Heliyon 10 (2024) e25816

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Review article

Spatio-temporal evolution and its policy influencing factors of agricultural land-use efficiency under carbon emission constraint in mainland China

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ARTICLE INFO

Keywords:
Agricultural land-use
Carbon emissions
Carbon neutrality
Peak carbon dioxide emissions
Super SBM (slack-based measure)-Undesirable DEA model

ABSTRACT

In the context of the vision to reach peak carbon dioxide emissions before 2030 and achieve carbon neutrality before 2060, Mainland China's agricultural development will face strict carbon constraints. This paper analyzes the agricultural land-use efficiency of Mainland China's agriculture under carbon emission constraint from 1996 to 2020, based on the unexpected super SBM (Slack-based measure)-Undesirable DEA, Malmquist index model, and quartile division-GIS method. The results show that: from 1996 to 2020, the agricultural output value per land and grain output per land show an upward trend, and the agricultural carbon emissions per land of most provinces show an increasing trend and larger emissions. The agricultural land-use efficiency in Mainland China rises first and then decreases, and technological progress is the decisive path to improving the agricultural land-use efficiency in Mainland China. The average *MI* in the prominent grain-selling area during 1996–2020 was as high as 1.071, which was significantly higher than that in the prominent grain-producing area (1.039) and the balance area (1.030). The improvement of agricultural land-use efficiency is mostly due to technological progress, but the instability of technical input and management in land use. To improve agricultural land-use efficiency in Mainland China, we should pay attention to the precise policy formulation of low-carbon and high-quality development and strengthen government investment in the difference between space resource endowment and development status.

1. Introduction

Among global agricultural development, increasing productivity and ensuring food security has always been one of the most central agendas. In global, moderate or severe food insecurity rose between 2015 and 2019 and now affects an estimated 25.9% of the world population – about 2 billion people, with women being more likely than men to face moderate or severe food insecurity [1]. Land as an important input factor in agricultural production is the key driver of agricultural productivity [2]. Increasing agricultural productivity through intensive operations of land is currently the main approach to increasing global agricultural productivity. However, an increasing body of evidence shows that intensive operation of land may intensify agricultural environmental problems such as excessive Greenhouse Gas (GHG) emissions [3]. The food-system has already become an important source of global GHG emissions. In

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https://doi.org/10.1016/j.heliyon.2024.e25816
Received 7 September 2023; Received in revised form 31 January 2024; Accepted 2 February 2024

2015, food-system emissions amounted to 18 Gt CO_2 equivalent per year in general, representing 34% of total GHG emissions. The largest contribution came from agriculture and land use/land-use change activities, 71% [4]. To address the problem, countries all over the world have taken actions in areas of food production, consumption, circulation and reduction of waste in order to reduce agricultural GHG emissions and alleviate the paradox between food security and carbon emissions.

Mainland China as the most populated country facing the largest challenge of agricultural productivity is confronted with a particularly prominent paradox between food security and carbon emissions. On the one hand, Mainland China is experiencing ongoing rapid industrialization and urbanization, causing a prevalently severe shortage of agricultural land resources. Especially after 2013, Mainland China's arable land has shown negative growth for five consecutive years. Given this, agricultural production, especially traditional land-intensive agriculture, has been facing increasingly prominent land resource constraints [5]. Therefore, against the backdrop of limited and shrinking land resources, Mainland China's agriculture has exhibited a distinct transition towards intensive use of land with a view of ensuring basic food security. In Mainland China's major grain-producing areas, intensive land operation approaches such as circulation of rural land contracting management and cooperative-based operation has been replacing small-scale household operation with a low degree of intensive land use. On the other hand, as a response to its 2020 pledges including advancing the sustainable development and construction of a community of shared future for mankind, Mainland China announced the vision to reach peak carbon dioxide emissions before 2030 and achieve carbon neutrality before 2060. In agricultural production, a large amount of carbon emitting factors such as fertilizers, pesticides, and agricultural machinery need to be invested, which play an important role in promoting agricultural development. If there are no environmental protection requirements such as reducing carbon emissions, these elements will still be required to increase investment, in order to greatly promote agricultural development and food production.The development of Mainland China's agricultural industry in the future will inevitably be brought under carbon emission constraint. This constraint is reflected in the structure of agricultural and rural industries, modes of production, lifestyles, and spatial patterns, all of which must reduce the intensity of greenhouse gas emissions while guaranteeing food security. Therefore, while reducing the input of agricultural production factors that generate carbon emissions, in order to ensure agricultural development and food production increase, it is necessary to fully utilize limited arable land resources and effectively improve arable land utilization efficiency, which can also be referred to as effectively improving agricultural land use efficiency under carbon emission constraints. Against this background, the central topic of Mainland China's agricultural development should be how to effectively improve the utilization efficiency of the limited agricultural land under the constraints of carbon emissions, thereby satisfying the increasing demand for productivity improvement.

At present, the majority of scholarly research has focused on arable land to explore the construction of a measurement system of land-use efficiency [6], analysis of the spatial difference in land-use efficiency [7] and influencing factors of land-use efficiency [8,9]. In terms of the scale of research, there are both studies on national, provincial, municipal, county-level and township scopes and those focusing on specific grain-producing areas [10]; the methodologies of this body of research mainly include analysis based on descriptive statistics [11], the Cobb-Douglas production function approach [12], the SFA-model approach [13] and the DEA model approach [14]. In general, agricultural land-use efficiency has gradually become one of the hot topics in research. Few studies present dynamic analyses of agricultural land-use efficiency or examine its driving factors, especially analysis on a provincial scale. In addition, county-level farmland abandonment has become a frequent phenomenon in Mainland China [15]. Between 2014 and 2015, the agricultural land abandonment rate in county-level mountainous regions was as high as 14.32% [16], and abandoned land may exert an important influence on agricultural land-use efficiency.

Therefore, from a dynamic analysis perspective, this paper combs through the spatio-temporal evolution characteristics of Mainland China's agricultural land-use (real crop sown area) efficiency from 1996 to 2020 under the constraint of carbon emissions in order to explore the driving factors for the evolution of agricultural land-use efficiency. This paper not only complements existing studies by addressing negative environmental impacts, dynamic perspective and land abandonment, but it also provides significant experience for Mainland China's agricultural development in the future.The structure of this paper is as follows, the second part is method and data, the third part is result, and the fourth part is conclusion and discussion.

2. Methodology and data

2.1. Methodology

2.1.1. The calculating model of agricultural land-use efficiency under carbon emission constraint

To calculate agricultural land-use efficiency under the constraints of carbon emissions, this paper adopts the super SBM (Slack-based measure)-Undesirable DEA (Data envelopment analysis) model. This model originated from the DEA method [17].

