



Shifting from Production-Based to Consumption-Based Nexus Governance: Evidence from an Input–Output Analysis of the Local Water-Energy-Food Nexus

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Abstract

The nexus approach is a promising method used to address issues regarding environmental dilemmas. However, effective consumption-based and production-based nexus governance strategies are not well understood. Using data envelopment analysis and China's provincial data for 2017, this study analysed the input–output efficiency of the water-energy-food nexus by considering production-based intensity, consumption-based intensity, and the quantity index system. The results show that policies involving consumption-based intensity metrics can be more efficient, and the efficiency of both production-based intensity (0.482) and consumption-based intensity (0.682) are much higher than the efficiency of the quantity (0.378) index system. The results also indicate that province-specific consumption-based governance strategies are crucial for 30 provinces in China. Finally, three policy directions for nexus governance in China are proposed, namely, shifting policy attention from production-based governance to consumption-based governance, focusing intensity metrics on scale efficiency and aiming quantity metrics on pure technical efficiency, and localizing province-specific management strategies. This paper compares consumption-based and production-based nexus approaches, and the results indicate that a call for consumption-based approaches in future nexus modelling and governance is appropriate. This paper also has implications for China's nexus governance.

Keywords Input–output analysis · Water-energy-food nexus · Intensity and quantity index system · DEA model · Efficiency

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1 Introduction

Nexus governance is critical for incorporating the water-energy-food nexus (WEF nexus) concept into policy (Karnib 2018; Benson et al. 2015). This topic has attracted great attention in recent research on the WEF nexus (Wu et al. 2021; Yan et al. 2020; Arthur et al. 2019; Nie et al. 2019). Leveraging production side or consumption side nexus governance to secure WEF resources is still controversial, but the importance of using metrics in nexus governance has been acknowledged (Voelker et al. 2019). Developing effective index systems for different countries or regions to evaluate their nexus practices is key to promoting the WEF nexus shift. Different types of index systems have been developed in recent studies focused on nexus modelling (Dai et al. 2018), including production-based and consumption-based metrics, and numerous intensity and quantity indicators have been used (Karnib 2018). In China, an index system was utilized for China's green development in 2016; this system covered production, consumption and waste disposal processes and considered both intensity and quantity indicators. Therefore, using the developed metrics, this research compares the production-based and consumption-based nexus approaches used for China's WEF nexus in terms of provincial input–output efficiency. This study focuses on the following question: *is the production side or consumption side more effective for leveraging nexus governance?*

Improving governance across sectors was noted by Hoff (2011) to be one of the four pillars of a nexus approach to achieve WEF resource security, but nexus governance research is still in the early stage. In terms of theory, Namany et al. (2019) reviewed the decision-making tools used for WEF resource governance and indicated that decision-making methodologies are necessary for nexus governance. The nexus approach is considered to be the eighth concept by the integrated environmental governance (IEG) community (Visseren-Hamakers 2015). Weitz et al. (2017) connected the nexus approach to decision-making processes by considering insights obtained from the IEG community. The current nexus governance literature on practices mainly focuses on governance heuristics at the local scale (Müller et al. 2015) and aims to identify the most effective operationalization practices and prioritize them. Mohtar and Daher (2016) proposed a stakeholder platform that involves stakeholders in governance processes and integrates local knowledge by using a bottom-up approach. Two hypothetical frameworks were developed, analysed and tested in nexus governance practice (Märker et al. 2018): a holistic framework was used to establish a nexus department, and a silo-thinking framework was used to establish nexus integration processes. The German samples demonstrated that both frameworks can be used for nexus governance practice and are necessary for effective nexus governance. This result contradicts Müller et al. (2015), who claimed that a silo-based framework should be emphasized. Current theoretical and practical studies on nexus governance call for sectoral integration, which has been implemented since the late 1940s. For example, the Harvard Water Program in 1955 devised techniques on choosing the right combination of uses to achieve net benefits through maximization (Wichelns 2017; Martin 2003). Integration barriers exist widely in practice, and these barriers can be addressed by identifying governance problems (Pahl-Wostl 2019), but sectoral boundaries and leverage points defined by considering only the production side or consumption side need further exploration.

