The total factor productivity index of freshwater aquaculture in China: based on regional heterogeneity

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Abstract

Continuously improving freshwater aquaculture efficiency will help promote the sustainable development of freshwater aquaculture, which is crucial to ensure fish food supply. In particular, finding ways to improve the freshwater aquaculture efficiency, by measuring and analyzing the total factor productivity (TFP) of freshwater aquaculture, is of great significance to the sustainable development of freshwater aquaculture industry. Therefore, this paper constructs a meta-frontier Malmquist index (MMI) model by considering the regional heterogeneity to evaluate the TFP of freshwater aquaculture of China from 2004 to 2019. The results show that: (1) From 2004 to 2019, the TFP of freshwater aquaculture shows dynamic fluctuations and spatial differences. Compared with coastal regions, there are obvious advantages in TFP of freshwater aquaculture in inland regions. (2) The change of TFP in freshwater aquaculture is driven by the combined effect of technology change (TC) and technical efficiency change (EC). (3) The technology gap in freshwater aquaculture of coastal regions is tiny, while that of inland regions is large. This paper finally gives some policy suggestions to improve the TFP to ensure the sustainable development of freshwater aquaculture.

Keywords: Freshwater aquaculture; Meta-frontier Malmquist index; Total factor productivity; Sustainable development; Coastal region; Inland region

1. Introduction

As an important food for human daily consumption, fish provides people with indispensable amino acids and protein (Merino et al., 2012). China is the main producer of farmed edible fish and has produced more of such edible fish than other countries combined every year since 1991 (FAO, 2018). Edible fish plays an increasingly important role in China's food supply (Troell et al., 2014). To ensure the demand of residents for fish food, it is significant to continuously improve the efficiency of fishery culture (Muir, 2005). As the main production mode of fishery aquaculture, freshwater aquaculture efficiency measurement is of great significance to improve the efficiency of aquaculture and ensuring the aquatic biomass. Hence, this paper will measure and analyze the total factor productivity of freshwater aquaculture in China, and get the sustainable development strategy of freshwater aquaculture through the analysis of the efficiency.

There are significant differences in the development of freshwater aquaculture in different regions. For example, there are obvious differences between coastal regions and inland regions in training intensity, technology level, technology promotion and management level of freshwater aquaculture (Ji and Wang, 2015). All of these may affect freshwater aquaculture efficiency. The level of human capital, fishery infrastructure, resource endowment and aquaculture scale will also affect the efficiency of freshwater aquaculture. In addition, coastal regions attach great importance to marine fisheries. In the later stage, with the gradual implementation of the policy of "expanding freshwater and offshore aquaculture", coastal regions gradually paid attention to

freshwater aquaculture and made great achievements. It is worth noting that there is no research to manifest whether the coastal areas attach importance to mariculture will influence freshwater aquaculture efficiency. Therefore, considering the regional heterogeneity, this paper uses directional distance function (DDF) and MMI model to analyze the total factor productivity of freshwater aquaculture in China from 2014 to 2019. Obviously, it will provide a powerful reference for the sustainable and coordinated development of freshwater aquaculture biomass to China.

The remainder of this study is as follows: The next section introduces the related literature. Section 3 describes the designed methodology applied in the study, the input-output variables and data sources. The presentation of empirical analysis is elaborated in Section 4. The main conclusions and policy suggestions are provided in Section 5. And there are many abbreviations are showed in Table 1.

2. Literature reviewed

TFP refers to the part of output that is not explained by input. It is a representative index to measure production efficiency (Lin and Ge, 2019). Squire (1992) first applied TFP to fishery, which made fishery research method and system more scientific and provided strong support for many scholars in fishery research. By combing the existing literature, it can be find that the common methods of measuring TFP are stochastic frontier analysis (SFA) and data envelopment analysis (DEA).

First, SFA was introduced by Aigner et al. (1977) and Meeusen and Van den Broeck (1977), which uses the metrology method to measure the growth structure. It is necessary to preset the production function, separate statistical errors and technical

inefficiencies during the measurement process (Battese and Coelli, 1995; Kumbhakar and Lovell, 2000). Iinuma et al. (1999) measured the technical efficiency of carp pond culture in the Malaysian archipelago by SFA method. Sharma and Leung (2000) applied a stochastic frontier production model to test and explain the differences in carp pond culture techniques among the major carp producing countries in South Asia (India, Bangladesh, Pakistan, and Nepal). Based on the cross-sectional data of 150 fish farms, Onumah et al. (2010) used stochastic frontier function to calculate the technical efficiency and its influencing factors of Ghana fish farms. It is found that the average output adjustment of input is positive. Moreover, the return to scale of fish farms is on the rise. Kim et al. (2011) estimated the production efficiency of sandfish coastal gillnet fishery on the east coast of South Korea with translog stochastic production frontier. Jamnia et al. (2013) employed Cobb-Douglas stochastic production frontier model to measure the technical efficiency of fishery in Chabahar region in southern Iran, and discussed the output elasticity and return to scale. At the same time, their research also found that the translog function cannot be used as an appropriate representation of data. Tingley et al. (2005) applied SFA and DEA method to measure the technical efficiency of the channel fishery, and analyzed the main factors affecting the technical efficiency. Finally, the conclusion is drawn that the two methods are basically the same in the analysis of technical efficiency. When the stochastic production frontier function is difficult to determine accurately, it can be replaced by DEA method. In other words, SFA has some defects. It cannot reasonably control the input-output variables and endogenous problems, and has high requirements for the setting of production function.

