disorderly layout of Zhejiang ports.

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