The importance of using leverage points for transformative change from a silo to a nexus has been widely acknowledged (Pahl-Wostl 2019; Albrecht et al. 2018), and leverage points have many place-specific policy implications. By focusing on the WEF nexus in the Lower Colorado River Basin (LCRB), Huckleberry and Potts (2019) identified the tipping

points of WEF resources in a production-based scenario and emphasized the formative role of the local governance structure that impacted nexus implementation. At the urban scale, Artioli et al. (2017) considered the political dimension of ‘urbanizing’ the nexus agenda and indicated that the current resource management system (governance structure and power relations) shaped the provision of urban water, energy and food. Covarrubias et al. (2019) analysed the structure, function and power dynamics of the WEF nexus network and conducted a case study using Amsterdam as the object; the study identified innovative ways to integrate the WEF resource network. With the aim of providing WEF in uncertain environments, a large portion of current policies are based on production modelling and focus on the production side (EL-Gafy et al. 2017; Leung Pah Hang et al. 2016). Hussien et al. (2017) explored the consumption interactions among WEF at the household level and developed scenarios based on the impacts of family size and climate change. Other studies that consider the consumption side focus on human behaviour and consumption patterns, which have a rebound impact on WEF provision (Wu et al. 2021; Pullinger et al. 2013). The consumption side has been largely ignored in the current nexus literature (Huang et al. 2020), and the difference in the policy implications that arise from focusing on production-based and consumption-based methods is still far from clear.

Transdisciplinary methods have been applied to evaluate the WEF nexus conundrum (Zhang et al. 2021, 2018; Zhang and Vesselinov 2017; Endo et al. 2015), but few of these methods have been applied to differentiate production-based policy implications from consumption-based policy implications. Data envelopment analysis (DEA) has been widely used for efficiency evaluations (Mardani et al. 2018). Li et al. (2016) first introduced and demonstrated the applicability of DEA in WEF nexus research. However, Li et al. (2016) failed to explore the abovementioned difference with DEA, which is the major contribution of this study. DEA is an appropriate method to achieve the goals of this research for the following two reasons. First, the WEF nexus conundrum is regarded as a black box in the DEA method by treating regional WEF holistically and ignoring the complex interconnections among WEF and instead focuses attention on exploring the differentiated policy implications. Second, DEA can be used to evaluate the input–output efficiency of the defined black box by using a changeable index system, which is the basis for the abovementioned exploration.

This paper seeks to address the gaps in current research. First, the methodology, DEA, the chosen BC² model, the index system and data sources are presented (Section 2). In our empirical analysis, China’s provincial data for 2017 is used to explore the differences in the policy implications of production-based and consumption-based methods. The results and discussion are presented in Section 3 followed by the conclusions (Section 4).

2 Method and Data

2.1 WEF Nexus in the DEA Method

DEA is a nonparametric estimation method that was proposed by Charnes and Cooper in 1978 (Wei 2004). By estimating the effective production frontier through linear programming, DEA evaluates the relative efficiency of decision-making units (DMUs) by considering input and output variables. A DMU is regarded as a black box in the DEA method.

Li et al. (2016) claimed that the WEF nexus in each province is a ‘black box’; WEF resources not only are consumed to create provincial socioeconomic output but also

involve the discharge of waste. This occurs because the Cobb–Douglas production function was employed to select the input and output indexes, and the structure of the WEF nexus was not well understood in 2016. Since then, transdisciplinary modelling techniques have bloomed in the WEF nexus literature, but no single nexus structure has been identified because of its place-specific nature. It has been widely acknowledged that some nexus structures include production, consumption, and waste disposal processes (Huang et al. 2020; Scanlon et al. 2017; Garcia and You 2016). Therefore, the WEF nexus in this study is defined as a type of synthesis that consists of production, consumption and waste disposal processes, and the input and output variables are selected with this definition in mind. The methodological framework is illustrated in Fig. 1.

WEF resources are critical inputs in urban areas and are consumed through human activities, which results in both discharged waste and urban development. This process is described as urban metabolism (Chen et al. 2020; Wolman 1965). The input side is measured by intensity and quantity metrics, which have been widely used in studies on the nexus and green economy (Karnib 2018). Production-based input metrics measure the amount of WEF resources that are produced, while consumption-based metrics measure the amount of WEF resources that are consumed. The black box refers to the interconnections that occur at the production, consumption and waste disposal stages of WEF. On the output side, desirable (socioeconomic development) and undesirable (ecosystem damage) outputs are included.

2.2 DEA Modelling Approach and the BC² Model

The modelling approach used in DEA first takes each evaluation object as a DMU and forms a group of DMUs to be evaluated. Then, a comprehensive analysis of the input and output ratio is conducted to determine the effective production frontier. Finally, based on the distance between each DMU and the effective production frontier, the efficiency of every DMU is defined. The advantage of using DEA to analyse the effectiveness of the WEF nexus conundrum has been described by Li et al. (2016). Although thousands of DEA models have been developed, this study employs the input-oriented BC² model, which has been widely used to evaluate environmental issues (Mardani et al. 2018; Zhang et al. 2017). This study also employs this model because of its variable returns-to-scale hypothesis and ability to decompose comprehensive efficiency into pure technical

