Ecological efficiency of hog scale production under environmental regulation in China: based on an optimal super efficiency SBM-Malmquist–Tobit model

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Abstract
China’s hog production is facing the dual pressures of the market and environment. A systematic analysis of the ecological efficiency (eco-efficiency) of hog cultivation is of great significance for the development of sustainability and distribution optimization in the industry. This paper investigates the eco-efficiency of hog production and the determinants of eco-efficiency in China using panel data (2004–2018). An optimal super efficiency slacks-based measure (SBM)-Malmquist–Tobit model is adopted for hog production analysis, and the empirical results show a great variation in eco-efficiency across provinces, ranging from 0.557 to 1.19 with a mean value of 0.937 in 2018. The predominant production area of hogs is found being transferred from north to south, with small- and medium-scale predominant production areas shifted from East China to Southwest China, and large-scale predominant production areas shifted from North China to South Central China. Another finding is that eco-efficiency increased by the improvement of technical efficiency. In addition, the Tobit regression results show that rural economic development, the government’s investment in environmental control, the market advantage index, and transportation conditions had positive effects on the eco-efficiency; meanwhile, the forbidden policy for livestock cultivation in certain areas, the structure of the hog breeding industry, the density of slaughtered fattened hogs, and the prices of hogs had negative effects on the eco-efficiency.

Keywords Ecological efficiency · Hog production · Environmental regulation · Optimized super efficiency SBM-Malmquist–Tobit model · China

Introduction
China is the world’s largest pork consumer and hog producer. The development of the hog breeding industry is of great significance to stimulating rural economic growth, ensuring the market supply, and promoting the stability of social development. Since the occurrence of African swine fever, China’s hog breeding industry has experienced a tightening trend of supply. Compared with 2018, China’s domestic pork production was reduced by 21.25% in 2019. Although imports of pork increased by 45.19%, when excluding exports, there was still a supply gap of 18.6% (about 10.3894 million tons). After the occurrence of COVID-19 in 2020, China’s domestic pork production is further reduced by 3.3%, which led to a sharp increase in pork prices (the data are from the China Statistical Yearbook, NBSC 2005–2020, and the Ministry of Agriculture and rural areas information website of the People’s Republic of China). Improving the efficiency of hog production is the key means to stabilize the market supply, while the continuous development of scale farming provides conditions for the improvement of production efficiency. Data show that the number of scale farms with more than...
500 slaughtered fattened hogs rise to 215,502 in 2017 (China Animal Husbandry and Veterinary Yearbook, AHVYEBBC 2018). China’s hog production is undergoing a great transformation from the small backyard, household-based farms towards large-scale breeding zones (Qiao et al. 2016).

However, environmental problems as a consequence of intensive hog feeding operations are gradually increasing. A significant feature of intensive feeding operation is production in scaled farming while resulting in large volumes of hog manure within small areas (Azzam et al. 2015). Under certain circumstances, hog manure can be a valuable source of fertilizer for crop production (Fleming et al. 1998). However, excessive volumes of manure boost the cost and are difficult to manage (Weiss and McMichael 2004) and inevitably seriously increase the risk of bad air quality through odor (Schiffman and William 2002), soil contamination, and ecosystem destruction and thus affect human and animal life (Ni et al. 1999; Heederik et al. 2007). Accordingly, there has also been an increase in the number and stringency of environmental regulations on the management of the hog breeding industry. The government has successively introduced prohibitions and restrictions policies for livestock cultivation in certain areas and put forward new development goals for hog production. The no. 1 central document formulated by China State Council (CSC 2013) in 2013 explicitly proposed conducting control efforts to prevent agricultural nonpoint source pollution and livestock farming pollution. In 2015, the Chinese government formulated the action plan for the prevention and control of water pollution (CSC 2015), which required local governments to scientifically demarcate forbidden areas of livestock farming and to close or relocate farms in forbidden areas by the end of 2017. The guiding opinions on promoting the adjustment and optimization of the distribution of pig breeding in the southern water network area (MAC 2015) and the National Development Plan for Hog Production (2016–2020) (MAC 2016) issued by the Ministry of Agriculture of China proposed to adjust hog breeding industry layout from the perspective of ecological environment. And thereafter, how to reduce environmental pollution and improve ecological efficiency (hereinafter referred to as “eco-efficiency”) while also achieving the development of the hog breeding industry has become the focus of social concern.

