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AGRIBUSINESS

Analysis of citrus production efficiency and inter-provincial variability in China under the constraints of non-point source pollution

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ABSTRACT: Globally, China is one of the primary citrus producers. This study provided a theoretical reference for sustainable production in the citrus industry in China by measuring citrus production efficiency under non-point source pollution and analyzing inter-provincial variability. In this study, non-radio logical and non-angled data envelopment analysis models were used in seven provinces during 2006–2018 based on non-desired outputs. The temporal and spatial characteristics were analyzed to determine the factors that cause efficiency losses. Results indicated that the citrus production efficiency had a general w-type trend with high inter-provincial variability, where the highest and lowest production efficiencies occurred in Hubei Province and Guangdong Province, respectively. In the past four years, a redundancy in labor and fertilizer inputs was also observed in Guangdong and Fujian, respectively. The shrinkable proportion of each factor input in the seven provinces was zero. An increase in citrus yield per hectare was recorded, in which the highest was in Guangdong. In each province, high emissions of total nitrogen and phosphorus generally caused the decrease in citrus production efficiency.
Key words: production efficiency, non-point pollution, inter-provincial variability, data envelopment analysis.

Análise da eficiência da produção de citros e da variabilidade interprovincial na China sob as restrições da poluição de fonte difusa

RESUMO: Globalmente, a China é um dos principais produtores de citros. Este estudo visa fornecer uma referência teórica para a produção sustentável na indústria cítrica na China, medindo a eficiência da produção cítrica sob poluição de fonte difusa e analisando a variabilidade interprovincial. Neste estudo, foram utilizados modelos de análise envoltória de dados não radiológicos e não angulares em sete províncias durante 2006–2018 com base em resultados não desejados. As características temporais e espaciais também foram analisadas para determinar os fatores que causam perdas de eficiência. Os resultados indicaram que a eficiência da produção de citros teve uma tendência geral do tipo w com elevada variabilidade interprovincial, em que as eficiências de produção mais altas e mais baixas ocorreram na província de Hubei e na província de Guangdong, respectivamente. Nos últimos quatro anos, também foi observada uma redundância nos fatores de trabalho e fertilizantes em Guangdong e Fujian, respectivamente. A proporção reduzida de cada fator de produção nas sete províncias foi zero. Foi registrado um aumento na produção de citros por hectare, sendo o mais elevado em Guangdong. Em cada província, as elevadas emissões de azoto e fósforo totais causaram geralmente a diminuição da eficiência da produção de citros.
Palavras-chave: eficiência produtiva, poluição difusa, variabilidade interprovincial, análise envoltória de dados.

INTRODUCTION

The main citrus production areas in China are located across seven provinces, namely: Guangdong, Fujian, Zhejiang, Jiangxi, Hunan, Hubei, and Chongqing (MOA, 2019; LIN et al., 2022; HUANG, 2022). Citrus is the most widely produced and operated agricultural cash crop and a major agricultural sector of the rural areas of southern China, in which it plays an important role in the development of the local rural economy (LI et al., 2018) Although, production and cultivated areas have been rapidly growing nationwide, an evident gap between yields achieved in China and those of other global citrus producers remains (FANG et al., 2019; ZHU, 2020). No significant improvements in the citrus production efficiency has been observed in the past years owing to the constant inter-annual and inter-regional fluctuations (CHEN et al., 2011; LIN et al., 2020). Moreover, the Chinese citrus industry cannot rely on the continuous expansion of production, such as increasing planting areas, usage of higher amounts of fertilizers, pesticides, and labor inputs, and other unsustainable practices, owing to the scarcity of natural agricultural resources and increasing pressure on the ecological environment. Alternatively, the industry should improve production, increase the income of citrus farmers, and eliminate resource and environmental constraints by increasing the total factor production efficiency (WU & QI, 2018; WU et al., 2022b; LEI et al., 2019; WANG & QI, 2018). The hilly and mountainous areas of south China, including

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the middle and upper reaches of the Yangtze River have been the main production areas, in which citrus production makes up majority of its total agricultural land. These areas are also key ecological and protected areas in the region. However, the non-point source pollution caused using fertilizers results in the emission of characteristic pollutants such as nitrogen and phosphorus, in which it is discharged through rainfall runoff and cause water eutrophication, especially in orchards located on sloping lands (KUANG et al., 2019). Therefore, estimating citrus production efficiency around areas with non-point source pollution can provide an important scientific basis for developing citrus production strategies while simultaneously ensuring ecological health of citrus orchards and surrounding areas.