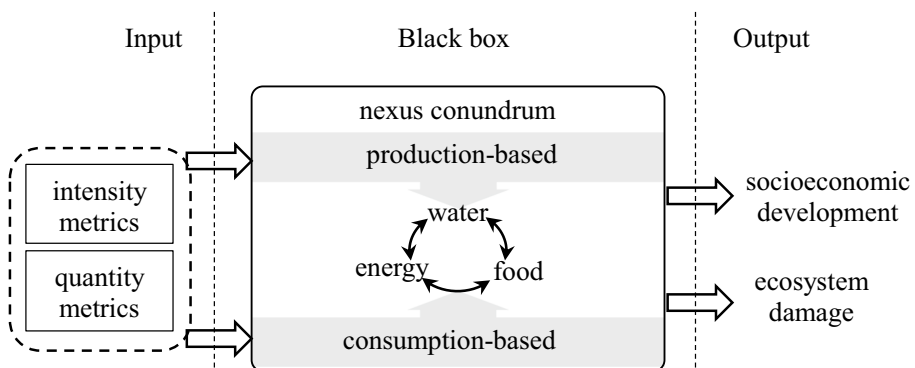


Fig. 1 Methodological framework of the DEA used to evaluate the WEF nexus

efficiency and scale efficiency. The input orientation assumes that decision makers try to reduce inputs under the condition of constant output.

The input BC² model is described as follows:

$$\min t_0 = \theta - \varepsilon \left(\sum_{i=1}^m s_i^- + \sum_{j=1}^n s_j^+ \right)$$

$$\left\{ \begin{array}{l} \sum_{r=1}^R \lambda_r X_{ir} + s_i^- = \theta X_{i0}, i = 1, 2, \dots, m \\ \sum_{r=1}^R \lambda_r Y_{jr} - s_j^+ = Y_{j0}, j = 1, 2, \dots, n \\ \sum_{r=1}^R \lambda_r = 1 \\ \lambda_r \geq 0, r = 1, 2, \dots, R \\ s_i^- \geq 0, s_j^+ \geq 0, i = 1, 2, \dots, m, j = 1, 2, \dots, n \end{array} \right. \quad (1)$$

where R is the number of DMUs; for the r th DMU, $x_{ir}(i = 1, 2, \dots, m)$ is the i th input indicator, $y_{jr}(j = 1, 2, \dots, n)$ is the j th output indicator, and s_i^- and s_j^+ are the input and output slack variables, respectively. λ is the weight coefficient.

Equation (1) achieves the optimal solution, and $\theta \leq 1$ when the following occur.

- (1) If $\theta = 1, s_i^- = s_j^+ = 0$, then DMU achieves strong DEA efficiency.
- (2) If $\theta = 1, s_i^- \neq 0$ or $s_j^+ \neq 0$, then DMU is weak DEA efficiency.
- (3) If $\theta < 1$ and $s_i^- \neq 0, s_j^+ \neq 0$, then DMU is DEA invalid, which means that the DMU does not reach a proper ratio.

A higher θ value indicates higher DEA efficiency. Scale efficiency is explained as follows.

- (1) If $\sum_{r=1}^R \lambda_r = 1$, then the scale efficiency of the DMU is constant.
- (2) If $\sum_{r=1}^R \lambda_r < 1$, then the scale efficiency of the DMU is incremental; that is, a certain increase in inputs could increase outputs. In this case, a smaller value indicates a larger incremental trend.
- (3) If $\sum_{r=1}^R \lambda_r > 1$, then the scale efficiency of the DMU declines, and a certain increase in inputs would reduce outputs. In this case, a larger value indicates a larger declining trend.

2.3 Input and Output Variables of the DEA

According to Huang et al. (2020), at the local scale, water and energy consumption always equals their production. Food consumption is not always equal to food production because food can be easily stored and transported. Based on the WEF consumption-production relationships and the methodology explained in Section 2.1, this paper calculates the input

metrics of the WEF nexus at the intensity level and quantity level. At the intensity level, WEF security aspects are critical factors in metric selection. This study adopts the WEF security aspects defined and operationalized by Pahl-Wostl (2019) and Su et al. (2020). Water and food security mean that every person has safe and affordable resources for daily life. The determination of energy security should take the economy, society and environment into account. Therefore, the per capita water consumption (X1), per GDP amount of energy consumption (X2), and per capita food consumption expenditure (X4) are selected as consumption-based intensity metrics. The production-based intensity metrics include X1, X2, and the per capita cultivated land area (X3) because the crop sown area largely determines the amount of food production (Huang et al. 2020). In terms of quantity, the input of WEF resources is the total amount consumed by the black box, that is, total water consumption (X5), total energy consumption (X6), and total food expenditure for food consumption (X7).