Eco-efficiency was firstly proposed by Schaltegger and Sturm (1990), usually be defined as the ratio of economic output to ecological input, and serves as a measurement of how efficient the economic activity is concerning its ecological impacts (Schmidheiny and BCSD 1992; Zhang et al. 2021). In this sense, the improvement of eco-efficiency means creating higher economic efficiency with a smaller investment of resources while reducing environmental pollution (Becker 2011; Zhang et al. 2017). Specifically, the eco-efficiency of the hog breeding industry can be improved through the following two aspects: increasing the benefit of scale output by technical efficiency and reducing pollution emission by technology innovation. At the national scale, production adjustments with the goal of eco-efficiency improvement are conducive to the realization of sustainable development in the hog breeding industry.

Heated discussions have been conducted on how to measure the synergistic growth of productivity and environmental protection. The eco-efficiency provides a reference for the measurement and quantification of the environmental efficiency of the industry. Compared with the traditional total factor productivity (TFP) evaluation method, eco-efficiency incorporates environmental pollution into the indicator system, which reflects the sustainable development of the industry. Regarding how to incorporate environmental factors into the econometric model, the main practices in the existing literature include incorporating pollution control input or environmental constraints as independent variables into the model (Ramanathan 2005) or incorporating environmental pollutant emissions (such as carbon emissions) into the production model as a type of undesired output to estimate the eco-efficiency (Pittman 1983; Chung et al. 1997; Zhao et al. 2015). And some utilized undesired output removal as a proxy for output in pollution (Yang et al. 2008; Yang 2009).

Early research mainly used the radial and angular data envelopment analysis (DEA) model (contains Charnes–Copper–Rhodes (CCR) model (Charnes et al. 1979) and Banker–Charnes–Cooper (BCC) model (Banker et al. 1984)) to estimate eco-efficiency. In the traditional DEA model, input and output factors are defined to vary in the same ratio or radial direction. However, typically, the input and output factors, in reality, do not change with the same proportion or radial direction, which makes a great difference between the theory of the traditional DEA model and the actual situation. Furthermore, DEA efficiency measures are often overestimated when there is excessive input or insufficient output. To improve this shortcoming, Tone (2001) put forward a slacks-based measure (SBM) of efficiency, which is non-radial and deals with input/output slacks directly. Since that usually, plural decision-making units (DMUs) will realize “efficient status,” which makes the efficiency score unity as 1. Therefore, Tone (2002) proposed super efficiency based on SBM (SE-SBM), which can rank the efficient DMUs by defining a DMU as being SBM efficient that provides a new approach to analyze the effects of environmental factor inputs.