First, SBM-Undesirable DEA model (equation (1)) has been broadly applied given its ability to address the overestimation of traditional DEA models for non-zero slacks of inputs and outputs through non-radial and non-angular distance functions [18]. The equation is as follows:

$$Min\ \varphi = \frac{1 - \frac{1}{M}\cdot\sum_{m=1}^{M}\frac{\delta_m^x}{X_{mp}}}{1 + \frac{1}{S+K}\cdot\left(\sum_{s=1}^{S}\frac{\delta_s^y}{Y_{sp}} + \sum_{k=1}^{K}\frac{\delta_k^z}{Z_{kp}}\right)} \tag{1}$$

$$s.t. \sum_{i=1}^{N} X_{mi}\lambda_i + \delta_m^x = X_{mp}, m = 1, 2, \cdots, M$$

$$\sum_{i=1}^{N} Y_{si}\lambda_i - \delta_s^y = Y_{sp}, s = 1, 2, \cdots, S$$

$$\sum_{i=1}^{N} Z_{ki}\lambda_i + \delta_k^z = Z_{kp}, k = 1, 2, \cdots, K$$

$$\lambda_i \geq 0, i = 1, 2, \cdots, N$$

$$p = 1, 2, \cdots, P$$

$$\delta_m^x \geq 0, \delta_s^y \geq 0, \delta_k^z \geq 0$$

where φ is the agricultural land-use efficiency value under the constraints of carbon emissions; *X, Y* and *Z* denotes inputs, desirable and undesirable outputs, respectively; δ_m^x, δ_s^y, δ_k^z *and M, S, K* denote slack vectors and their numbers corresponding to *X, Y, Z; P* is the number of provinces; λ_i is the weight vector.

In the meantime, super efficiency can be used to compare Decision-making units (DMUs) with an efficiency value of 1, thereby allowing for the total ordering of efficiency values. The agricultural land-use efficiency function based on carbon emissions constraints (equation (2)) can be expressed as follows:

$$Min\ \varphi = \frac{\frac{1}{M}\cdot\sum_{m=1}^{M}\frac{\overline{x}}{X_{mp}}}{1+\frac{1}{S+K}\cdot\left(\sum_{s=1}^{S}\frac{\overline{y}}{Y_{sp}}+\sum_{k=1}^{K}\frac{\overline{z}}{Z_{kp}}\right)} \tag{2}$$

$$s.t. \overline{x} \geq \sum_{i=1,\neq p}^{N} X_{mi}\lambda_i \ \& \ \overline{x} \geq x_p, m = 1, 2, \cdots, M$$

$$\overline{y} \leq \sum_{i=1,\neq p}^{N} Y_{si}\lambda_i \ \& \ \overline{y} \leq y_p, s = 1, 2, \cdots, S$$

$$\overline{z} \geq \sum_{i=1,\neq p}^{N} Z_{ki}\lambda_i \ \& \ \overline{z} \geq z_p, k = 1, 2, \cdots, K$$

$$\lambda_i \geq 0, i = 1, 2, \cdots, N$$

2.1.2. *The analysis model of the driving factors of the growth of agricultural land-use efficiency under carbon emission constraint*

To better understand the endogenous drivers for the growth of agricultural land-use efficiency under the constraints of carbon emissions and compensate for the inability of the super SBM-undesirable DEA model to analyze dynamic efficiencies, the Malmquist index (MI) model (equation (3)) is applied to estimation and decomposition of efficiency:

$$MI_t^{t+1} = \left[\frac{1+\underset{D_0^t}{\rightarrow}(x^t, y^t, z^t; y^t, -z^t)}{1+\underset{D_0^t}{\rightarrow}(x^{t+1}, y^{t+1}, z^{t+1}; y^{t+1}, -z^{t+1})}\cdot\frac{1+\underset{D_0^{t+1}}{\rightarrow}(x^t, y^t, z^t; y^t, -z^t)}{1+\underset{D_0^{t+1}}{\rightarrow}(x^{t+1}, y^{t+1}, z^{t+1}; y^{t+1}, -z^{t+1})}\right]^{1/2} \tag{3}$$

$$EC_t^{t+1} = \frac{1+\underset{D_0^t}{\rightarrow}(x^t, y^t, z^t; y^t, -z^t)}{1+\underset{D_0^{t+1}}{\rightarrow}(x^{t+1}, y^{t+1}, z^{t+1}; y^{t+1}, -z^{t+1})}$$

$$TC_t^{t+1} = \left[\frac{1+\underset{D_0^{t+1}}{\rightarrow}(x^t, y^t, z^t; y^t, -z^t)}{1+\underset{D_0^t}{\rightarrow}(x^t, y^t, z^t; y^t, -z^t)}\cdot\frac{1+\underset{D_0^{t+1}}{\rightarrow}(x^{t+1}, y^{t+1}, z^{t+1}; y^{t+1}, -z^{t+1})}{1+\underset{D_0^t}{\rightarrow}(x^{t+1}, y^{t+1}, z^{t+1}; y^{t+1}, -z^{t+1})}\right]^{1/2}$$

Where *MI* denotes the total factor productivity index; *EC* is the technological efficiency change index, *TC* denotes the technological progress change. *EC* can be further decomposed into pure technical efficiency change (*PEC*) and scale efficiency change (*SEC*). $MI = EC \times TC = PEC \times SEC \times TC$ denotes the growth, unchangingness or decrease of agricultural land-use efficiency under the constraints of carbon emissions when *MI* is larger, equal to or smaller than 1, and in the same vein, it respectively denotes growth, unchangingness or decreases when *PEC,SEC* and *TC* are larger, equal to or smaller than 1.

2.1.3. The analysis model of policy factors on the main driving force of MI

Policy factors have a driving effect on agricultural development. They will use tax, subsidies, market control, and other means to affect the use of agricultural inputs, thus affecting *MI*. A regression model (equation (4)) is established to study the influence of policy factors on the main driving force of *MI*:

$$\mathrm{Y} = \beta_0 + \beta_i \bullet \mathrm{X} + \varepsilon \tag{4}$$

Where Y represents the main driving force of MI; β_0 represents a constant term; β_i represents policy factors; the regression coefficient of the independent variable; X represents the set of all policy factors, and ε represents the error term.

2.2. The evaluation system of agricultural land-use efficiency under carbon emission constraint

Drawing on relevant literature, the inputs, desirable outputs and undesirable outputs of agricultural land-use efficiency are selected to construct the evaluation system of agricultural land-use efficiency under carbon emissions constraint (Table 1). Specifically, as an unexpected output in the process of agricultural production, agricultural carbon emission can be considered as a negative factor in the evaluation of agricultural land use efficiency, that is, the constraint of agricultural land-use efficiency evaluation.

The descriptive statistical analysis of the main variables is presented in the Table 2.

The table above shows that the mean of LF is 2024.788, with a maximum value of 21817 and a minimum value of 361. The standard deviation is 1042.344, indicating a significant dispersion of labor force values relative to the mean, reflecting heterogeneity in labor force across these regions. The mean of ACE is 656.981, with a maximum value of 1997.46 and a minimum value of 205.72. The standard deviation is 281.221, suggesting a noticeable gap in ACE. The mean of FI is 323.98, with a maximum value of 873.37 and a minimum value of 95.38. The standard deviation is 125.261, indicating a significant difference in FI. The mean of APF is 15.205, with a maximum value of 83.685 and a minimum value of 0.027. The standard deviation is 13.27, showing a notable gap in APF. The mean of FAI is 5.954, with a maximum value of 85.78 and a minimum value of 0.36. The standard deviation is 11.451, revealing a significant difference in FAI. The mean of PI is 10.293, with a maximum value of 56.44 and a minimum value of 1.259. The standard deviation is 7.845, indicating a significant gap in PI.