To achieve the goals of understanding the policy implications of production-based and consumption-based methods and reducing the impact of the output side, the output metrics in this study remain constant, including the socioeconomic and ecosystem dimensions. The socioeconomic dimension represents the urban development that results from WEF resource production and consumption, and the GDP per capita (Y1) is selected. The ecosystem dimension refers to the waste disposal process in which different wastes (e.g., wastewater, SO₂, and solid waste) are discharged, and the environmental pollution index (Y2) is employed. The input–output variables are presented in Table 1.

2.4 Data Sources

The primary data set in this study is constructed from data obtained from the *China Statistical Yearbook (2018)*, the *China Energy Statistical Yearbook (2018)*, the *China Rural Statistical Yearbook (2018)*, and the *Ministry of Water Resources (2017)*.

The environmental pollution index is calculated with data from the abovementioned data set using the entropy method and Eqs. (2) to (5). In this study, the environmental pollution index considers five wastes, that is, SO₂, smoke (dust), wastewater, nitrogen oxide, and industrial solids; thus, it is more comprehensive than the index proposed by Li et al. (2016).

$$y_{ij} = \frac{x_{ij}}{\sum_{i=1}^n x_{ij}} \quad (2)$$

$$f_i = -\frac{1}{\ln n} \sum_{i=1}^n y_{ij} \cdot \ln y_{ij} \quad (3)$$

$$w_j = \frac{1 - f_j}{\sum_{j=1}^m (1 - f_j)} \quad (4)$$

$$p_i = \frac{1}{\sum_{j=1}^m y_{ij} \cdot w_j} \quad (5)$$

Table 1 Input–output variables of the DEA method for the WEF nexus

Categories	Indicators	Specification	Units
Input intensity	Water	Production-based and consumption-based	Water consumption per capita
	Energy	Production-based and consumption-based	Energy consumption per GDP
	Food	Production-based	Cultivated land area per capita
Input quantity	Water	Consumption-based	Food consumption expenditure per capita
	Energy	Production-based and consumption-based	Total water consumption
	Food	Production-based and consumption-based	Total energy consumption
Output	Socioeconomic		GDP per capita
	Ecosystem		Environmental pollution
		X1 = Total water consumption/ Total number of residents	Cubic metre per capita
		X2 = Total energy consumption/ GDP	Tons of standard coal per Yuan
		X3 = Total amount of cultivated land/ Total number of residents	Hectare per capita
		X4 Total amount of food consumption expenditure/ Total number of residents	Yuan per capita
		X5 The amount of water consumed in a provincial district	Billion cubic metres
		X6 The amount of energy consumed in a provincial district	Ten thousand tons of standard coal
		X7 The amount of residential expenditure on food consumption in a province	Ten thousand Yuan
		Y1 =GDP/ Total number of residents	Yuan per capita
		Y2 =f(SO ₂ , smoke, wastewater, nitrogen oxide, and industrial solids)	-

where x is the index value, y is the standardized value of the x metric, f is the entropy, n ($=30$) is the number of provinces, w is the weight, and p is the environmental pollution index.

3 Results and Discussion

Using the prepared data set, the DEA efficiency of 30 Chinese provinces in 2017 is evaluated via Windeap 2.1 software. Since efficiency has been proven to provide theoretical guidance for energy governance (Han et al. 2020), DEA efficiency in this study involves comprehensive efficiency, pure technical efficiency and scale efficiency (Table 2). Thus, the results can provide theoretical guidance for China's nexus governance.

3.1 The Comprehensive Input–Output Efficiency of the WEF Nexus

Comprehensive efficiency (CE) varies by the index system, which is shown in Table 2. The input metrics of production-based intensity, consumption-based intensity, and quantity are (X1, X2, X3), (X1, X2, X4), and (X5, X6, X7), respectively, while their output metrics (Y1, Y2) are the same.

The 30 provinces' average CE indicates that the consumption-based intensity index system achieves the highest efficiency (0.682) when using a constant output index, followed by the production-based intensity index system (0.482) and quantity index system (0.378). The intensity index systems have a higher CE than the quantity index systems, which means that a policy that uses intensity metrics, especially consumption-based intensity, can largely promote CE. However, the provinces that achieve DEA efficiency ($=1$) vary by the index system. In terms of the quantity index, the CE of Beijing, Tianjin, Hainan, Ningxia, and Qinghai is equal to 1, which indicates DEA efficiency, but only Beijing and Hainan achieve DEA efficiency in terms of the intensity index system. This occurs because quantity is a much more extensive management indicator, and using this indicator, the results show more provinces with DEA efficiency. In China, resource management practices involve both intensity metrics (e.g., water resource carrying capacity) and quantity metrics (e.g., water entitlements), which have been emphasized in China's 2016 *Action Plan on Quantity and Intensity Control of Water Consumption* (Ministry of Water Resources, National Development and Reform Commission 2016).