Recently, eco-efficiency has been gradually applied to the study of efficiency in agricultural production (Li 2014; Meng et al. 2019). In the research of hog production, Wu et al. (2013) used the output-based directional distance function (DDF) to construct a Malmquist–Luenberger productivity index that accounts for the desired output and undesired output as well as the measured eco-efficiency and endogenous power of the efficiency growth of China’s 16 main hog-breeding
provinces. Based on the same method, Wang et al. (2015) proposed the concept of an environmental technology innovator, made a comparative analysis of eco-efficiency in advantageous hog production provinces, and proposed that environmental regulation would promote the formation of a certain number of environmental technology innovators to promote the outer migration of the production possibility frontier. Zhang et al. (2015) used the stochastic frontier approach (SFA) to calculate the individual technical efficiency and used the radial output technical efficiency (OTE) function to compare the current output with the maximum possible output and to calculate the technical and eco-efficiency of different scales of hog production across provinces. Zuo et al. (2016) constructed a fixed-window-Malmquist–Luenberger (FWML) index containing the undesired output and measured the efficiency of large-scale hog production in China’s 29 provinces based on the variable return to scale (VRS) model from the perspective of the output. Zuo and Feng (2017) analyzed the TFP’s spatial–temporal variation and its convergence of scale hog production in China under the view of environmental regulation using the SML index, spatial autocorrelation, and spatial β convergence analysis methods. Du and Wang (2020) constructed evaluation indication systems for the eco-efficiency of hog scale production and evaluated the eco-efficiency of different scales of 17 main hog production provinces in China, applying a non-radical and non-oriented SE-SBM model, and discussed the appropriateness of the hog breeding scale.

The existing research has provided many experiences for the measurement methods of eco-efficiency and enlightenment. However, there are still some improvements needed in the following aspects. First, previous studies only provided the decomposition and calculation value of eco-efficiency, and there are few works on the analysis of the influencing factors of eco-efficiency in hog production of different scales, which would reduce the persuasiveness of the research conclusions and the correctness of the policy recommendations (Wang et al. 2015). Second, undesired output occurs in the whole hog cycle, and the environmental constraints can only act as shock variables to describe changes in the external environment, and a method that only incorporates environmental constraints or undesired output into the econometric model to calculate the eco-efficiency cannot be a complete description of reality.

Based on the discussion earlier, the marginal contributions of this paper are as follows: first, to strengthen the credibility of research conclusions and provide empirical evidence for subsequent policy enlightenment, we conducted Tobit regression to analyze the influencing factors of eco-efficiency in the hog industry. Second, we incorporated an undesired output and environmental constraints into the analysis framework simultaneously to analyze the eco-efficiency of the hog industry and its influencing factors to be closer to the actual production conditions. Third, we used the net value of hog production as the desired output. Some studies used the net weight of hogs to express the desired output; however, in reality, interest is the main influencing factor for farmers in deciding on the breeding behavior. Therefore, based on the selection experience of output indicators in the existing literature on the efficiency of livestock farming, this paper chose the net value of hogs as the desired output (Reinhard et al. 1999; Geng and Li 2013; Han et al. 2019), which provides a new discussion perspective for the study of hog production efficiency.

Changes in hog production areas

The changes in the distribution of pork production in China’s 30 provinces in 2004 and 2018 are shown in Fig. 1. From 2004 to 2018, China’s hog production was mainly concentrated in South Central and Southwest China, with a further trend of concentration and agglomeration. In 2018, the eight main hog-producing provinces in China were Henan, Hubei, Hunan, and Guangdong in South Central China; Sichuan and Yunnan in Southwest China; Hebei in North China; and Shandong in East China.

Compared with 2004, the proportion of pork production in North, East, and Southwest China out of the country’s pork production declined by 18.81%, 0.24%, and 8.35%, respectively (the total national production is the total value including Tibet). Pork production in South Central China accounted for 34.24% of the country’s total output (31.1% in 2004), and this demonstrated a 10.07% increase over 2004, while the proportion in the north decreased by 28.81%. This indicates that there was a shift of hog production from North to South Central China and a spread to the surrounding areas with the south central as the primary production area.

In terms of the growth rate, hog production in Shanghai, Guangxi, Xinjiang, and Jiangxi developed rapidly and increased by 93.49%, 63.16%, 55%, and 50.88%, respectively. However, while Shanghai’s pork production increased a great deal, its gross production was relatively small with 113,000 tons in 2018. Pork production in Beijing, Zhejiang, and Tianjin dropped significantly, reaching 57.57%, 41.5%, and 35.85%, respectively. Only Heilongjiang essentially maintained the previous production (with a growth rate of 0.27%).