2.2.1. Data sources

In this paper, data of practitioners in the primary sector are from provincial statistical yearbooks in different periods; data of effective irrigation area, rural electric power consumption, rural diesel consumption, pesticide consumption and plastic farm film

Table 1
Evaluation system of agricultural land use efficiency and policy factors.

Variable type	Name		Description
Input variables	Labor force per hectare	LF	Number of agricultural employees/total sown area of crops (capita/k hm^2)
	Machinery total power per hectare	MTP	Total power of agricultural machinery/total sown area of crops (kW/hm^2)
	Rural electricity consumption per hectare	REC	Rural electricity consumption/total sown area of crops (kW·h/hm^2)
	Effective irrigation rate	EI	Effective irrigation area/total sown area of crops (%)
	Diesel input per hectare	DI	Agricultural diesel consumption/total sown area of crops (t/hm^2)
	Fertilizer input per hectare	FI	Pure fertilizer application rate/total sown area of crops (kg/hm^2)
	Pesticide input per hectare	PI	Pesticide consumption/total sown area of crops (kg/hm^2)
	Agricultural plastic film input per hectare	APF	Agricultural plastic film consumption/total sown area of crops (kg/hm^2)
Desirable output variables	Agricultural output value per hectare	AOV	Gross output value of agriculture/total sown area of crops (10,000 yuan/hm^2)
	Grain output per hectare	GOP	Grain output/sown area of grain (t/hm^2)
Non-expected output variables	Agricultural carbon emission	ACE	$E = \sum T_i \cdot r_i$
Policy variables	Fiscal agricultural investment intensity	FAI	(Financial agriculture, forestry and water affairs expenditure/fiscal expenditure)/total sown area of crops (%/hm^2)
	Government investment in science and technology	GIS	Agricultural technicians of public economic enterprises and institutions/agriculture labor force (%)
	Farmer income level	FIL	Annual per capita disposable income of farmers (10,000 yuan/person)
	Chemical fertilizer input subsidy	CFI	The implementation of chemical fertilizer subsidy policy drives the substitution efficiency (virtual variable, assigned value of 0 in 1996–2005, 1 in 2006–2015, −1 in 2016–2020)

Note: In the formula calculating the carbon emission E, T_i is the input of agricultural carbon source, r_i is the carbon emission coefficient related to carbon source. Carbon sources and relevant carbon emission coefficients included in this study are: Efficiency irrigation area ($r_1 = 266.48$ kg/hm^2) [10], diesel consumption ($r_2 = 0.59$ kg/kg) [19], ploughing area ($r_3 = 3.13$ kg/hm^2) [20], fertilizer application rate ($r_4 = 0.90$ kg/kg) [21], pesticide consumption ($r_5 = 4.93$ kg/kg) [22], agricultural plastic film consumption ($r_6 = 5.18$ kg/kg) [19], rice ($r_7 = 5.18$ kg/kg).

Table 2
Descriptive statistics.

Variable	Obs	Mean	Std. dev.	Min	Max
area	775	16	8.95	1	31
year	775	2008	7.216	1996	2020
LF	775	2024.788	1042.344	361	21817
MTP	775	5.493	4.23	0.983	78.926
REC	775	0.87	3.506	0.01	42.17
EI	775	0.414	0.196	0.139	2.598
DI	775	0.146	0.146	0.006	1.018
FI	775	323.98	125.261	95.38	873.37
PI	775	10.293	7.845	1.259	56.44
APF	775	15.205	13.27	0.027	83.685
AOV	775	4.793	4.307	0.67	30.62
GOP	775	4.942	1.076	2.41	8
ACE	775	656.981	281.221	205.72	1997.46
FAI	775	5.954	11.451	0.36	85.78
GIS	775	0.004	0.005	0	0.037
FIL	775	0.707	0.586	0.11	3.491
CFI	775	0.2	0.749	−1	1

consumption are from the Mainland China Rural Statistical Yearbook; and the remaining data are all from the Mainland China Financial Yearbook, Mainland China Statistical Yearbook, Mainland China Basic Unit Statistical Yearbook and Mainland China Statistical Yearbook of Science and Technology. In addition, Taiwan, Hong Kong and Macao are not covered in the research due to data unavailability.

3. Results

3.1. *The spatio-temporal evolution of agricultural land-use and its carbon emissions in mainland China*

In the past 25 years, the sown area of agricultural crops and grain output per hectare have remained basically stable in Mainland China, but the average agricultural output value has significantly increased. Specifically, i) the sown area of crops in Mainland China has generally exhibited a fluctuating and gradually growing trend, with an annual growth rate of only 0.41% (Fig. 1a). From the perspective of stages, the growth rate of the agricultural crops sown area showed a fluctuating upward trend in 1996–2007, a continuous downward trend in 2008–2017, and a continuous upward trend in 2018–2020. ii) Changes in grain output per hectare are similar to those in sown land, presenting a fluctuating and slowly growing trend with an annual growth rate of 1.10% (Fig. 1a). However, yearly changes in the growth rate of grain output per hectare present significant fluctuations (Fig. 1b). Grain output per hectare did not drop in sync with fluctuating the sown area of crops. In year 2003, there was a noticeable drop in sown area, while grain output per hectare did not decrease significantly at all. The significant increase in sown area of crops from 2007 onwards did not correspond with significant increases in grain output per hectare, which showed a small gradual increase only. iii) Agricultural output per hectare has shown a totally different trend compared with the previous two indicators mentioned earlier. Generally, agricultural output per hectare has presented a significant uptrend, rising from 14,589 yuan/hm^2 in 1996 to 82,264 yuan/hm^2 in 2020, representing a growth rate of 19.33% (Fig. 1a). It is worth noting that the growth rate of agricultural output value and grain output per hectare is significantly higher than the growth rate of the total sown area of crops.

The carbon emissions per hectare in Mainland China has exhibited a trend of “two-stage” changes. But generally increased consistently with the average agricultural output value per hectare, that is, the negative impact of Mainland China’s agro-production on the environment has been continuously growing (Fig. 2a). Specifically, the first stage spanned from 1996 to 2015, where the carbon emissions per hectare had grown continuously from 446.98 kg/hm^2 to 663.33 kg/hm^2 in this stage; the second stage started after 2015, where the carbon emissions per hectare began to drop. Compared to 1996 and 2015, the average carbon emissions per hectare decreased by 10.69% and 34.63% respectively in 2020. Agricultural carbon emissions have been well controlled, but there is still a long way to go in recovering the agricultural environment.