Once the production function is set unreasonably, the result will be biased (Simar and Wilson, 1998).

Second, DEA model constructs nonparametric piecewise surface of data by linear programming, and then calculates the relative effectiveness of multiple input-output decision-making units (DMUs) (Charnes et al., 1978; Coelli, 1998). Compared with SFA model, DEA does not need to calculate any function forms related to input and output (Song and Zheng, 2016), which can avoid strong hypothesis bias such as production function setting and random interference normal distribution (Färe et al., 1989). For this reasons, DEA model has more advantages in evaluating efficiency. Sharma et al. (1999) applied DEA method to measure the economic efficiency and technical efficiency of Chinese fish farms and showed that the low production efficiency of fish farms in China is mainly caused by the low technical efficiency. Rasmus (2011) analyzed the technical efficiency of aquaculture in Denmark with CCR-DEA model. Pascoe and Herrero (2004) pointed out that the fishery production function needs to consider the stock, so it is difficult to set. Through research, they proposed that the use of DEA Malmquist productivity index model can avoid the consideration of stock. After verifying the effectiveness, Pascoe used this method to study the fishery production efficiency in the South Atlantic of Spain. Hassanpur et al. (2011) estimated the TFP of rainbow trout aquaculture in Iran by Malmquist index. It is found that the TFP growth of rainbow trout aquaculture in aquaculture sector is mainly caused by the progress of technical efficiency, while the effect of technical change is not significant. Norway is a major country in salmon farming. Terje and Helen (2011) utilized DEA

Malmquist productivity index method to measure the efficiency of salmon farming in Norway. The results showed that the change of TFP was mainly caused by the change of technology, while the change of efficiency had little effect on it. It is also concluded that agglomeration externality is the main factor affecting salmon productivity and technical efficiency. Ji and Wang (2015) evaluated aquaculture efficiency of 16 provinces in China with SBM-DEA model, and they found that technology expansion and improvement of technology level have obvious positive effects on aquaculture. Pipitone and Colloca (2018) used Malmquist index method to decompose TFP of Italian trawl fishery. The results showed that overfishing had a negative effect on fishery efficiency, and capital accumulation and pricing strategy had a positive effect on fishery efficiency. Xu (2020) measured the TFP of mariculture in nine coastal provinces of China based on DEA Malmquist method, and pointed out that the growth of mariculture efficiency belongs to technology induced growth.

From the above studies, it can be seen that most of the existing research on fishery efficiency focuses on single species breeding, fishing, mariculture and overall fishery production efficiency, while few on the freshwater aquaculture efficiency. Moreover, no studies have considered the importance of regional heterogeneity for freshwater aquaculture efficiency by the meta-frontier. In terms of research methods, SFA function method, traditional DEA method and traditional Malmquist index method are mostly used. As for the analysis of the results, most of the existing studies are directly based on a frontier to analyze the overall situation. In order to make up for the defects of the existing research, this paper uses the meta-frontier method to measure the TFP of

freshwater aquaculture in China based on the regional heterogeneity. The inherent assumption of meta-frontier method is that the technological progress of different groups is heterogeneous, so DMUs should be divided into different groups. Previous studies have suggested that geographical proximity and self-characteristics are the decisive factors for grouping (Oh and Lee, 2010). Considering the characteristics of freshwater aquaculture, this paper divides the areas into coastal regions and inland regions, which follows this principle.

In summary, there are three innovations in this paper. First, in terms of data and sample selection, this paper selects the input-output panel data of freshwater aquaculture in 11 coastal provinces and 17 inland provinces in China from 2003 to 2019. Compared with previous studies, this study has a larger time span and a wider area, which can more accurately reflect the contemporary freshwater aquaculture TFP in China. Second, in terms of research method, considering the regional heterogeneity, this paper uses DDF-MMI model to analyze the TFP of freshwater aquaculture in coastal and inland regions through the comparison of meta-frontier and group-frontier. Third, in the analysis of the results, this paper analyzes the TFP under the two conditions of overall and cluster group, and discusses the freshwater aquaculture technology gap rate (TGR) in coastal and inland regions.

3. Methodology

3.1DDF

DDF was proposed by Chung et al. (1997) proposed to measure the production efficiency. DDF can actually reflect the economic effect (Yang et al., 2020), which is

suitable for the measurement of freshwater aquaculture efficiency. This paper takes provinces as DMUs. Assuming that the number of DMUs is K , and the number of inputs and outputs for each DMU is M and N , respectively, then the production possibility set of the current period can be expressed as:

$$P^t(x^t) = \{y^t | x^t \text{ can produce } y^t\}, t = 1, 2, 3, \dots, T \quad (1)$$

The definition of output oriented DDF is as follows:

$$\vec{D}(x, y; g) = \max\{\beta | y + \beta g \in P(x)\} \quad (2)$$

Where x is the input vector and y is the output of the production. g is the direction vector, where is the output expansion direction, denoted by $(0, y)$. β is the the value of DDF and represents the ratio of output expansion.

The specific process of using DDF to evaluate freshwater aquaculture efficiency is as follows:

$$\text{Max} \vec{D}(x, y; g) = \beta \quad (3)$$

$$s. t. \begin{cases} \sum_{k=1}^K \lambda_k x_k \leq x \\ \sum_{k=1}^K \lambda_k y_k \geq (1 + \beta)y \\ \lambda_k \geq 0, k = 1, 2, \dots, K \end{cases}$$

The closer each DMU is to the meta-front curve, the greater the efficiency of DMU is. The efficiency index of DMU is $1 / (1 + \beta)$.