In Table 2, the column for production-based intensity indicates that CE is lower in the provinces located in the northwest region than in the other provinces, except for Shaanxi Province. A smaller value indicates that the WEF production in these provinces (Ningxia, Gansu, Qinghai, and Xinjiang) is less efficient than in the other provinces because of their poor water and cultivated land area. For example, Ningxia is located in a semi-arid region with scarce water resources; in 2018, this area had 1.47 billion cubic metres less than Beijing (3.55 billion cubic metres) (Ministry of Water Resources 2019). The column for consumption-based intensity shows the highest CE; only Sichuan Province (0.436) has a value lower than 0.5. Although WEF consumption intensity in China is not the best in the world (Wang et al. 2019), it is currently under control, and policies regarding consumption intensity increase efficiency. Finally, the column for quantity includes 5 DEA efficiency provinces, but two-thirds of the provinces have low CE (<0.3), which indicates unbalanced

Table 2 Results regarding the comprehensive efficiency (CE), pure technical efficiency (PTE) and scale efficiency (SE) of the WEF nexus in China

Regions	Production-based intensity			Consumption-based intensity			Quantity		
	CE	PTE	SE	CE	PTE	SE	CE	PTE	SE
North region average	0.5344	0.7972	0.6398	0.8098	0.957	0.8444	0.5518	0.5772	0.9182
Beijing	1	1	1	1	1	1	1	1	1
Tianjin	0.915	1	0.915	0.915	1	0.915	1	1	1
Hebei	0.276	0.785	0.351	0.651	0.924	0.705	0.131	0.147	0.895
Inner Mongolia	0.198	0.326	0.61	0.735	0.861	0.854	0.339	0.393	0.861
Shanxi	0.283	0.875	0.323	0.748	1	0.748	0.289	0.346	0.835
East region average	0.6283	0.893	0.7107	0.701	0.89	0.8	0.279	0.2874	0.9696
Shanghai	0.935	1	0.935	0.724	0.732	0.989	0.61	0.627	0.972
Shandong	0.482	0.865	0.557	0.877	1	0.877	0.151	0.153	0.988
Jiangsu	0.666	0.735	0.906	0.914	0.953	0.959	0.211	0.225	0.937
Anhui	0.515	0.989	0.521	0.515	0.989	0.521	0.157	0.162	0.965
Zhejiang	0.62	0.804	0.771	0.688	0.764	0.9	0.252	0.253	0.994
Fujian	0.635	0.858	0.74	0.644	0.792	0.813	0.341	0.35	0.975
Jiangxi	0.545	1	0.545	0.545	1	0.545	0.231	0.242	0.956
Central region average	0.4943	0.9153	0.546	0.6353	0.9213	0.691	0.1673	0.1743	0.9573
Henan	0.469	1	0.469	0.716	1	0.716	0.136	0.15	0.906
Hubei	0.499	0.793	0.629	0.649	0.851	0.763	0.207	0.213	0.975
Hunan	0.515	0.953	0.54	0.541	0.913	0.593	0.159	0.16	0.991
Northeast region average	0.3437	0.671	0.5073	0.6083	0.85	0.7143	0.3057	0.3143	0.9687
Heilongjiang	0.306	0.589	0.52	0.543	0.835	0.65	0.241	0.244	0.984
Jilin	0.454	0.785	0.578	0.737	0.983	0.749	0.471	0.482	0.978
Liaoning	0.271	0.639	0.424	0.545	0.732	0.744	0.205	0.217	0.944
Southwest region average	0.4005	0.9093	0.4423	0.544	0.9423	0.5795	0.246	0.294	0.8198
Sichuan	0.427	0.935	0.457	0.436	0.923	0.473	0.11	0.142	0.773
Chongqing	0.509	0.878	0.58	0.623	0.878	0.709	0.405	0.453	0.895
Guizhou	0.312	0.835	0.374	0.579	0.968	0.598	0.269	0.323	0.833
Yunnan	0.354	0.989	0.358	0.538	1	0.538	0.2	0.257	0.778
South region average	0.7113	0.972	0.725	0.7407	0.963	0.769	0.4433	0.456	0.941
Guangxi	0.435	0.916	0.475	0.523	1	0.523	0.203	0.239	0.85
Guangdong	0.699	1	0.699	0.699	0.89	0.785	0.127	0.13	0.972
Hainan	1	1	1	1	1	1	1	1	1
Northwest region average	0.2294	0.5364	0.4382	0.6748	0.9578	0.7044	0.5768	0.6074	0.9248
Shaanxi	0.42	0.874	0.481	0.792	1	0.792	0.347	0.347	0.999
Ningxia	0.13	0.278	0.469	0.826	1	0.826	1	1	1
Gansu	0.27	0.789	0.342	0.511	1	0.511	0.265	0.413	0.641
Qinghai	0.183	0.446	0.411	0.618	0.92	0.672	1	1	1
Xinjiang	0.144	0.295	0.488	0.627	0.869	0.721	0.272	0.277	0.984
30 provinces' average	0.482	0.808	0.582	0.682	0.926	0.74	0.378	0.398	0.929

development because the WEF consumption quantity in China is extensive and results in low WEF consumption efficiency.