By the standard of economic regions prevalently utilized in Mainland China, among the four major economic areas, that is, the Northeastern, Eastern, Central, and Western Regions, and the 31 provinces, the majority of provinces, especially the Eastern Region, have experienced considerably continuous growth in carbon emissions per hectare; however, provinces required to enter the "peak carbon emissions" stage have initiated the carbon emissions reduction stage quite late, reflecting an resistance to the reduction of agricultural carbon emissions in Mainland China. As shown in Fig. 2b, specifically, i) Beijing had the highest carbon emissions (1779.46 kg/hm^2), while Guizhou was ranked the lowest (327.26 kg/hm^2) in 2020. Eastern provinces like Beijing, Zhejiang, Fujian, and Hainan had an average carbon emission exceeding 1200 kg/hm^2, which are 2.94, 2.27, 2.22, and 2.01 times the national level, respectively. Except for Hainan, 80% of the top 5 provinces are located in the eastern region. It shows that the eastern region is the highest dependence on carbon source input in agricultural development.The eastern region is typically the economic focal point of China, and agricultural production may be more concentrated and intensive, leading to concentrated carbon emissions. There might be certain region-specific agricultural activities or land-use practices exacerbating this trend. ii) 15 provinces reached the "carbon

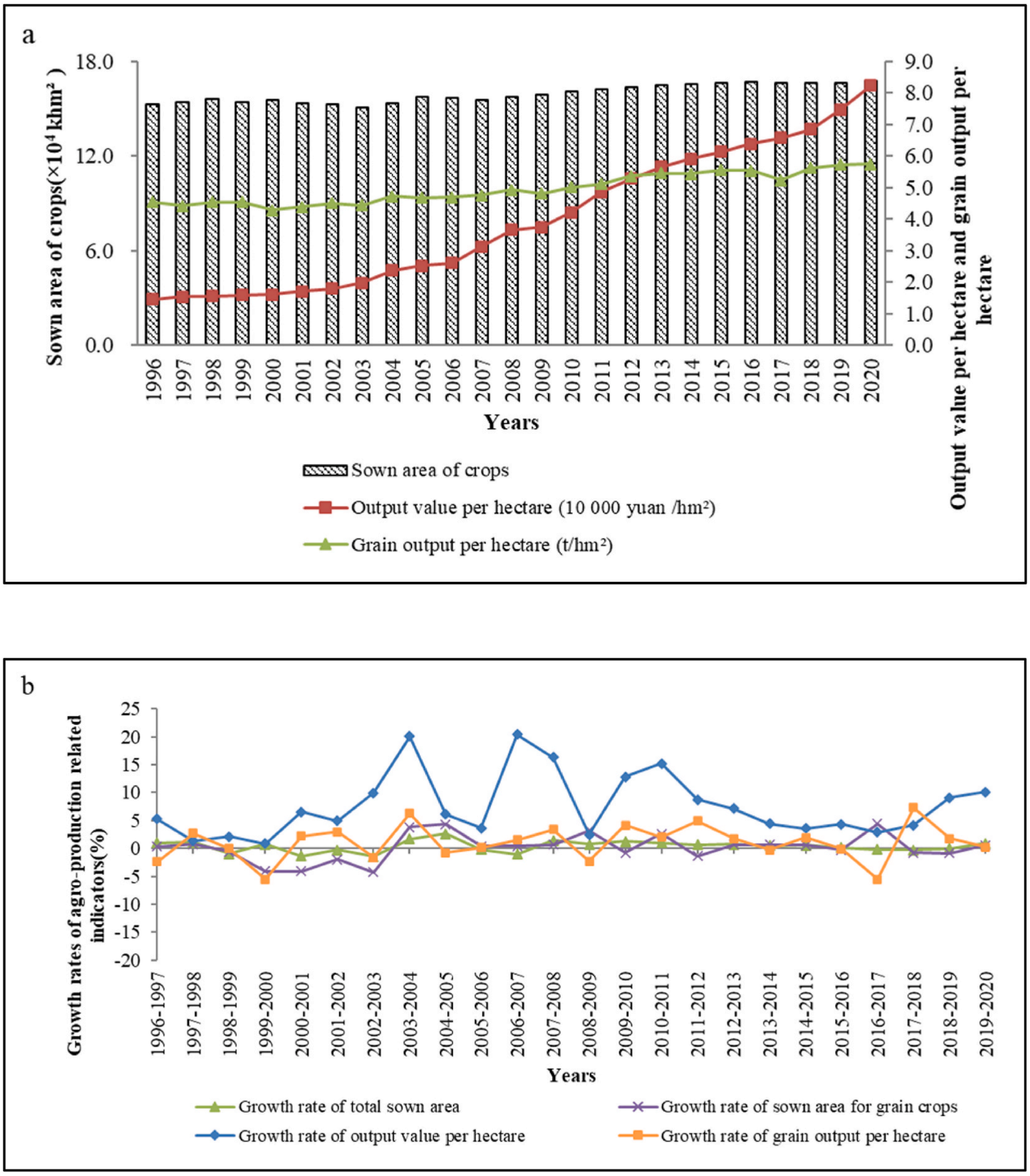

Fig. 1. Agricultural land-use in Mainland China from 1996 to 2020.

emission peak" per unit of agricultural land later than the whole country (2015). That is, the average carbon emission per unit of agricultural land has reached the highest level and started to decline. Specifically, Tianjin, Hebei, and Shandong reached their "peak carbon emissions" in 2007, which may be attributable to the stringent environmental policies implemented in the Bohai Economic Rim. In short, Mainland China's agricultural carbon emissions situation is not optimistic. The average carbon emissions of agricultural land in most provinces are increasing, and the emissions are significant. The situation in the eastern region is worse than in other areas; Provinces that have entered the reduction stage generally start late. Therefore, we guess that the more resistance to reducing agricultural carbon emissions in Mainland China. Facing a series of challenges, there are issues related to the uneven distribution of carbon emissions among regions.

According to the calculation result of equations (1) and (2) , In terms of agricultural land-use efficiency, four periods showed particularly noticeable changes, which were 1996–2000, 2004–2011, 2011–2017, and 2017–2020, respectively (Fig. 3). From the perspective of stage, the annual average of changes in carbon emissions per unit of agricultural-land showed an overall reduction, and the first province to reduce carbon emissions was Hebei in 2004–2011 (Fig. 3b). Specifically, agricultural carbon emissions in Zhejiang, Guangdong, Hainan, and Fujian fluctuated wildly, with high emissions in 1996–2011 (Fig. 3a–b) and rapid emissions reduction in 2017–2020 (Fig. 3d). This may be related to the fact that these areas do not focus on agriculture and can rapidly change the mode of