3.2 The double-hierarchy meta-frontier DDF-DEA model

Hayami and Ruttan(1971) proposed the concept of meta-frontier when considering heterogeneity. This method has been widely used in efficiency measurement after development (O'Donnell et al., 2008). On the basis of DDF, this paper adds regional

194 factors to the model by considering the meta-frontier and regional frontier. The regional
 195 frontier includes coastal regional frontier and inland regional frontier. As shown in
 196 Fig.1, there are two regional fronts under the envelope of the meta-frontier.

197 **Fig.1.** Double-hierarchy meta-frontier

198 First, the DDF function model based on the meta-frontier is shown in Eq.(4).

$$199 \quad \text{Max} \overrightarrow{D^M}(x_{mo}^t, y_{no}^t; g) = \beta^M \quad (4)$$

$$200 \quad \text{s. t.} \begin{cases} \sum_{t=1}^T \sum_{k=1}^{K_M} \mu_k^t x_{m,k}^t \leq x_{mo,k}^t, m = 1, 2, \dots, M \\ \sum_{t=1}^T \sum_{k=1}^{K_M} \mu_k^t y_{n,k}^t \geq (1 + \beta^M) y_{no,k}^t, n = 1, 2, \dots, N \\ \mu_k^t \geq 0, k = 1, 2, \dots, K_M; t = 1, 2, \dots, T \end{cases}$$

201 Where β^M is the proportion of output expansion under the meta-frontier. M, N and T
 202 are the number of inputs, the number of outputs, and the number of periods respectively.
 203 μ is the intensity variable under the meta-frontier. K_M is the number of DMUs in the
 204 meta-frontier, $K_M = 28$.

205 Second, the DDF function model at the regional frontier is shown in Eq.(5).

$$206 \quad \text{Max} \overrightarrow{D^R}(x_{mo}^t, y_{no}^t; g) = \beta^R \quad (5)$$

$$\begin{aligned}
& \left\{ \begin{aligned} & \sum_{t=1}^T \sum_{k=1}^{K_R} \theta_k^t x_{m,k}^t \leq x_{mo,k}^t, m = 1, 2, \dots, M \\ & \sum_{t=1}^T \sum_{k=1}^{K_R} \theta_k^t y_{n,k}^t \geq (1 + \beta^R) y_{no,k}^t, n = 1, 2, \dots, N \\ & \theta_k^t \geq 0, k = 1, 2, \dots, K_R; t = 1, 2, \dots, T \end{aligned} \right.
\end{aligned}$$

Where β^R is the proportion of output expansion under the regional frontier. θ is the intensity variable under the regional frontier. K_R is the number of DMUs in the regional frontier. In coastal region, $K_R = 11$, and in the inland region, $K_R = 17$.

3.3 The double-hierarchy meta-frontier Malmquist index

This paper aims to measure the TFP of freshwater aquaculture. Färe et al. (1994) proposed to apply Malmquist index (MI) method to measure TFP. The concept of MI was first proposed by Malmquist (1953) to analyze the cost change in different periods. However, the traditional MI is based on the relative change of production frontier in the calculation process, rather than the absolute technology change (Zhong et al., 2020). In addition, the traditional MI has some limitations, such as no feasible solution, lack of transitivity and technical regression (Pastor and Lovell, 2005). Oh and Lee (2010) applied the method of meta-frontier to the global reference Malmquist model, constructed the meta-frontier Malmquist index (MMI) model, and further decomposed it. This method includes all the evaluated DMUs in the global reference set, which overcomes the shortcomings of the traditional MI. MMI can measure TFP more accurately. The global production possibilities can be expressed as Eq.(6).

$$P^G(x) = P^1(x^1) \cup P^2(x^2) \cup \dots \cup P^T(x^T) \quad (6)$$

$$\text{Where, } P^t(x^t) = \{y^t | x^t \text{ can produce } y^t\}, t = 1, 2, 3, \dots, T \quad (7)$$

The calculation formulas of TFP of freshwater aquaculture at different frontiers

are as follows:

$$MMI_{t-1,t}^M$$

$$= \sqrt{\frac{1 - \overrightarrow{D}_{t-1}^M(x^t, y^t; g)}{1 - \overrightarrow{D}_{t-1}^M(x^{t-1}, y^{t-1}; g)}} \times \frac{1 - \overrightarrow{D}_t^M(x^t, y^t; g)}{1 - \overrightarrow{D}_t^M(x^{t-1}, y^{t-1}; g)} \quad (8)$$

$$MMI_{t-1,t}^R$$

$$= \sqrt{\frac{1 - \overrightarrow{D}_{t-1}^R(x^t, y^t; g)}{1 - \overrightarrow{D}_{t-1}^R(x^{t-1}, y^{t-1}; g)}} \times \frac{1 - \overrightarrow{D}_t^R(x^t, y^t; g)}{1 - \overrightarrow{D}_t^R(x^{t-1}, y^{t-1}; g)} \quad (9)$$