Although the WEF nexus is place-specific, provinces that share the same river and similar climate conditions are affected by high spatial interdependence (Conway et al. 2015). Therefore, the 30 provinces are divided into 7 regions in this research, which is a refinement compared with the division proposed by Zhang et al. (2017) that includes only 3 regions. The CE results of the 7 regions are presented in Fig. 2.

The average CE values for the 30 provinces are ranked as follows: consumption-based intensity; production-based intensity; and the quantity index system. Figure 2 shows that consumption-based intensity remains at the highest level across the 7 regions, but the quantity index system is higher than the production-based intensity in the northwest region. This occurs not only because of the semi-arid climate conditions with low water resource endowment but also because poor arable land is subject to environmental stress, such as drought, high salinity, and low temperatures (Lam et al. 2013). In China, approximately 40% of the highest value arable land is located on the east coast of China (Lam et al. 2013), that is, the northeast region, east region, and central region in this paper.

In Fig. 2, the CE of production-based intensity in the southern region (0.7113) is similar to its consumption-based intensity (0.7407), and both are higher than the quantity (0.4433). A higher CE based on the intensity metric in the southern region indicates effective production-based and consumption-based governance in this region. In the ‘northern’ region, including the north and northeast regions, effective governance is indicated only by consumption-based intensity. The CE of production-based intensity in the ‘northern’ regions is similar to the value obtained for quantity, and both are lower than consumption-based intensity. The difference between the southern region and the ‘northern’ region is largely due to the climate and soil quality, which results in better water and food production in the southern region. The humid southern region has better water resource endowment than the ‘northern’ region. The acidic soil in the southern region allows plants to better absorb micronutrients (e.g., iron and zinc) than the

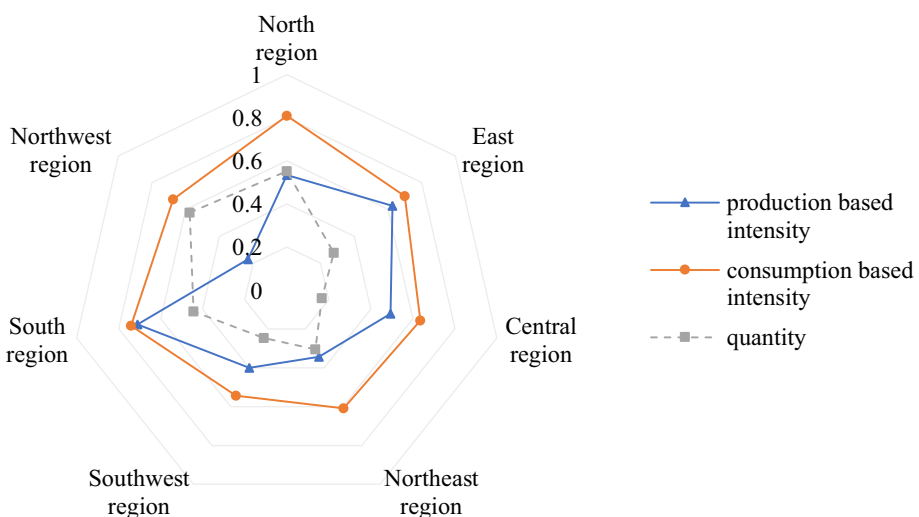


Fig. 2 Regional differences in comprehensive input–output efficiency

calcareous soil found in the ‘northern’ region and is thus key to improving agricultural productivity (Zou et al. 2008).

3.2 Pure Technical Efficiency (PTE) and Scale Efficiency (SE) Employed for DEA

The BC² model decomposes CE into PTE and SE, where $CE = PTE * SE$. The aim is to explore the different results and better understand how to improve CE (Wei 2004; Li et al. 2016). The PTE and SE of the WEF nexus are presented in Table 2.

In terms of the 30 provinces’ average, PTE is higher than SE in terms of intensity (production-based and consumption-based), but the result for the quantity dimension is the opposite, as SE (0.929) is much higher than PTE (0.398). This trend is also apparent for different regions, as shown in Fig. 3.