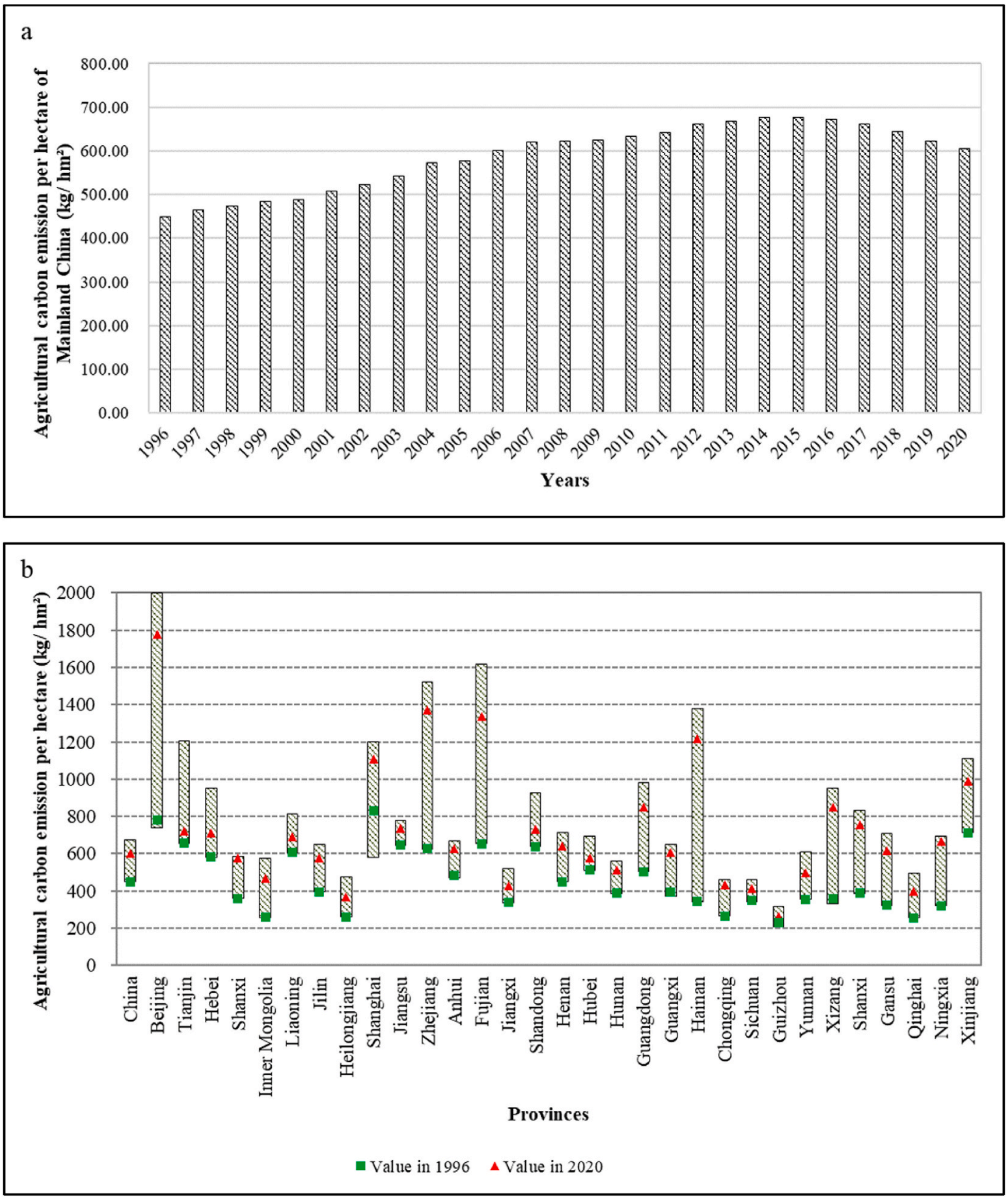

Fig. 2. Spatio-temporal evolution of agricultural carbon emissions in Mainland China from 1996 to 2020.

agricultural production. It could also be due to structural adjustments in agricultural production, the implementation of new agricultural technologies, improved fertilizer utilization efficiency, and more effective agricultural management practices.In addition, the average agricultural carbon emissions in Beijing are relatively high, Beijing's high carbon emissions can be seen in 2011–2017 (Fig. 3c), while only Beijing experienced a carbon increase during 2017–2020 (Fig. 3d). Among the 13 provinces with low emission reduction, 8 are central agricultural provinces, which indicates that rapid carbon decoupling cannot be achieved under the promotion of agricultural production.[1]It may be due to the characteristics of agricultural structure or constraints in agricultural production methods. These regions may require more efforts to achieve the goal of reducing agricultural carbon emissions.

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[1] There are 13 major grain producing areas in Mainland China, including Heilongjiang, Henan, Shandong, Sichuan, Jiangsu, Hebei, Jilin, Anhui, Hunan, Hubei, Inner Mongolia, Jiangxi, Liaoning.

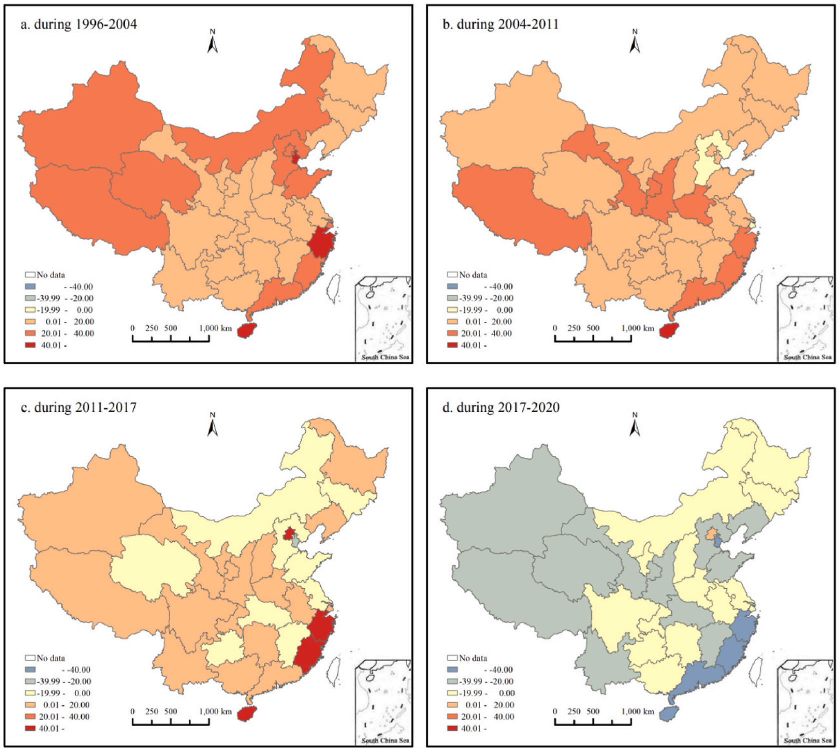

Fig. 3. Spatial pattern of annual average of changes in carbon emissions per unit of agricultural-land.