$MMI_{t-1,t}^M$ 、 $MMI_{t-1,t}^R$ represents the TFP of freshwater aquaculture under the meta-frontier and regional frontier respectively. If the value of MMI is greater than 1, it indicates that the productivity increases from the previous period to this period. MMI can be further decomposed into EC and TC, its decomposition is shown in Eq.(10):

$$\begin{aligned} MMI_{t-1,t} &= \sqrt{\frac{1 - \overrightarrow{D}_{t-1}(x^t, y^t; g)}{1 - \overrightarrow{D}_{t-1}(x^{t-1}, y^{t-1}; g)}} \times \frac{1 - \overrightarrow{D}_t(x^t, y^t; g)}{1 - \overrightarrow{D}_t(x^{t-1}, y^{t-1}; g)} \\ &= \sqrt{\frac{1 - \overrightarrow{D}_{t-1}(x^{t-1}, y^{t-1}; g)}{1 - \overrightarrow{D}_t(x^{t-1}, y^{t-1}; g)}} \times \frac{1 - \overrightarrow{D}_{t-1}(x^t, y^t; g)}{1 - \overrightarrow{D}_t(x^t, y^t; g)} \times \frac{1 - \overrightarrow{D}_t(x^t, y^t; g)}{1 - \overrightarrow{D}_{t-1}(x^{t-1}, y^{t-1}; g)} \\ &= TC_{t-1,t} \times EC_{t-1,t} \end{aligned} \quad (10)$$

A key index of meta-frontier method is technology gap ratio (TGR), which is the ratio of meta-frontier efficiency and group frontier efficiency. It can be used to measure the gap between the actual technology level and the potential optimal technology level of a group. Taking point A under group 1 as an example (combined with Fig.1), TGR can be expressed as: $TGR_t = (BA/BD)/(BA/BC) = BC/BD$. The value range is $[0,1]$, and the closer to 1, the closer the actual technology level is to the potential optimal technology level.

3.4 Variables and sources of data

The accuracy of DEA in measuring TFP is closely related to the choice of input-output variables. According to the viewpoint of western economics, the choice of input variables should combine land, capital and labor (Mankiw, 1997). Combined with the existing literature (Asche et al., 2013; Ji et al, 2015), this paper selects three variables to build an input variable system, which are freshwater aquaculture area, freshwater aquaculture professionals and freshwater seedling quantity. These three variables reflect land, labor and capital respectively. As for the selection of output variables, it is usually to use gross economic value of fishery to reflect the total scale and total results of fishery production in a period of time at fishery application (Zheng et al., 2019). Based on the actual situation of freshwater aquaculture, the output variable of this paper is the fishery production value of freshwater aquaculture. The specific explanation is as follows:

(1) Freshwater aquaculture area. The water surface area of aquaculture products in freshwater areas, including pond culture area, lake culture area, river aquaculture area and reservoir aquaculture area, etc. The unit of measurement is hectare.

(2) Freshwater aquaculture professionals. Fishery practitioners who have been engaged in freshwater aquaculture for more than six months or more than 50% of their livelihood sources depend on freshwater fishery activities throughout the year. Compared with the part-time and temporary employees of freshwater aquaculture, the professionals from industry are more representative. The unit of measurement is person.

(3) Freshwater seedling quantity. Including fry and fingerlings. The unit of measurement is tail.

(4) The fishery production value of freshwater aquaculture. It refers to the output and outcomes of freshwater aquaculture fishery activities in the accounting period in the form of currency. The unit of measurement is 10000 yuan.

The input-output variable system is listed in Table 2.

The variables expressed in currency are bound to be affected by inflation, which will lead to the lack of objectivity and accuracy of data. For this reason, this paper selects 2003 as the base year to deal with the output variables, so as to eliminate the impact of inflation. The relevant data of input-output variables are all from “China

Fisheries statistical yearbook”.

3.5 study area

Fig.2. Spatial distribution sampling in freshwater aquaculture areas

The paper aims to study freshwater aquaculture efficiency in China. The relevant data of some provinces are missing, and the output of freshwater fishery in Tibet, Gansu

and Qinghai provinces and cities is small, which is lack of research value. For these reasons, this work selects 28 provinces with more freshwater aquaculture, such as Fujian, Guangdong, Anhui and Beijing, as samples. As shown in Fig.2, the areas involved are divided into coastal and inland regions.

4. Empirical analysis

This work uses MaxDEA software to calculate the TFP and its decomposition index values of freshwater aquaculture in 11 coastal provinces and 17 inland provinces from 2004 to 2019. According to the calculation results, this part analyzes the development trend and regional characteristics of China's freshwater aquaculture.

4.1 Temporal and spatial characteristics of TFP in freshwater aquaculture

The overall fluctuation trend of TFP, EC and TC in China's freshwater aquaculture is basically the same at the meta-frontier and group frontier (Fig.3). The average annual TFP of freshwater aquaculture basically reached more than 1 both at the meta-frontier and group frontier, except in 2009 and 2011. From 2004 to 2013, TFP fluctuated greatly. After 2013, TFP is relatively stable. Specifically, TFP was the lowest in 2011 and the highest in 2012. Between these two years, TFP fluctuated the most, with meta-frontier of 0.811 and group frontier of 0.827. This is mainly because in 2012, the central government attached great importance to the development of Fisheries and gave the highest amount of funding in the history of Fisheries Finance. According to statistics, the total investment in fishery infrastructure construction in the whole year reached 8.933 billion yuan, nine times that of 2011. Driven by the strong central investment, the level of fishery infrastructure has been significantly improved. In addition, the