In terms of the intensity dimension, a higher PTE drives CE, which indicates that technical progress in WEF production and consumption intensity is clearly occurring across China. For example, urban water leakage can be detected and addressed, which will effectively reduce water loss, and water saving technology is widely applied to conserve agricultural water in China (Hu et al. 2021; Geng et al. 2019; Wang et al. 2019). In terms of PTE, many provinces achieve DEA efficiency (= 1), specifically, 5 more provinces (Tianjin, Shanghai, Jiangxi, Henan, and Guangdong) in terms of the production-based levels and 10 more provinces (Tianjin, Shanxi, Shandong, Jiangxi, Henan, Yunnan, Guangxi, Shaanxi, Gansu, and Ningxia) in terms of the consumption-based levels, which indicates that advanced techniques are employed in these provinces. A lower value for SE emphasizes future directions for CE improvement. For most provinces, except for Shanghai, Zhejiang, and Jiangsu Provinces, the focus should be on increasing the production and consumption scale (Li et al. 2016). For Shanghai and Zhejiang Provinces, SE (> 0.9) is higher than PTE (< 0.8) at the consumption level, which indicates the successful application of the land-use quota tool (Wang et al. 2010; Huang et al. 2020). Both provinces focus on consumption-based technical progress to improve productivity. This result contradicts the results presented by Li et al. (2016), who claimed that in Shanghai, the scale issue is key to improving CE. Shanghai is one of the metropolitan areas in China and is transferring some of its industries to Zhejiang and Jiangsu Provinces, which creates a shift of its WEF consumers. New types of WEF consumers have arisen in Shanghai; thus, consumption-based technical progress and effective management strategies are needed. In Jiangsu Province, SE (> 0.9) is higher than PTE (< 0.8) at the production level; therefore, production-based technical progress and local land-use quotas should be the focus of further promotion.

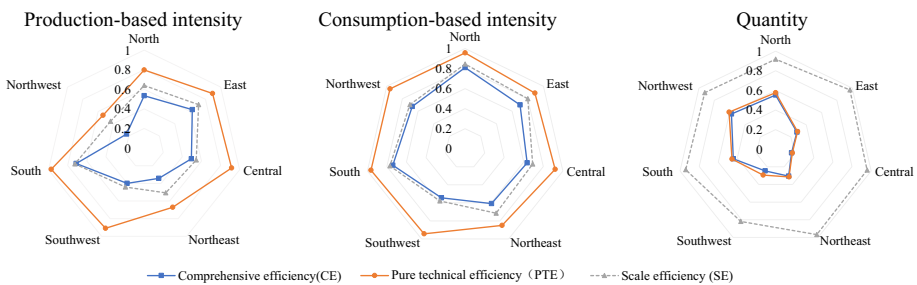


Fig. 3 Variations in PTE and SE in 7 regions with 3 metrics

In terms of the quantity dimension, the provinces that achieve DEA efficiency for both PTE and SE are the same as the provinces that achieve DEA efficiency for CE. The SE of each province is larger than the PTE, which indicates that the governance for WEF resource quantity management is effective. A lower PTE indicates that technical progress should be urgently promoted by introducing new techniques or implementing innovation-driven strategies (Li et al. 2016) to control the total amount of WEF consumption in the future.

3.3 Policy Directions for Nexus Governance in China

First, policy attention should shift from being production-based to consumption-based. A higher CE in terms of the consumption-based intensity metrics used in this research indicates that nexus governance regarding consumption could be more efficient. The consumption process bridges the production process and waste disposal process (Huang et al. 2020) and is thus located in the middle of the WEF resource flow, and it forms the core of the WEF nexus with numerous forward and backward linkages. Furthermore, the WEF resource intensity is much higher for consumption activities than for production and waste disposal activities, which indicates that consumption activities may be more effective for WEF resource conservation. In Beijing, for example, the energy intensity of domestic water consumption is 11.04 kWh/m^3 , which is much higher than the energy intensity of surface water extraction (0.2 kWh/m^3), groundwater extraction (0.49 kWh/m^3), public water supply (0.3 kWh/m^3), recycled water treatment (0.82 kWh/m^3), and wastewater treatment (0.32 kWh/m^3) (Shen et al. 2015; Liu et al. 2019). However, scattered and unpredictable human behaviours inhibit a shift to consumption-based policies and could be effectively evaluated by employing agent-based modelling techniques and game theory (Namany et al. 2019). Technologies and policies are necessary to bridge the gap between nexus-based thinking and actions in WEF consumption activities; thus, there is a call for more social science research (Dalla Fontana et al. 2020).

Second, in terms of improving CE, the intensity and quantity metrics are focused on different aspects. Table 2 indicates that the intensity metrics (production-based and consumption-based) should focus on SE, and the quantity metrics should give more attention to PTE. In the DEA method, SE is regarded as a gap that exists between the actual DMU scale and the optimal scale subject to the same technical conditions. This gap could be bridged by optimizing the industry structure and enlarging the scale of infrastructure operations (Li et al. 2016; Zhang et al. 2017). For example, both intraregional and interregional industry transfer always follow technology and managerial technique transfer, which could optimize the industry structure in developed provinces and promote PTE in developing provinces (Zhang et al. 2017).