Two main methods are used for measuring citrus production efficiency: parametric and non-parametric methods. The former is based on the stochastic frontier approach (SFA) (JOSEPH et al., 2021), whereas the latter is based on the data envelopment analysis (DEA) (QI et al., 2021; MAFUSE et al., 2021). Using the parametric method, CHEN et al. (2011) and WU (2018) constructed a transcendental logarithmic stochastic frontier approach to measure the technical efficiency of production and analyzed various factors using the cost-benefit panel data of citrus-producing provinces in Fujian, Guangdong, Hunan, Hubei, and Chongqing. The results indicated that the technical efficiency of citrus production gradually increased while having constant fluctuations. The rising cost of wages and pest control, including the frequency of natural disasters, were then considered by CHEN et al. (2011) as drivers of these fluctuations, in which WU (2018) suggested that chemical fertilizers and pesticides had a negative effect on technical efficiency. LAMBARRAA et al. (2011) and CARRER et al. (2015) used the SFA to measure the technical efficiency of citrus farms. Meanwhile, the non-parametric approach was used by KARINA & DANAE (2019), PICAZO-TADEO & REIG-MARTÍNEZ (2010), and HO et al. (2022) for measuring the technical efficiency of citrus using DEA. BELTRAN-ESTEVE & REIG-MARTINEZ (2014) observed that policy regulations and the level of technology directly influenced the efficiency of organic citrus orchard production. Meanwhile, ZHANG (2014) observed that the main factors affecting the technical efficiency of China's citrus industry were institutional reform, rising labor costs, and production structure adjustment. CLEMENTE et al. (2015) demonstrated that the variables that mostly contributed to the increased efficiency were "producer schooling" and "experience as rural producers." LI et al. (2010) measured the total factor productivity of citrus plants in China from 2003 to 2008, in which large differences in citrus production efficiency were observed between provinces, which is consistent with the study of XU & YANG (2018). LI et al. (2018), YU (2018), FANG et al. (2019), and WANG & TAN (2011) demonstrated that the technical efficiency of citrus had significant variations between provinces. Excessive inputs of substances such as pesticides also had the highest influence on the technical efficiency of citrus, which was more aligned with that of the results of TANG (2012), CHEN et al. (2011) and WU (2018). However, MADAU (2015) observed that the estimated citrus technical efficiency from the SFA model was essentially equivalent to that estimated using the DEA model.

According to existing literature, studies on citrus production efficiency do not often include the negative environmental impacts associated with the citrus production process, including the effects of major pollutants such as nitrogen and phosphorus as non-desired output indicators on the citrus production efficiency; these are crucial parameters as excessive fertilizer use is prolific in the major citrus producing regions in China (KUANG et al., 2019).

This study attempts to measure the production efficiency of Chinese citrus and its inter-provincial variability under the constraint of non-point source pollution using a non-angle and non-radial DEA model, in which the emissions of total nitrogen and phosphorus were considered as the non-expected outputs. Further, the inputs and outputs within the model were measured to explore the factors affecting the production efficiency and provide a theoretical reference for sustainable Citrus production in China.

This study was organized as follows: Section 2 describes the research methods and data sources, while Section 3 provides the data processing results and analysis. Lastly, Section 4 presents the conclusion of the study.

Research methods and data sources

The research methodology and data sources of this study are described below. Specifically, this includes the slacks-based measure (SBM)-DEA model, selection of input and output indicators, and study area and data sources.