305 technological system of modern fishery industry was further improved in 2012. Seven
306 key fishery technology research projects have been included in the national public
307 welfare agricultural industry research special plan, with funding support of 106 million
308 yuan. 184 patents were invented in fishery in the whole year, with a year-on-year
309 increase of 142.11%. At the same time, the promotion of aquatic technology has been
310 steadily promoted. In 2012, a total of 2.9534 million fishermen were trained, which
311 effectively promoted the improvement of fishermen's quality and the popularization of
312 aquaculture technology and management technology. From 2012 to 2013, TFP fell the
313 most, with the meta-frontier of 0.617 and the group frontier of 0.619. From 2013 to
314 2019, the trend of TFP is moderate. It shows that the development of China's freshwater
315 aquaculture has begun to stabilize after 2013. This may be caused by the following
316 reasons: First of all, during the "Eleventh Five Year Plan" period, the national fishery
317 system adheres to the guidance of the scientific development and solidly promotes the
318 construction of modern fishery. This makes the structure of China's fishery industry
319 further optimized, and the level of fishery development and industrial competitiveness
320 significantly improved; then, during the "Twelfth Five Year Plan" period of fishery
321 development, fishery is facing the following favorable conditions: First, China has
322 begun to improve the long-term mechanism of promoting agriculture through industry
323 and leading rural areas by cities. It is in the critical period of speeding up the
324 transformation of traditional agriculture and taking the road of agricultural
325 modernization with Chinese characteristics. In this way, the freshwater aquaculture
326 industry is promoted in an all-round way. Second, after long-term development, fishery

327 has formed a large industrial scale and a good industrial foundation. And fishery has
328 accumulated rich experience in production, management and technology. At the
329 beginning of the “Thirteenth Five Year Plan”, the industrial structure of China’s
330 freshwater aquaculture has been further adjusted. The input of resource elements,
331 technical level and management level have developed to a relatively saturated level.
332 These factors make the input-output conversion rate of freshwater aquaculture develop
333 more smoothly. However, it could not be ignored that the degree of scale, intensification
334 and organization of China’s fishery production is still low on the whole. The quality of
335 aquaculture practitioners is also low. These factors will restrict the sustainable
336 development of freshwater aquaculture industry, and then make the efficiency of
337 freshwater aquaculture at an effective but not high level. As shown in Fig.3, the average
338 annual TFP in 2013-2019 is closely around 1. Taking the year with the highest annual
339 TFP as an example, in 2017, the average annual TFP under the meta-frontier and group
340 frontier was only 1.146 and 1.153, respectively. At the meta-frontier, the provinces that
341 do not reach the effective state of freshwater aquaculture are: Fujian (0.869), Hebei
342 (0.999), Liaoning (0.699), Tianjin (0.906) in coastal region, Henan (0.980), Hubei
343 (0.944), Shaanxi (0.589), Xinjiang (0.743) in inland region. At the group frontier,
344 provinces with inefficient freshwater aquaculture are as follows: Fujian (0.869), Hebei
345 (0.995), Liaoning (0.697), Tianjin (0.906) in coastal region, Shaanxi (0.636), Xinjiang
346 (0.810) in inland region. The ineffectiveness of input and output of freshwater
347 aquaculture in these provinces has caused great losses.

Fig.3. The trends of TFP、EC and TC at two frontiers

The changing trend of TFP is roughly the same as that of EC and TC both at meta-frontier and group-frontier (Fig.3). This shows that the changes of TFP in China's freshwater aquaculture is driven by the combined effect of EC and TC. Especially under the meta-frontier, the changing trends of TFP and TC are more suitable. Specially, in 2007, TC only changed slightly, while TFP increased significantly, which increased by 53.6% and 45% compared to the previous year in meta-frontier and group frontier, respectively. It is mainly driven by the substantial increase of EC. The value of EC under the meta-frontier increased by 38.2%, and that under the group frontier increased by 28.4%. In 2008, the value of TC increased both under the meta-frontier and the group frontier, while MI decreased. This is mainly dominated by the decline in EC, and its value directly dropped below 1. This means that the management level of freshwater aquaculture in China had declined in 2008. This may be caused by the following two factors. On the one hand, in 2008, the impact of the global financial crisis began to appear to China. On the other hand, many key freshwater aquaculture provinces of China suffered rare freezing rain and snow disasters in 2008. Faced with the more

364 severe fishery production situation, it is difficult for fishery production management to
365 keep up in a short time. From 2013 to 2019, both EC and TC maintained a relatively
366 stable level, and fluctuated closely around 1 slightly. This showed that after 2013, the
367 management level and technical level of China's freshwater aquaculture were at a
368 relatively stable level of development. In general, the development of freshwater
369 aquaculture in China has management advantages. The technology level has also
370 reached a stable and better level. However, there is still no breakthrough. Therefore, it
371 is very necessary to cultivate professional management and technical personnel. At the
372 same time, China should pay attention to the construction of freshwater aquaculture
373 technology system, increase investment in fishery technology elements, continue to
374 carry out technological innovation, and strive to achieve technological breakthroughs
375 as soon as possible. This will effectively promote the improvement of freshwater
376 aquaculture TFP and contribute to the sustainable development of freshwater
377 aquaculture.