Hog production in China demonstrated a shift from the north to the south (especially to the south central of China) from 2004 to 2018. This is inconsistent with the conclusion of Hu et al. (2005) regarding the shift of pork production from the south to the north of China from 1980 to 2002. The classification of provinces in the regional division is slightly different; thus, in the present study, we only analyzed the significant trend. This different result can be explained by the change of the advantage of feed production in North China.
and the industrial function of provinces. Before 2002, the southwest (25.68%) and north (24.31%) of China were the main producing areas, and the growth rate of North China ranked first in the country. However, with the improvement of transportation convenience, the decrease in transportation cost weakened the advantage of the feed-producing areas in North China. In 2018, due to the sharp decline in the production of Beijing and Tianjin, the proportion of pork production in North China dropped significantly. As the administrative capital and surrounding areas, environmental regulation in
Beijing and Tianjin are more stringent, and the rapid cost growth of land, labor, and other inputs lead to a shift in pork production to other regions. Thus, compared with the trend of hog production from the south to the north before 2002, this trend reversed after 2004. In addition, on the basis of 2002, the main hog production provinces added Yunnan and Hubei in 2018.

Methodology

To calculate and decompose the eco-efficiency of specific environmentally detrimental outputs, two steps are usually taken. First, the optimal SE-SBM model is used to calculate the eco-efficiency; second, the Malmquist–Luenberger index is decomposed to describe the dynamic trend characteristics of the eco-efficiency. The Tobit regression function was also used to analyze the influencing factors on eco-efficiency at different scales in hog production.

Optimal SE-SBM model

The process of hog production not only obtains the desired output but also brings certain undesired outputs that have negative external effects on the environment. Färe et al. (2007) constructed an environmental production set that considered both the desired output and undesired output; this set reflects the input–output technological structure, including all types of outputs.

Suppose that there exist DMUs in the production system, and each DMU has three types of elements: input factor \( (m) \), desired output \( (Y_g) \), and undesired output \( (Y_b) \). The DMU can be expressed by a vector as \( x \in R^m, y^d \in R^n, y^b \in R^o \). We define the matrices \( X, Y^d \), and \( Y^b \) as \( x = [x_1, \cdots, x_n] \in R^m \times n, Y^d = [y^d_1, \cdots, y^d_n] \in R^n \times n, \) and \( Y^b = [y^b_1, \cdots, y^b_n] \in R^o \times n \), where \( X \) is the eco-efficiency value of hog production; \( S^g \), \( S^b \), and \( S^o \) are slack variables of the input variables, desired output, and undesired output, respectively; \( x, y^d, \) and \( y^b \) are input, desired output, and undesired output values, respectively; and \( o \) is the DMU being evaluated. To ensure that the denominator is not zero, \( \varepsilon \) is non-Archimedean infinitesimal.

Malmquist–Luenberger index

Malmquist (1953) first proposed the Malmquist index, as a kind of consumption quantity index. Based on the theory of Malmquist, Caves et al. (1982) proposed a Malmquist productivity index. And then, Färe and Norris (1997) decompose the Malmquist productivity index into the rate of technical progress and the rate of change of technical efficiency. After that, the Malmquist productivity index has been popularly applied in multiples study areas. Chung et al. (1997) further develop the Malmquist productivity index to Malmquist–Luenberger (ML) index which contains environmental factors. The Malmquist–Luenberger (ML) index not only includes the Malmquist index’s requirement for increasing desired output, but also takes environmental factors into account and requires that undesired output continue to decrease.