SBM-DEA model

CHARNES et al. (1978) proposed a DEA method to evaluate the relative efficiency of the decision units. The DEA method does not predetermine the specific form of the production function, and the input and output data are not required as dimensional problems. However, the evaluation process of the method may also result in issues related to input or output factors known as "slack" or "crowding" issues. For instance, when the input or output factor contain non-zero slack, overestimation of the evaluation object of the production efficiency may occur. The "relaxation" or "crowding" issue can be consequently addressed using the non-angle, non-radial SBM-DEA model proposed by TONE (2001). This study considered the SBM-DEA model formulated by WANG (2019) and modified the model as follows:

$$Min\varphi = \frac{1-\left(\sum_{m=1}^{M}\left(S_m^x / X_{m0}\right)\right)/M}{1+\left(\sum_{s=1}^{S}\left(S_s^y / Y_{s0}\right)+\sum_{k=1}^{K}\left(S_k^b / Z_{k0}\right)\right)/\left(S+K\right)} \quad (1)$$

φ: The efficiency value of the decision-making unit (DMU).

X & M: Variables and number of each input for each DMU.

Y & S: Variables and number of each desired output.

Z & K: Variables and number of each undesired output.

The meaning of S_m^x, S_s^y, S_K^b are as follows:

$$X_{m0} = \sum_{i=1}^{M} X_{mi}\lambda_i + S_m^x, m = 1,2,\ldots, \quad M, \lambda_i \geq 0, i = 1,\ldots, N, S_m^x \geq 0; \quad (2)$$

S_m^x : Input redundancy.

$$Y_{S0} = \sum_{i=1}^{S} Y_{si}\lambda_i - S_s^y, s = 1,2,\ldots, \quad S, \lambda_i \geq 0, i = 1,\ldots, N, S_s^y \geq 0; \quad (3)$$

S_s^y : Desired output deficiency.

$$Z_{k0} = \sum_{i=1}^{K} Z_{ki}\lambda_i + S_K^b, k = 1,2,\ldots, K, S_K^b \geq 0; \quad (4)$$

S_K^b: Undesired output redundancy.

Combining the above four formulas, S_m^x, S_s^y, S_K^b represent the amount of "slack adjustment" that occurs in the production process. φ is the objective function is strictly $0 \leq \varphi \leq 1$. The molecule of φ is the shrinkable proportion of the actual input of the DMU in the production process to its production frontier. The denominator of φ is the expandable proportion of the actual output of the DMU in the production process to its production frontier. If φ = 1, that is, $S_m^x = 0, S_s^y = 0, S_K^b = 0$, the decision-making unit is efficient. If φ < 1, that is, at least one of the three slack adjustments S_m^x, S_x^y, S_K^b is not equal to zero, the decision unit is invalid, and improving the output of the DMU is required.

Input-output indicator selection

The SBM model has been widely used in the study of agricultural non-point source pollution, production efficiency, and ecological efficiency (CHEN et al., 2021; WU et al., 2022a; CHEN, 2023; WANG et al., 2019). Based on the methods of JI & LEE (2010), YANG et al. (2023), and WANG & WANG (2020), this study divided the source of losses in citrus production efficiency based on three redundancies: the input, undesired, and desired redundancies.

$$IE_{\text{x}} = \left(\sum_{m=1}^{M}\left(S_{\text{m}}^x / X_{m0}\right)\right) / M \quad (5)$$

IE_X: Input redundancy ratio.

Input redundancy refers to the input shrinkable proportion per hectare of citrus orchards, in which the capital, labor, and fertilizer are the input variables. Model interpretation is the same as Equation (1).

$$IE_{\text{z}} = \left(\sum_{k=1}^{K}\left(S_{\text{k}}^b / Z_{k0}\right)\right) / \left(S+K\right) \quad (6)$$

IE_Z: Unexpected output redundancy ratio.

The undesired output redundancy refers to the undesired output shrinkable proportion per hectare of citrus orchards, in which total nitrogen emissions and total phosphorus emissions are the undesired output variables. Model interpretation is the same as Equation (1).

$$IE_{\text{y}} = \left(\sum_{s=1}^{S}\left(S_{\text{s}}^y / Y_{s0}\right)\right) / \left(S+K\right) \quad (7)$$

IE_y: Insufficient expected output.

The desired output deficiency refers to the expandable output proportion per hectare of citrus orchards, in which citrus yield per hectare is the desired output variable (Table 1). Model interpretation is the same as Equation (1).