3.2. *The spatio-temporal evolution of agricultural land-use efficiency under carbon emission constraint*

According to the calculation result of equation (3), Mainland China's agricultural land-use efficiency under the constraints of carbon emissions (*MI*) showed a fluctuating trend during 1996–2020. Specifically, the *MI* in 1996–2020 was 1.043, and the average yearly growth rate was 0.46% (Fig. 4). The *MI* fluctuated between increase and decrease during 1996–2006. Still, through careful analysis, it was found that the growth rate of average grain yield per land area decreased in 2002–2003 and 2004–2005, while the change in *MI* was just the opposite. Therefore, the fluctuation during this period may be due to the significant carbon emissions associated with agricultural production. Despite the trend of increasing production in agriculture, *MI* did not show a growth state under the comprehensive evaluation of unexpected and expected outputs. Fig. 4 shows that after 2009, *MI* remained stable at levels above 1, although it decreased in 2008–2009, 2011–2012, and 2016–2017, but overall it showed a fluctuating upward trend. From 2017 to 2018, it increased to 1.15 (the maximum value), and then decreased to around 1.10. The *MI* shows an overall upward trend. From the perspective of decomposition, it can be seen that this is closely related to the driving effect of *TC* (Technical Efficiency). When *TC* is higher than 1.10, *MI* is higher than 1.08. Therefore, the role of technical efficiency in promoting the improvement of land use efficiency.

Based on the natural breakpoint method, it is found that the first echelon of the improvement of *MI* is constantly expanding in fluctuation. The overall land use efficiency from 1996 to 2004 was relatively low. High efficiency areas appear in Beijing, Tianjin, Zhejiang, Fujian, Xinjiang, and Tibet (Fig. 5a), presenting a relatively scattered layout. From 2004 to 2011, there was a general improvement in efficiency nationwide, but it was mainly led by the eastern region (Hebei, Jiangsu, and Zhejiang), with 3/5 of the high-efficiency provinces located in the eastern region (Fig. 5b). From 2011 to 2017, there was another overall decrease in efficiency, with the advantages of the eastern region spreading to the northeast region (Fig. 5c). From 2017 to 2020, the high-efficiency circle converged with neighboring provinces such as Henan, Hebei, and Shaanxi, and agricultural land use efficiency gradually moved northward. Low efficiency areas were mainly located in the western region (Fig. 5d). Specifically, *MI* has roughly gone through the process from giving priority to the advancement of eastern provinces (during 2004–2011), to an overall decrease in land use efficiency (2011–2017), and then to an overall northward shift in high-efficiency areas (2017–2020).

PEC, SEC and TC jointly affect MI during 1996–2004. They alternately promote the improvement of MI. In terms of the contributions of TC to MI during 2005–2020, TC exhibited basically the same trend over time as MI (Fig. 4). The average values of PEC, SEC, and TC are 1.014, 1.013, and 1.018, and the average annual growth rate are −0.33%, −0.48% and 1.15%, respectively, indicating that a more significant part of the increase in Mainland China's agricultural land-use efficiency came from technical change, that is, Mainland China has constantly enhanced its technical inputs and management approaches in the process of agricultural land-use. It shows that the prominent driving role of TC for MI has formed a steady state, and the improvement of agricultural land-use efficiency needs to continue to promote TC. In terms of temporal evolution, under carbon emissions constraint, Mainland China's agricultural

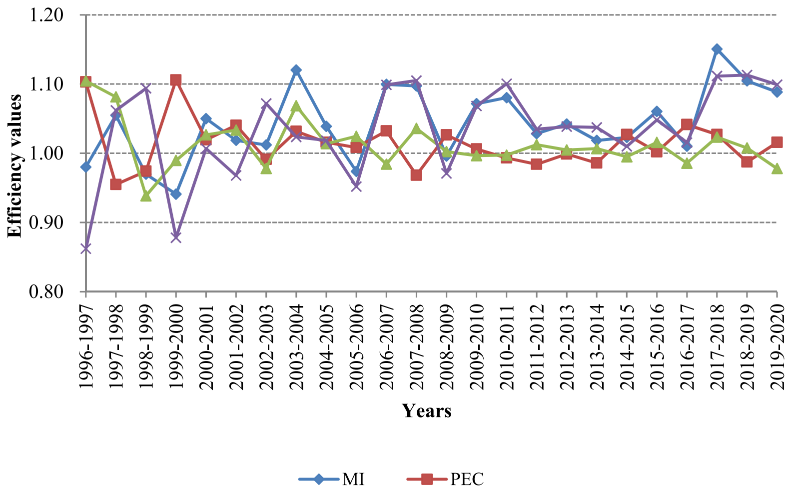

Fig. 4. Agricultural land-use efficiency in Mainland China from 1996 to 2020 (MI refers to Malmquist Index, PEC refers to Pure Technical Efficiency, SEC refers to Scale Efficiency, TC refers to Technological Efficiency).

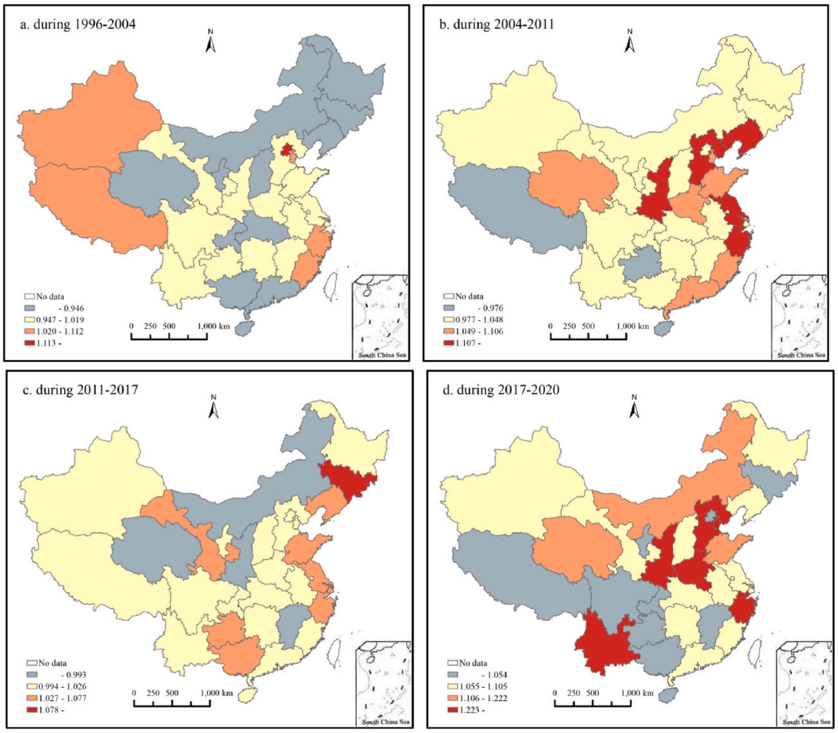

Fig. 5. Spatial evolution of annual average MI.

land-use efficiency growth in the past 25 years has been driven by technical change. That is, technical inputs and management approaches have promoted an increase in land-use efficiency. However, there is still much room for improvement in the degree of attention to technical inputs and management approaches. The TC has shown significant fluctuations over time, with maximum and minimum values being 1.113 and 0.862, respectively, indicating relative instability in technical progress and management amidst land use.