To analyze the dynamic trend characteristics of eco-efficiency in hog production, we drew on the theory of Malmquist–Luenberger (ML) index and decompose it into the rate of technical progress and the rate of change of technical efficiency. The specific decomposition formula is as follows:

\[
\rho^* = \min \left( \frac{1 + \frac{1}{m} \sum_{s=1}^{m} S^g_s}{1 - \frac{1}{S_1 + S_2} \left( \sum_{j=1}^{n} \frac{Y^g_{ij} S^g_j}{Y^b_{ko}} + \sum_{k=1}^{o} S^b_k \right)} \right) \\
\]

where Eq. (2) is a super-efficiency SBM model based on the assumption of variable returns to scale, and \( \rho^* \) is the eco-efficiency value of hog production; \( S^g \), \( S^b \), and \( S^o \) are slack variables of the input variables.
\[ M_{t+1}^{+1} = \left[ \frac{1 + D_0'(x', y', b', y', -b')}{1 + D_0'(x^{t+1}, y^{t+1}, b^{t+1}, y^{t+1}, -b^{t+1})} \right]^{\frac{1}{2}} \times \left[ \frac{1 + D_0'(x', y', b', y', -b')}{1 + D_0'(x^{t+1}, y^{t+1}, b^{t+1}, y^{t+1}, -b^{t+1})} \right]^{\frac{1}{2}} \]

where \( M_{t+1}^{+1} \) (Malmquist–Luenberger) is the total factor productivity, \( M_{t+1}^{EFFCH} \) presents the technical progress rate, and \( M_{t+1}^{EFFCH} \) denotes the rate of change in technical efficiency. The index is based on the sample technology in period \( t \) and is calculated from the trend of the productivity change in period \( t \) to \( t+1 \). An index value greater than 1 indicates that productivity is on the rise, equal to 1 indicates that there is no change in productivity, and less than 1 indicates that productivity is on the decline.

### The Tobit regression

According to the model setting, the eco-efficiency calculated by the SE-SBM model and the Malmquist–Luenberger productivity index is a truncated segment value or cut value. That means the ordinary least squares (OLS) regressions estimate is inconsistent and biased. Therefore, we chose the Tobit regression model to analyze the impact factors of eco-efficiency in hog production. We propose the following Tobit regression model:

\[ \rho^*_i = \alpha_0 + \sum_{j=1}^{p} \alpha_j x_{ij} + \gamma_i \]

where \( \rho^*_i \) is the latent variable, \( \rho_i \) is the actually observed dependent variable, \( x_{ij} \) presents the independent variable, \( \alpha_0 \) is the constant term, \( \alpha_j \) denotes the correlation coefficient vector, and \( \gamma_i \) is the random error term. In particular, we used the maximum and minimum values of eco-efficiency as the upper and lower cutoff points in the Tobit regression.

### Data

The input and desired output data for the different scales of hog production of 30 provinces in China from 2004 to 2018 used in the present study were directly obtained from the China Agricultural Product Cost-Benefit Compilation (CAPCBC, NDRC 2005–2019), which was issued by the National Development and Reform Commission (NDRC) of China. The cost–benefit data of hog production were collected from individual farms by a three-stage random sampling procedure. The individual farms included traditional backyard households (less than 30 hogs), small-scale farms (raising 30 to 100 hogs), medium-scale farms (100 to 1000 hogs), and large-scale farms (more than 1000 hogs). Due to missing data on traditional backyard households in some provinces, this paper only took small-, medium-, and large-scale farms into consideration. These data contained each slaughtered hog’s weight and value, each piglet’s weight and cost, feeding days, labor inputs (including days and cost), feed usage, water and fuel cost, medical treatment, epidemic prevention costs, and so on (Zhou et al. 2015).
The data of the undesired outputs were from the First National Census of Pollution: Manual of Discharge Coefficient of Livestock and Poultry Industry (FNCP, IEDA, and NIES 2009). These data came from the research of the pollution conditions of the livestock and poultry industry in China as measured by the Ministry of Agriculture of China, the Chinese Academy of Agricultural Science, and the Ministry of Environmental Protection of China. The respondents of this research consisted of specialized households (more than 50 hogs), scaled farms (more than 500 hogs), and raising zones (without definition in breeding scale) in the north, northeast, east, south central, southwest, and northwest of China (The Northern region includes Beijing, Tianjin, Hebei, Shanxi, and Inner Mongolia; the Northeastern region includes Liaoning, Jilin, and Heilongjiang; the Eastern region includes Shanghai, Jiangsu, Zhejiang, and Anhui; Fujian, Jiangxi, and Shandong; the South Central region includes Henan, Hubei, Hunan, Guangdong, Guangxi, and Hainan; the Southwestern region includes Chongqing, Sichuan, Guizhou, Yunnan, and Tibet; and the Northwestern region includes Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang). These data included the chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), copper (Cu), and zinc (Zn) per hog per day. Other data were from the China Statistical Yearbook (NBSC 2005–2020), which is collected by the National Bureau of Statistics and published annually.