Total nitrogen and phosphorus emissions were closely related to the production and management practices of citrus orchards and intensity of regional rainfall in the region. Therefore, this study used the discharge coefficient method to analyze the runoff and leaching emissions of total nitrogen and phosphorus from citrus orchards, which were measured as follows:

$$E = E_0 + F \times C, \quad (8)$$

where E denotes the runoff or leaching emissions of the total nitrogen and total phosphorus in kg/ha; E_0 is the emission of total nitrogen and total

Table 1 - Citrus input–output indicators.

	---------------------------------------Specific indicators---------------------------------------
Input factors	Fertilizer usage per ha
	Capital input per ha = repair and maintenance + tooling and materials + Depreciation of fixed assets + machinery operating costs;
	Labor days per ha
Desired outputs	Citrus yield per ha
Non-desired outputs	Total nitrogen emission and total phosphorus emission

phosphorus without fertilizer application (kg/ha); *F* is the amount of total nitrogen and total phosphorus applied to the citrus orchard (kg/ha); and *C* is the runoff emission rate or leaching emission rate of total nitrogen and total phosphorus, respectively.

Study areas and data sources

Based on the characteristics of the regional distribution of citrus production in China, the study area was selected from seven provinces, namely: Guangdong, Zhejiang, Fujian, Jiangxi, Hubei, Hunan, and Chongqing, which account for majority of citrus production areas in the country. The study period was set to 2006—2018. The raw data for input-output indicators were collected from the *Compilation of National Agricultural Product Cost and Income Data* (NDRC, 2019). All capital inputs were converted to constant 2018 prices based on price indices from *the China Statistical Yearbook* (NBS, 2019), which were applied throughout the set time period of this study. E_0 and *C* in Equation 2 were obtained from *The First National Pollution Source Census - Manual on Fertilizer Emissions Coefficients for Agricultural Pollution Sources* (The State Council of the PRC, 2009). Owing to insufficient data from the *Compilation of National Agricultural Product Cost and Income Data* on the individual provinces of selected years (NDRC, 2019), the individual data below were also considered to be missing.

RESULTS AND ANALYSIS

The results of this study were analyzed based on the inter-provincial variability in citrus production efficiency and factors affecting the loss of citrus production efficiency, in which the latter was analyzed based on input and output.

Inter-provincial variability in citrus production efficiency

The dynamics of citrus production efficiency from 2006 to 2018 in the study areas are shown in table 2. Inter-provincial variability exhibited a W-shaped trend in citrus production efficiency, in which it showed fluctuating trends. It was increasing

Table 2 - Dynamic change of citrus production efficiency in China from 2006 to 2018

	Zhejiang	Fujian	Jiangxi	Hubei	Hunan	Guangdong	Chongqing	mean	standard deviation
2006	0.58	0.55	--	0.8	0.5	0.59	--	0.60	0.12
2007	0.6	0.51	--	1	0.7	0.38	0.56	0.63	0.21
2008	0.82	0.58	--	1	1	1	0.43	0.81	0.25
2009	0.65	0.62	0.54	0.76	1	0.49	0.53	0.66	0.18
2010	--	0.56	0.49	0.64	0.68	0.5	0.5	0.56	0.08
2011	--	0.58	0.55	0.8	0.5	0.59	0.63	0.61	0.10
2012	0.57	0.58	0.53	0.63	0.7	0.5	0.5	0.57	0.07
2013	0.57	0.59	0.57	1	0.65	0.44	0.51	0.62	0.18
2014	0.6	0.56	0.51	0.75	0.6	0.5	1	0.65	0.18
2015	0.68	0.55	0.58	0.57	0.55	0.5	0.56	0.57	0.05
2016	0.52	0.56	0.49	0.55	0.61	0.42	0.58	0.53	0.06
2017	0.79	0.68	1	0.41	0.77	0.51	1	0.74	0.23
2018	1	0.7	1	0.48	1	0.57	0.88	0.80	0.22

in 2006– 2008, decreasing in 2008–2012, increasing in 2013–2014, and reaching its the lowest yield in 2015–2016 followed by h a rapid and sudden increase in 2017–2018. This result differed from that of XU & YANG (2018) and FANG et al. (2019), in which it may be attributed to the different observation periods and the exclusion of undesired outputs.