3.3. Analysis of agricultural land-use efficiency under carbon emission constraint based on the division of grain production and marketing relationship

Since 2012, Mainland China has been facing a severe food security crisis. From a demand perspective, Mainland China's food consumption has shown a solid growth trend without any sign of a decrease over the short term. From a supply perspective, the growth rate of Mainland China's grain output has exhibited downward fluctuations due to a gradual decrease in sown agricultural land caused by land abandonment and problems with grain importation caused by deteriorated foreign trade conditions[23]. Against this backdrop, Mainland China's agricultural development in the future should attach equal importance to the ecological goal of reducing carbon emissions and the production goal of effectively the yield[24]. That is, not only should carbon emissions from agricultural production factors should be reduced, but the quantity of inputs in agricultural production factors should not be significantly reduced. Therefore, the only operable development route is to increase the agricultural land-use efficiency. Mainland China has made efforts in many fields. For example, the utilization rate of fertilizers and pesticides in grain crops, such as wheat, rice and corn, has reached somewhere around 40% with an annual growth rate of 1% in recent years, indicating an increase in the efficiency of fertilizer and pesticides inputs and thus a potential decrease in carbon emissions arising therefrom.

To ensure the gradual increase of grain production capacity, Mainland China has divided the prominent grain-producing area (13 provinces), the balance area (7 provinces), and the prominent grain-selling area (11 provinces) according to the natural resource endowment (Fig. 6).

As can be seen from the *MI* during 1996–2020, *MI* in the prominent grain-selling area was lower than the national average in only 4 years, while *MI* in the prominent grain-producing area and the balance area were lower than the national average in 13 and 16 years, respectively. The average *MI* in the prominent grain-selling area during 1996–2020 was as high as 1.071, which was significantly higher than that in the prominent grain-producing area (1.039) and the balance area (1.030). However, it is particularly noteworthy that the *MI* in grain producing areas has shown a continuous decline since 2017. This may be due to the increased pressure on agricultural output value and grain production in the prominent grain-selling area, so special attention is paid to agricultural land-use efficiency [19].It could also be due to the increasing pressure on land resource utilization, and inappropriate or inadequate agricultural policies, land planning, and resource allocation policies may also impact the efficiency of agricultural land use. However, agricultural land-use efficiency comes from the poor driving force of the pure technical efficiency change (*PEC*) and the technological progress change (*TC)*, whose average values are the lowest, indicating that the prominent grain-selling area's technical efficiency and technical level need to be further improved (Fig. 7).

3.4. Analysis of policy factors on technological progress change

Since technological progress change has a high promotion effect on agricultural land-use efficiency, according to the calculation results of equation (4), the impact of policy factors on technological progress change is further analyzed from 1996 to 2020 (Table 3).

The results show that: i) Fiscal agricultural investment intensity showed a significant negative correlation, indicating that each percentage point increase in the proportion of financial agriculture investment per unit of the agricultural-land area will result in a decrease in the technological progress of 0.001. ii) Farmer income level showed a positive correlation. For every 10000 yuan increase in farmers' income, technological progress will increase by 0.070. This is because the improvement of agricultural technology needs sufficient financial support. The increased income of farmers can be used to increase capital investment in agricultural production technology, promote scientific and technological progress, and thus promote agricultural land-use efficiency. Financial agricultural

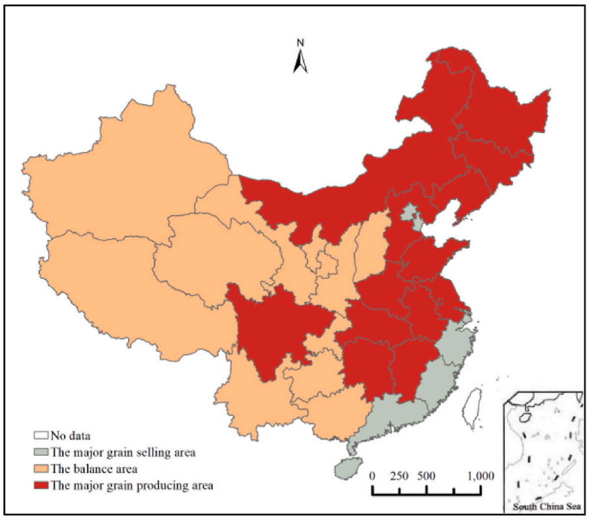

Fig. 6. Regions division of grain production and marketing relationship.

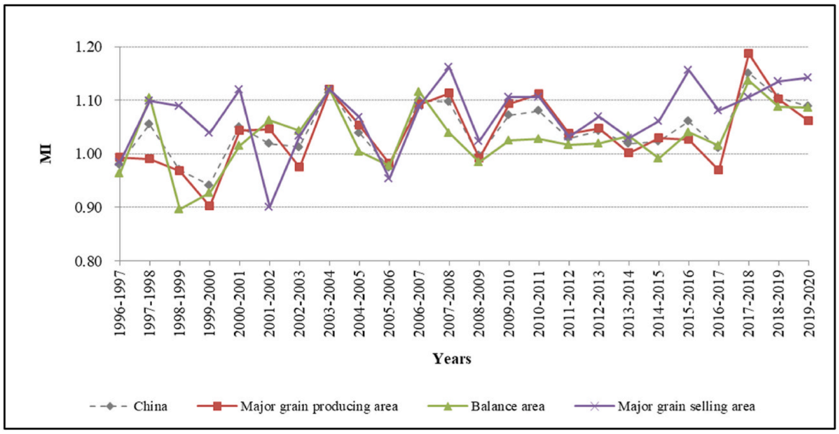

Fig. 7. *MI* of the division of grain producing and selling relationship from 1996 to 2020.

Table 3

The regression results of policy factors.

Variable	Min	Max	Mean	Coef.	Std. Err.
Fiscal agricultural investment intensity	0.36021	85.77757	6.00616	−0.00126*	0.00057
Government investment in science and technology	1.04295	143.07540	34.07988	0.00022	0.00031
Farmer income level	0.11850	3.49110	0.72757	0.06954***	0.01025
Chemical fertilizer input subsidy	−1	1	0.12500	0.01695***	0.00653
Constant term				0.98006***	0.01169
σ_u				0.02746	
σ_e				0.12274	
ρ				0.04768	

Note: *, ** and *** indicate significant levels at 10%, 5% and 1%, respectively.

investment may be primarily directed towards traditional infrastructure, land, or agricultural production methods, with less emphasis on technological innovation. In this scenario, although investment has increased, the driving force for technological progress is relatively weak. The government may be more focused on enhancing agricultural production quantity through direct financial support, neglecting the potential benefits of technological innovation in improving agricultural efficiency and quality.iii) Chemical fertilizer input subsidy showed a positive correlation. However, the chemical fertilizer input subsidy policy has encouraged agricultural development expectations (expected output) and agricultural carbon emissions (unexpected output). However, from the perspective of the effect of chemical fertilizer input subsidies on agricultural technology progress, chemical fertilizer input subsidies have played a role in promoting agricultural technology progress. It may be because, in the process of policy from zero to incentive and then to control, chemical fertilizer enters agricultural production with the elements of agricultural technological progress, and the incentive of subsidies to chemical fertilizer input behavior leads to the improvement of technological advancement. Another possible explanation is that farmers will not have a clear direction of fertilizer input when using subsidies and may invest in other agricultural technologies, causing agricultural technology progress.It may also be because fertilizer input subsidies can be seen as a form of financial support, providing a financial foundation for agricultural technological innovation. This may include funding for the research and development of more advanced fertilizer technologies, the cultivation of new varieties, or funding for training and education. Such financial support helps create an environment conducive to innovation, driving the continuous development of agricultural technology.