Fig.4. Averages of TFP of freshwater aquaculture in two frontiers

Fig.4 shows the spatial distribution characteristics of freshwater aquaculture TFP

under the two frontiers. Obviously, no matter it is at the meta-frontier or the group

frontier, the TFP shows large spatial differences. Moreover, areas with similar

efficiencies show a trend of spatial aggregation. Comparing coastal region and inland

region, it can be seen that higher TFPs are located in inland region. At meta-frontier,

only Liaoning in the coastal region has a higher level. At the group frontier, the situation

is slightly more impressive, with Fujian, Jiangsu and Liaoning in the coastal region at

a higher level. Moreover, Liaoning ranks among the top 5 in China under the group

frontier. This may be because, on the one hand, Liaoning has always paid attention to

scientific and technological investment in aquaculture and used scientific guidance to effectively prevent the development of diseases. On the other hand, Liaoning has a good level of aquaculture management. Liaoning has been committed to the establishment and improvement of aquaculture mechanisms, including inputs and aquaculture water testing. At the same time, with the continuous development of the level of technology and management, the scale of the aquaculture industry in Liaoning has also continued to expand. Shaanxi, Guizhou and Xinjiang are in the top five of TFP both at the two frontiers (Fig.4. (II), (IV)), and these three provinces are all inland cities. Among them, Shaanxi is in the first place. This is mainly because Shaanxi had a very high TFP in 2012, which was largely due to the strong investment and support of the central government for fishery infrastructure construction in 2012. At the same time, Shaanxi government have also implemented financial discounts to support fishery infrastructure. In addition, the fishery department of Shaanxi organizes fishery science and technology personnel to go to the grassroots level to promote aquaculture technology. It can be seen that technological progress and management level improvement are really critical for the sustainable development of freshwater aquaculture. Shanghai, Zhejiang, Jiangxi, and Beijing are all ranked in the bottom five under the two frontiers (Fig.4. (II), (IV)). Among them, Shanghai and Zhejiang are both coastal provinces.

As shown in Fig.5, the EC and TC of Shaanxi, Guizhou and Xinjiang in the two frontiers are really considerable, especially in Shaanxi and Guizhou. This determines that these provinces have higher TFP. As for the provinces with the lowest TFP, The values of TC in Shanghai, Zhejiang, Jiangxi and Beijing are not low, all greater than 1.

In other words, the technology of freshwater aquaculture in these four provinces is progressive. The lower TFP of Shanghai, Zhejiang and Beijing is mainly due to the lower EC value. The average EC Value of Shanghai, Zhejiang and Beijing is less than 1. This shows that the management level of Fisheries in these provinces is at a declining level. This is mainly because, in recent years, Shanghai, Zhejiang, Beijing, Jiangxi pay more and more attention to the development of electronic information industry and modern service industry, and gradually develop into the main gathering place of China's electronic information industry cluster and business exhibition cluster area, while ignoring the management of fishery. It can be further found that if these provinces with high technical level are willing to further improve their fishery management level, their TFP of freshwater aquaculture will be greatly improved, which will help to promote the sustainable development of freshwater aquaculture.

Fig.5. Averages of EC and TC of freshwater aquaculture in two frontiers

In addition, the TC value of each province is greater than 1 on the whole, which means that the technology is in a state of progress. However, in the single frontier, more than half of the provinces' TC values are below the average. In the meta-front and group front, the provinces with TC values below the average are Anhui, Hunan and Jiangxi in inland region, and 7 provinces in coastal region, including Guangxi, Hainan and Hebei etc. This also shows that there is a large spatial differences in freshwater aquaculture technology, and there is a large space for improvement of technology. Hence, it is necessary to strengthen the exchange and cooperation of freshwater aquaculture technology between provinces. Especially for provinces with low level of freshwater aquaculture technology, the local government should actively introduce advanced technology and strengthen the promotion of freshwater aquaculture technology.

Fig.6. Average annual TFP of freshwater aquaculture in two regions

4.2 Temporal and spatial characteristics of TFP in freshwater aquaculture between regions

It can be seen from Fig.6, whether it is in coastal or inland regions, freshwater aquaculture TFP fluctuated greatly during 2004 to 2012. In the coastal region, the TFP was the lowest in 2009, with 0.868 and 0.867 at the meta-front and the group front, respectively, representing a decrease of 13.2% and 13.3% from the previous year. TFP was the highest in 2012, with 1.472 for both frontiers, an increase of 47.2% over the previous year. As for the inland region, the lowest TFP was in 2011, and the meta-frontier and group frontier were 0.819 and 0.800 respectively, they are decreased by 18.1% and 20% from the previous year. In the inland area, the lowest TFP was in 2011, and its values were 0.819 and 0.800 under the meta-frontier and group frontier, respectively, which were 18.1% and 20% lower than the previous year. The highest TFP was in 2012, which was 1.768 under the meta-frontier, an increase of 76.8% over the previous year, and 1.777 under the group frontier, an increase of 77.7% over the previous year. From 2012 to 2013, TFP showed a decline both at coastal and inland regions. After 2013, TFPs began to show steady and small fluctuations. It can be seen that after 2013, both coastal and inland regions have begun to enter a relatively stable level in the development of freshwater aquaculture. Moreover, after 2013, TFPs were greater than 1, which means freshwater aquaculture remained in an effective state, except in 2015. This also indicates that the development level of freshwater aquaculture in coastal and inland regions has been steadily improved after 2013. The freshwater

456 aquaculture industry has gradually become competitive in the market, and the industrial
 457 structure has been further optimized. However, there has not been an amazing
 458 breakthrough value. This is consistent with the analysis of the time characteristics of
 459 the overall national TFP in Section 4.1.