Meanwhile, production efficiency varied greatly according to each province. Between 2006 and 2018, the standard deviation of citrus production efficiency was above 0.2 for four years, between 0.1 and 0.2 for five years, and below 0.1 for four years. It could be seen that the inter-provincial fluctuations were large. This was consistent with the findings of LI et al. (2018) and LI et al. (2010), in which the fluctuation of citrus production efficiency in Hubei Province was the largest, dropping precipitously from 1 to 0.48 from 2013 to 2018. In Fujian Province, the fluctuation of citrus production efficiency was the smallest, ranging from 0.5–0.7 over an extended period.

Causes of loss of citrus production efficiency

To prevent potential errors from incidental factors in a particular year and the varying production methods with the relative price of various economic factors, including the regular fluctuations of citrus yield per year (ZHAO et al., 2011), the citrus production efficiency in the past four years (2015–2018) was calculated to analyze the causes of its loss and determine potential improvements in the methods applied in the future.

Inputs

Labor input and redundancy

A little redundancy exists in labor inputs in the Chinese orange industry, with redundancies mainly arising from redundancies in domestic or hired labor. As shown in table 3, in the period between 2015 and 2018, the highest redundancy was recorded in Guangdong Province, indicating an inefficient labor input. Meanwhile, there were no redundancies recorded in the other six provinces, indicating that labor input was efficient. However, the results obtained were different from that of WANG & TANG (2011), and this may be attributed to the different observation periods, with WANG & TANG (2011) selecting data in 2009. Despite being one of the most developed provinces in China, Guangdong Province was observed to have labor input inefficiencies, in which it has been a major factor in the reduction of their margins. Based on the *Compilation of National Agricultural Product Cost and Income Data* (NDRC, 2019), the cost of labor per ha in 2018 was 49, 527.75 Yuan. Of which, the cost of hired labor per ha was 40, 739.10 Yuan. Hired labor was prominent in Guangdong Province, hence, it was more sensitive to labor expenditures than other provinces that implements family labor as the primary employer. The inefficiency in Guangdong Province may be attributed to its more intensive citrus cultivation than other citrus-producing provinces (CHEN et al., 2011), and the outbreak of the serious citrus yellow dragon disease epidemic area in China in recent years, that also affected Guangdong Province. In turn, this required more labor inputs to further prevent and control the disease (QIU, 2016; HUANG et al., 2020).

Capital input and redundancy

The capital input in the Chinese citrus industry was largely efficient. As shown in table 4, from 2015–2018, capital inputs have the highest redundancy in the citrus industry in Hubei Province. In 2016, the highest redundancy was observed only in Jiangxi Province. In general, the capital input in citrus production in China is relatively appropriate to the current level. Capital investment mainly includes repair and maintenance costs, tool and material costs, depreciation of fixed assets, and machinery operation costs. However, the level of capital input redundancy in Hubei Province was higher than in other provinces, owing to the capital investment from fixed asset depreciation based on the *Compilation of National Agricultural Product Cost and Income Data* (NDRC, 2019). For instance, its share in 2018 was 98.84%, which is significantly higher than that of other provinces, with the respective multipliers for

Table 3 - Labor shrinkable proportion for citrus in China from 2015 to 2018 (%).

	Zhejiang	Fujian	Jiangxi	Hubei	Hunan	Guangdong	Chongqing
2015	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2016	0.00	0.00	0.00	0.00	0.00	71.34	0.00
2017	0.00	0.00	0.00	0.00	0.00	67.43	0.00
2018	0.00	0.00	0.00	0.00	0.00	64.30	0.00

Table 4 - Capital shrinkable proportion for citrus in China from 2015 to 2018 (%).