4. Conclusion and discussion

Utilizing the super SBM-undesirable DEA model, this paper presents a static analysis of Mainland China's agricultural land-use efficiency from 1996 to 2020 based on the constraints of carbon emissions. In the meantime, adopting the *MI* model, this research estimated the dynamic total factor productivity index and its decomposed indexes and examined their spatio-temporal evolution. The following conclusions are drawn.

i) The average agricultural output value per unit of land and average grain yield per unit of land between 1996 and 2020 have both exhibited an upward trend. Fig. 1b shows that, from the perspective of the growth rate of average agricultural yield per unit of land, the growth of average agricultural yield per unit of land can be roughly divided into 4-stage encompassing increase in growth rate fluctuation (1996–2004), sharp fluctuation in high growth rate (2004–2011), sustained and slow decrease in growth rate (2011–2017), and annual increase in growth rate (2017–2020). In contrast, the growth rate in average grain yield per unit of land has shown considerably less fluctuating. Further, the situation of agricultural carbon emissions in Mainland

China is less than satisfactory: a majority of provinces have their average carbon emissions per unit of agricultural land increased, coupled with significant total emissions. In contrast, the control over reducing average carbon emissions per unit of agricultural land in the Bohai Economic Rim started relatively early. This finding suggests that, although the increase in agricultural output and grain production has made a positive contribution to the agricultural economy, there is a need for greater attention to agricultural carbon emissions issues and the formulation of corresponding sustainable development strategies.

ii) Mainland China's agricultural land-use efficiency under the constraints of carbon emissions (MI) showed a fluctuating trend during 1996–2020. Specifically, the MI in 1996–2020 was 1.043, and the average yearly growth rate was 0.46% (Fig. 4).The land use efficiency shows a trend of first overall improvement and then partial decline nationwide (Fig. 5). *MI* has roughly gone through the process from giving priority to the advancement of eastern provinces (during 2004–2011), to an overall decrease in land use efficiency (2011–2017), and then to an overall northward shift in high-efficiency areas (2017–2020).This complex dynamic variation indicates that the agricultural land use efficiency in mainland China is influenced by various factors, including regional disparities, policy changes, and carbon emission constraints. Conducting in-depth research into these trends will aid in better understanding the evolution of land use efficiency and provide targeted policy recommendations for future agricultural sustainable development.

iii) Mainland China's agricultural land-use efficiency based on the carbon emissions constraint experienced a fluctuating trend. The average *MI* in the prominent grain-selling area during 1996–2020 was as high as 1.071, significantly higher than that in the prominent grain-producing area (1.039) and the balance area (1.030). Technical progress change is the decisive route for the increase in overall efficiency, especially after 2005. However, technological progress and management in land use are relatively unstable. Agricultural land-use efficiency comes from the poor driving force of *PEC* and *TC*, whose average values are the lowest, indicating that the prominent grain-selling area's technical efficiency and technical level need to be further improved. This research emphasizes the critical importance of technological innovation and management levels, especially in the primary grain-consuming regions, providing valuable insights for achieving higher levels of agricultural sustainability. Future research and policy formulation should focus on how to enhance technological efficiency and management levels in these areas, in order to better adapt to the constraints imposed by carbon emissions.

iv) Fiscal agricultural investment intensity showed a significant negative correlation, indicating that each percentage point increase in the proportion of financial agriculture investment per unit of the agricultural-land area will decrease the technological progress by 0.001. On the other hand, farmer income level and chemical fertilizer input subsidy showed a positive correlation. It may be because chemical fertilizer enters agricultural production with the elements of agricultural technological progress, and the incentive of subsidies to chemical fertilizer input behavior leads to the improvement of technological progress; another possible explanation is that farmers will not have a clear direction of fertilizer input when using subsidies, and may invest in other agricultural technologies.This suggests that the use of agricultural subsidies may be guided to some extent by farmers' own decision-making and demands, requiring further in-depth research to fully understand the impact mechanisms of agricultural subsidies on technological progress. These findings offer insights into the relationship between fiscal agricultural investment and farmers' decision-making behaviors, providing references for future policy formulation, especially in promoting sustainable agricultural development and enhancing agricultural productivity

Under the guidance of the "carbon neutralization and carbon peak" target, Mainland China is in a crucial stage of vigorously controlling its carbon emissions; the considerable spatial difference in agricultural land-use efficiency and driver model will require the government to establish differentiated policy measures in its policies on agricultural carbon emissions.Firstly, guiding the transformation of agricultural production methods, encouraging sustainable agricultural practices, and promoting the adoption of efficient resource utilization technologies can better control carbon emissions. In response to the overall declining trend in the annual changes in carbon emissions from agricultural land, it is important to further investigate the reasons for the decline in carbon emissions in provinces such as Hebei and apply these successful experiences to other regions. For regions with significant fluctuations in agricultural carbon emissions, such as Zhejiang, Guangdong, Hainan, and Fujian, it is necessary to effectively reduce agricultural carbon emissions through the establishment of relevant monitoring and evaluation systems. Strengthening control over agricultural carbon emissions in key grain distribution areas such as Beijing is crucial, seeking a balance between agricultural land use and carbon emissions.Second, technical innovation and management improvement in agricultural production should be advanced with attention focused on technical progress in agricultural structure adjustment and effective improvement of agricultural land-use efficiency. Emphasizing the low efficiency of agricultural land use in some areas of the western region and major grain producing areas in recent years, priority should be given to rapid developments in the Western Region to promote the "high-quality development" of low-carbon and high-yield agriculture. Large-scale agricultural economies should be maintained at an appropriate level to guide a reduction in inputs associated with high carbon emissions, such as pesticides and fertilizers, in agricultural production, encourage mechanical inputs, and implement a fallow system to alleviate the pressure of reduction in agricultural carbon emissions. Third, infrastructural construction should be enhanced, and the government should step up its effort to compensate for the declined margin returns from households' inputs in land use intensification. Regarding spatial differences, resource allocation should be optimized to advance the construction of agricultural projects like water conservation to improve agricultural land-use efficiency. Finally, agricultural support policies should be adjusted to shift the intensity of agricultural investment into sustained support for investment subsidies such as fertilizers, and various means should be used to effectively increase farmers' income.\

Funding

This research was funded by the National Natural Science Foundation of China (Grant No. 42001249) and the National Social Science Foundation of China (21BJY133).

Data availability statement

The data related to my research has been stored in a public database, and it will be provided as requested.

CRediT authorship contribution statement

Jianhui Yang: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Rui Ma:** Writing – review & editing, Visualization. **Lun Yang:** Writing – review & editing, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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