Third, it is important to both localize management strategies in the shift to consumption-based nexus governance and think holistically. The four combinations of PTE and SE in terms of consumption-based intensity (Fig. 4) shed light on the focus of localizing the WEF management strategy in various provinces in China. Figure 4 indicates that improvement measures should be province-specific, even for provinces in the same group. For example, for provinces in the 'high-high' group where both PTE and SE achieve DEA efficiency, Beijing is the exemplary province and limits its urban scale based on its WEF resources. For the 'high-low' province groups, scale expansion should be the future investment direction because it is key to sustaining WEF resource consumption and should be implemented in all province groups. The 'low-high' province groups should focus on pure efficiency to improve the entire scale using advanced

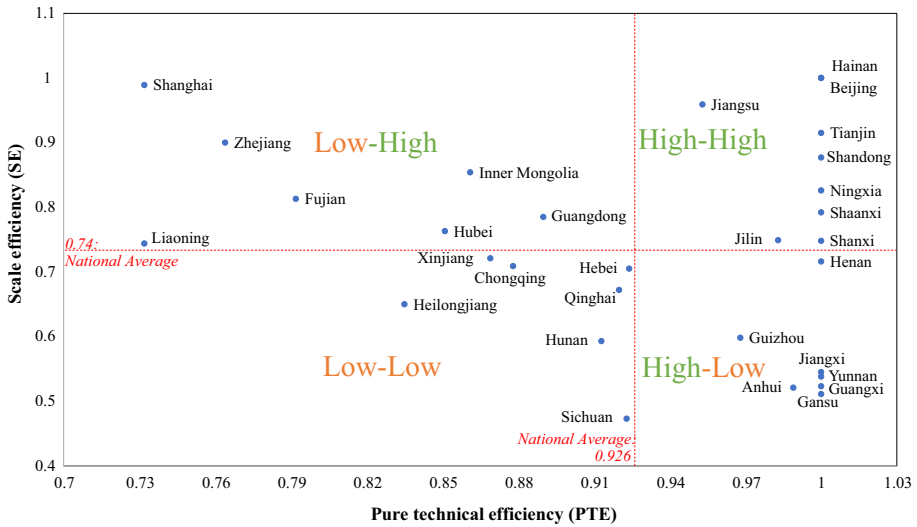


Fig. 4 PTE and SE based on the consumption-based intensity of 30 provinces in China

technologies and managerial techniques. For the ‘low-low’ province groups, although both PTE and SE are within policy mandates (Zhang et al. 2017), developing strategies should be more place-specific, that is, either PTE or SE should be the main focus. In this research, Hebei, Qinghai, Hunan, and Sichuan Provinces in the ‘low-low’ group should adopt a strategy that focuses on PTE first by following the route of “‘low-low’ → ‘high-low’ → ‘high-high’”. Xinjiang, Chongqing, and Heilongjiang Provinces should employ a strategy that focuses on SE, and “‘low-low’ → ‘low-high’ → ‘high-high’” is their development route.

4 Conclusion and Policy Implications

Leveraging production or consumption to achieve effective nexus governance is critical but has attracted less attention in recent nexus research. The results of this study indicate that consumption-based intensity metrics lead to the highest CE scores, and a call to shift policy attention from production-based to consumption-based strategies is appropriate. Although both intensity metrics and quantity metrics can be used to monitor China’s WEF resource consumption, the intensity metrics focus more on improving SE (e.g., industry structure optimization), while the quantity metrics should focus on improving PTE (e.g., advanced technologies and managerial techniques). According to the results of the consumption-based intensity metrics, province-specific improvement measures and development routes should consider the four components of PTE and SE. In the future, nexus research should unpack the WEF nexus conundrum by focusing on the consumption dimension and specify the leverage points in local WEF consumption activities. Agent-based modelling (ABM) techniques and game theory are promising directions to explore this nexus from a behaviour perspective.

Authors' Contributions D.H. designed and wrote the manuscript, Z.S. collected the data and conducted the calculation, C.S. drafted the methodology section, and G.L. participated in the manuscript design and drafted the discussion section. C.S. and G.L. participated in the revision, D.H. wrote the responses to editor and reviewers.

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Data Availability The data used in this study are statistical data. The China Statistical Yearbook (2018), the China Energy Statistical Yearbook (2018), the China Rural Statistical Yearbook (2018), and the Ministry of Water Resources (2017) are publicly published.

Code availability Win4deap 2.1 software, which is free software, was employed to conduct the DEA efficiency calculation. All figures in this paper were mapped with Microsoft office software.

Declarations

Ethical Approval Not applicable.

Consent to participate Not applicable.

Consent to publish Not applicable.

Conflict of interest The authors declare no conflict of interest.

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