	Zhejiang	Fujian	Jiangxi	Hubei	Hunan	Guangdong	Chongqing
2015	0.00	0.00	0.00	31.90	0.00	0.00	0.00
2016	0.00	0.00	7.43	19.22	0.00	71.34	0.00
2017	0.00	0.00	0.00	95.11	0.00	67.43	0.00
2018	0.00	0.00	0.00	93.29	0.00	64.30	0.00

Zhejiang, Fujian, Jiangxi, Hunan, Guangdong, and Chongqing being 11.15, 3.46, 1.16, 25.25, 6.77, and 6.27. This may be attributed to high investments on infrastructures such as orchards renovations, roads, and drainage and irrigation by the local citrus growers, in which it caused a large amount of redundancy in capital inputs, and in turn, high efficiency losses.

Fertilizer inputs and redundancy

There is less redundancy in fertilizer input in the Chinese citrus industry. As shown in table 5, the largest value of fertilizer input redundancy occurred in Fujian Province from 2015–2018. Meanwhile, there was only one year where fertilizer input redundancy occurred in Jiangxi Province and Hubei Province, while no fertilizer input redundancy occurred in Zhejiang, Hunan, and Guangdong Provinces. This trend may be attributed to the higher fertilizer-input intensity of citrus growers in Fujian Province than those in other provinces, in which the average fertilizer input per hectare was 1003.95 kg, which was the highest among all the provinces (NDRC, 2019). Meanwhile, Hubei had the lowest fertilizer input intensity with an average fertilizer input per hectare of 438.48 kg, which was slightly less than half of that of Fujian Province. A correlation between fertilizer input intensity and fertilizer shrinkable proportion was observed; however, the suitability of fertilizer input quantity is also related to the variety of citrus and quantity of other input factors, and when the inputs of the other factors were constant, the marginal increase effect of fertilizer input diminished, leading to a redundancy.

Outputs

Desirable output and output shortfall ratios

The citrus industry in China suffers from a shortage in yield per ha. The maximum value of the expandable proportion of yields occurred in 2015 in Guangdong Province, and the expandable proportion of yields was greater than zero in all four years in Guangdong Province (Table 6), in which this occurred over three years in Hubei Province and over two years in each of the other provinces. According to the four-year average value of the expandable proportion of yields, the citrus industry had the largest expandable proportion/production area at 104.94% in Guangdong Province, and the lowest in Jiangxi with approximately 14.67%. The citrus industry in the seven major producing provinces suffers from a yield shortage, resulting in efficiency losses, which may be attributed to the rainy weather in the south, including the occurrence of pests and diseases, mainly Huang Long disease (CHEN et al., 2011; WANG & TANG, 2011). Hence, there is yield increases have a higher potential.

Non-desired output and output redundancy

The redundancy of total nitrogen and total phosphorus in the study areas was observed to rapidly decline. As shown in table 7, the shrinkable proportions of total nitrogen and phosphorus emissions were high in all the seven study areas from 2015 to 2016. However, it and had over 50% declines from 2017 to 2018. The shrinkable proportion also existed in all provinces from 2015 to 2016, and no redundancy occurred in Jiangxi and Chongqing in 2017, including three provinces in 2018. This may be attributed to the active promotion

Table 5 - Chemical fertilizer input shrinkable proportion for citrus in China from 2015 to 2018 (%).

	Zhejiang	Fujian	Jiangxi	Hubei	Hunan	Guangdong	Chongqing
2015	0.00	24.08	0.00	0.00	0.00	0.00	0.00
2016	0.00	20.92	28.71	0.00	0.00	0.00	0.00
2017	0.00	20.18	0.00	17.19	0.00	0.00	0.00
2018	0.00	24.51	0.00	0.00	0.00	0.00	0.00

Table 6 - Citrus yields expandable proportion in China from 2015 to 2018 (%).

	Zhejiang	Fujian	Jiangxi	Hubei	Hunan	Guangdong	Chongqing
2015	0.00	0.00	17.97	0.00	54.98	239.35	76.36
2016	146.29	0.00	40.70	13.54	0.00	44.26	13.80
2017	0.16	44.27	0.00	43.39	14.09	99.19	0.00
2018	0.00	16.53	0.00	19.22	0.00	36.96	0.00

of structural reforms on the supply side of agriculture by the Chinese government since 2017. Here, the supply of green and high-quality agricultural products for horticultural crops such as apples, citrus, facility vegetables, and branded tea were preferred, in which pilot projects were conducted to replace chemical fertilizers with organic fertilizers and promote zero-growth actions for chemical fertilizers and pesticides. Despite this, total nitrogen and phosphorus redundancy still occurred, which can be one of the factors for the loss of citrus production efficiency in these provinces.