Fig.7. Provinces average TFP of freshwater aquaculture in two regions

460 From 2004 to 2019, TFP (MMI) of coastal region and inland region under the
 461 meta-frontier were 1.101 and 1.154 respectively (Fig.7). It can be seen that under the
 462 meta-frontier, the freshwater aquaculture efficiency of coastal region is significantly
 463 lower than that of inland region. TFP (GMI) of coastal and inland at group frontier were
 464 1.101 and 1.143, respectively. That is to say, the freshwater aquaculture efficiency in
 465 inland region is still better than that in coastal region. It shows that the development of
 466 freshwater aquaculture in inland region is more advantageous regardless of the regional
 467 factors. Combined with Fig.8, the average values of TC and EC in coastal region are
 468 lower than those in inland region. Especially for EC, the average value of EC in coastal
 469 region is significantly lower than that in inland region. In addition, the EC values in
 470 coastal region are more concentrated, while those in inland areas are more dispersed. It
 471 coastal region are more concentrated, while those in inland areas are more dispersed. It

can be seen that there are great differences in the management level of freshwater aquaculture of inland provinces. This means that there is still much space for improvement in freshwater aquaculture management in many inland provinces.

Fig.8. EC and TC of freshwater aquaculture in two regions

Coastal region has relatively developed economies and high levels of science and technology. With the development of society, they have increasingly concentrated on the development of high-tech industries and tertiary industries, thus they have ignored the development of agriculture to a certain extent. At the same time, coastal region are rich in seawater resources, and the emphasis on marine fisheries has made a lot of fishery production factors invested in marine fisheries, thus slowing the development of freshwater fisheries. However, many provinces in the inland region still focus on the primary industry. Taking Heilongjiang and Shanxi as examples, the primary industry in Heilongjiang accounts for the highest proportion of the three industries, and it is also showing a gradual upward trend. The emphasis on the primary industry has made its agriculture, including the freshwater fishery industry, develop on a larger scale. Therefore, the local freshwater aquaculture TFP is relatively high. As for Shanxi, although it is not a major fishery province, the province attaches great importance to

the development of fisheries. In the past few years, Shanxi has been committed to the transformation of fishery production methods and improving the level of intensification of the fishery industry. In addition, advanced aquaculture technology has been introduced through the "Three North" technical cooperation group. And at the same time, the local area is also making efforts to promote freshwater aquaculture technology. With the joint action of many parties, the technical ability of fish farming management in Shanxi has been greatly improved. In summary, the top priority for freshwater aquaculture in coastal region is to invest necessary management resources to increase their freshwater aquaculture management level. Some provinces with lower management levels in inland region should actively seek communication between provinces to coordinate the improvement of freshwater aquaculture management.

4.3 Analysis of TGR in regional freshwater aquaculture

The full name of TGR is technology gap rate, which reflects the technology gap between group frontier and meta-frontier. The higher the TGR value is, the closer the DMU's technical level is to the potential optimal level.

The average TGR of coastal and inland regions are 0.997 and 0.740 respectively (see Fig.9(I)). The results show that the technical level of freshwater aquaculture in coastal region has reached 99.7% of the meta-frontier level, while that in inland region has only reached 74%. This means that the technical level of freshwater aquaculture in coastal region is more in line with the potential optimal technology level, while the technical efficiency in inland region has a large gap with the optimal level, and there is more space for improvement. From the TGR value of each province, the value of TGRs

511 in the coastal region were concentrated in a really close level, which shows that the
 512 freshwater aquaculture technology level of each place in the coastal region has
 513 agglomeration. The TGRs of the provinces in the inland region were relatively scattered,
 514 which means that the development of freshwater aquaculture technology in the inland
 515 region was quite uneven. Hence, it is very necessary to strengthen the exchange and
 516 cooperation in freshwater aquaculture technology between provinces in inland region.

(I)

(II)

Fig.9. TGR of freshwater aquaculture

519 From a dynamic point of view (Fig. 9(II)), from 2004 to 2019, TGR in coastal
 520 region had been stable at around 1, with no major fluctuations. It also shows that the
 521 level of freshwater aquaculture technology in coastal region is very close to the optimal
 522 level of potential technology. On the whole, the TGR in the inland region showed a
 523 rising state from 2004 to 2019, with the value from 0.708 to 0.77. During the period
 524 from 2008 to 2010, the TGR in the inland region experienced successive declines,
 525 which may be affected by the rising labor and resource costs. After 2010, TGR began
 526 to rebound and showed a relatively stable trend. In recent years, TGR in inland region

has shown an upward trend. With the continuous introduction of advanced technologies in inland areas, its TGR is expected to maintain a growing trend.

Combining the previous section of the analysis of freshwater aquaculture TFP in coastal and inland regions, the overall performance of inland region is better than coastal region in the freshwater aquaculture industry. But when it comes to TGR, coastal region has absolute advantages. The main reason is that coastal areas have been the frontiers to take the lead in developing industrial clusters since reform and opening up in China. Then, through in-situ expansion, market pull, off-site incubation, and foreign transplantation and other ways, new technologies are continuously introduced and popularized, and development restrictions on the original location are broken. This has led to further advances in technology, so as to drive the development of the local economy. Obviously, there is a high correlation between economic development and technological development. Thus, the development of economy further promotes the progress of science and technology, and the development of economy and science and technology form a complementary effect. For these reasons, the technical efficiency level of freshwater aquaculture in coastal region is relatively high. Coastal region should give full play to their technological advantages, invest necessary elements in freshwater aquaculture, and continuously optimize the fishery industry. As for inland region, the overall economic development is not as good as that of the coastal region. In contrast, the aquaculture technology level is lagging behind, and it is more inclined to traditional aquaculture methods in terms of fish farming. Therefore, in addition to giving full play to their own resource advantages, inland region should also devote

themselves to the improvement of freshwater aquaculture technology, and constantly approach the potential optimal technical level. Thereby promoting the sustainable development of the freshwater fishery industry.