CONCLUSION

In this study, a non-radio logical and non-angled DEA model based on non-desired outputs was used to measure the production efficiency of citrus under non-point source pollution constraints in seven provinces in China between 2006 and 2018. The temporal and spatial characteristics, including the factors affecting efficiency loss, were also analyzed to provide a scientific basis for sustainable citrus production in China. The main conclusions are as follows:

First, the citrus production efficiency of the seven main production areas exhibited a W-shaped trend, in which significant observable differences existed among the provinces. Here, the highest and lowest production efficiencies were observed in Hubei Province and Guangdong Province, respectively. At the individual province level, Fujian was observed to have a stable medium citrus production efficiency in the long-term, whereas Zhejiang and Jiangxi exhibited an upward efficiency trend. Hubei Province and Guangdong Province had low production efficiencies, whereas Hunan Province upturned its efficiency from 2015 onwards. Despite the significant production-efficiency changes in Chongqing City over the past five years, a high production efficiency was still maintained.

Second, the Chinese citrus industry had redundancies in input factors while having yield shortage per hectare. For citrus inputs, redundancies in labor, capital, and fertilizer inputs were observed in Guangdong Province, Hubei Province, and Fujian Province, respectively. Here, the diminishing proportion of each input in other provinces was zero. Meanwhile, for citrus outputs, the citrus industry in China suffers from a shortage of yield per hectare. However, a certain potential for yield increase existed in all provinces, in which the highest potential was observed in Guangdong Province. The redundancy of total nitrogen and phosphorus in the non-desired output also rapidly declined, which may be primarily

Table 7 - Total nitrogen and total phosphorus emission shrinkable proportion for citrus in China in 2015–2018 (%).

	------------2015-------------		-------------2016------------		-------------2017------------		-------------2018-------------	
	total nitrogen	total phosphorus	total nitrogen	total phosphorus	total nitrogen	total phosphorus	total nitrogen	total phosphorus
Zhejiang	65.99	77.64	63.73	70.24	41.23	36.18	0.00	0.00
Fujian	99.92	99.92	99.92	99.92	21.13	45.10	28.48	46.14
Jiangxi	99.81	99.80	99.90	99.89	0.00	0.00	0.00	0.00
Hubei	83.83	86.02	99.91	99.89	50.91	58.62	54.96	56.52
Hunan	94.87	96.51	96.45	97.81	27.29	49.22	0.00	0.00
Guangdong	0.45	60.20	99.90	99.94	6.59	51.67	24.88	55.02
Chongqing	76.76	84.57	99.90	99.90	0.00	0.00	15.13	26.74

attributed to the high intensity of total nitrogen and total phosphorus emissions. Specifically, Hubei had the highest redundancy, whereas Jiangxi had the lowest. Relative to 2015–2016, the total nitrogen and total phosphorus emissions from seven provinces in 2017–2018 reduced by more than 50%.

In this study, the use of emissions of citrus production characteristic pollutants, such as total nitrogen and phosphorus, as non-desired output indicators can directly reflect their negative impact on production efficiency based on the non-radial and non-angle DEA model. Hence, this study recommends the following:

Expanding the research perspective on the measurement of citrus production efficiency by extending research area to prefecture, city, and county levels.

Including carbon emissions as non-desired outputs in the research area to further enrich the measurement of citrus production efficiency.

Analyzing production efficiency at a smaller micro-level, such as citrus producers or small farmers.

AUTHORS' CONTRIBUTIONS

Conceptualization, LIN Chun-tao; Data curation, WANG Ming-xin; Formal analysis, WANG Ming-xin; Methodology, SU Bao-cai; Writing—original draft, Writing—review & editing, LIN Chun-tao and SU Bao-cai. All authors have read and agreed to the published version of the manuscript. All authors contributed equally for the conception and writing of the manuscript. All authors critically revised the manuscript and approved of the final version.

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DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest.

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