5. Conclusions and policy recommendations

This paper constructs a double-hierarchy meta-frontier Malmquist index based on the DDF-DEA model to calculate the freshwater aquaculture TFP of 28 provinces in China from 2004 to 2019, and draws the following conclusions through analysis:

(1) TFP of freshwater aquaculture shows dynamic fluctuations and spatial differences both at meta-frontier and group frontier. From the perspective of time, TFP fluctuated sharply, especially from 2004 to 2013. After 2013, TFP showed slight and stable fluctuations between years. From a spatial point of view, combined with regional heterogeneity, inland region has obvious advantages in freshwater aquaculture efficiency compared with coastal region.

(2) According to the calculation of the decomposition index of TFP, the change of TFP in freshwater aquaculture is driven by the combined effect of EC and TC. In terms of regions, the relatively low TFP in coastal region is largely due to the low value of EC. It means that coastal regions are not making efforts to improve freshwater aquaculture management. The overall situation in the inland region is better than that in the coastal region, but the spatial differences of EC in the inland region are greater. Therefore, it can be seen that there is still a lot of space for development in freshwater aquaculture management capabilities in both coastal and inland regions.

It is an entry point to promote the sustainable development of freshwater

aquaculture.

(3) The TGR of freshwater aquaculture in coastal region has always been in a leading position, with the value maintained at around 1, which is quite close to the potential optimal technology level. The TGR in inland region is generally on the rise, but its value is much lower than that in coastal region, and it is volatile, which is far from the potential optimal level. It limits the sustainable development of freshwater aquaculture to a certain extent.

Based on the above conclusions, this paper proposes the following suggestions to improve the efficiency of freshwater aquaculture and promote the sustainable development of freshwater aquaculture industry.

(1) Strengthen the construction of aquatic science and technology system, and form a long-term mechanism for transforming technological achievements of freshwater aquaculture into actual productivity. Technical level plays a very important role in the freshwater aquaculture process. However, both the TC value and the TGR show an imbalance in space. Many provinces in China have greater space for improvement in freshwater aquaculture technology. Especially in inland region, the TGR is significantly lower than that in coastal region. Therefore, the government should increase the R&D of freshwater aquaculture, and implement the research results into the breeding process, thus to increase the conversion rate of aquatic science and technology achievements, and promote the development of freshwater fishery technology industrialization. Especially in areas with low freshwater aquaculture technology, more attention should be paid to the improvement of

technology, strengthen cooperation with other areas in the freshwater aquaculture industry, and actively introduce advanced technologies to improve the freshwater aquaculture production efficiency and promote its sustainable development.

(2) Improve the management level of freshwater aquaculture. The management level of freshwater aquaculture in coastal region is generally lower than that of inland region. Hence, on the basis of its technical advantages, coastal region should vigorously cultivate management talents and strengthen the improvement of freshwater aquaculture management capabilities. As for inland region, there are obvious spatial differences in the degree of change in technical efficiency. Therefore, inland region should improve the coordination of management capabilities between provinces according to their own management level, so as to increase the contribution of management capabilities to the freshwater aquaculture efficiency.

(3) Coordinate the differences between regions and balance the spatial layout of the freshwater aquaculture industry. Based on the considerable spatial differences of freshwater aquaculture in China, regional resource endowments, economic development level and technological level should be fully considered to form an interactive cooperation mechanism between coastal region and coastal region, coastal region and inland region, inland region and inland region. Thus to enable each region to play its own comparative advantage. This will ensure that advanced freshwater aquaculture technology and management methods can be effectively promoted and popularized. So that the efficiency of freshwater aquaculture in each area can be improved, and a spatial pattern of coordinated development will be

presented, which will provides support for the sustainable development of
freshwater aquaculture.

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Authors' contributions

Shen Zhong: Conceptualization, Methodology, Software. Aizhi Li: Investigation,
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Table 1
Abbreviations used in this paper

Abbreviation	Full-name
DDF	Directional distance function
DEA	Data envelopment analysis
DMU	Decision-making unit
EC	Technical efficiency change
MMI	Meta-frontier Malmquist index
MI	Malmquist index
R&D	Research and development
SBM	Slack-based measurement
TC	Technology change
TFP	Total factor productivity
TGR	Technology gap ratio

Table 2
Variables of freshwater aquaculture efficiency evaluation

Variables type	Variables	Unit
Input variables	Freshwater aquaculture professionals	person
	Freshwater seedling quantity	million tail
	Freshwater aquaculture area	hectare
Output variable	The fishery production value of freshwater aquaculture	10,000 yuan

Figures

Figure 1

Double-hierarchy meta-frontier

Figure 2

Spatial distribution sampling in freshwater aquaculture areas. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 3

The trends of TFP, EC and TC at two frontiers

Figure 4

Averages of TFP of freshwater aquaculture in two frontiers. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 5

Averages of EC and TC of freshwater aquaculture in two frontiers

Figure 6

Average annual TFP of freshwater aquaculture in two regions

Figure 7

Provinces average TFP of freshwater aquaculture in two regions

Figure 8

EC and TC of freshwater aquaculture in two regions

515

(I)

(II)

Figure 9

TGR of freshwater aquaculture