The input variables are four conventional input variables. (1) Feeding input: This includes the cost of concentrated feed and the cost of green roughage. We used the feed price index to deflate the depreciation data. (2) Labor input: Tian et al. (2015) used person-days spent on hog production. However, this cannot reflect the changes in labor prices and, thus, cannot properly describe the actual labor costs. Therefore, we used the cost of labor, which includes the conversion cost of family labor and the cost of hired labor. In particular, we deflated the depreciation data using the resident consumption index. (3) Fixed capital input: This includes the depreciation of fixed assets, tool and material costs, repair and maintenance costs, and feed processing costs (Li and Cao 2017). We used the fixed capital price index to deflate the depreciation data. (4) Other inputs: These refer to all material and service costs except the piglet cost, the depreciation of fixed assets, and feeding input. As there are different types of expenses included in “other inputs,” we deflated the depreciation data using the agricultural production material price index. Thus far, almost all the costs of hog production have been included in our input indicators.

In this paper, the desired output variable is the net value of slaughtered fattened hogs for each province. The net value equals the total value (including the value of the main product and the by-products) minus the cost of each piglet. We used the production price deflator of hogs to calculate the real price of the net value, as the production price index measures the trend and degree of changes in the ex-factory price of products. The undesired output was measured by the total amount of the substances that are harmful to the environment in hog manure. We considered the hog manure emissions with different clean methods, including dry clean manure and water flush manure. Zhang et al. (2005) considered the ratio of dry clean manure and water flush manure as 8:2. In the present study, we are concerned with the aggregate undesired output of every hog; hence, we propose the following equation:

\[
QP = \sum AD \times (0.8PD_{a1} + 0.2PD_{a2}) \times (W/W_0), \quad a = 1, 2, \cdots, 5
\]

where \(QP\) is the undesired output; \(AD\) is the average raising days where raising days are the number of days the hog is fattened until reaching slaughter weight; \(PD_{a1}\) and \(PD_{a2}\) are the pollutant discharge coefficients of the \(a\)th pollutant in the dry manure and water flush manure, respectively; \(W\) denotes the actual weight of hogs; and \(W_0\) presents the reference weight. Previous literature usually related the small-scale, medium-scale, and large-scale farms in CAPCBC (NDRC 2005–2019) to the specialized households, scaled farms, and raising zones, respectively in IEDA and NIES (2009) (Du and Wang 2020).

Thus, in this paper, we utilized the mean value for input and output factors of different scales, and we discuss the eco-efficiency across 30 provinces in China. In addition, all price data are deflated to 2003 constant prices by the price index. Finally, a total of 1239 samples were obtained. We used the MaxDEA pro software to solve the SE-SBM model and obtain the annual eco-efficiency in each province. The description of variables is reported in Table 1.

As Table 1 shows, for all types of inputs, except for the total feeding cost, the mean value of each input at the small scale was higher than in other scales, reflecting that the average cost can be reduced through large-scale production. The undesired output level was not significantly different among different farming scales, and the medium scale was the lowest. The standard deviation of the desired output was large, indicating that there were great differences across provinces. Among all scales of farms, the small-scale farms had the highest desired output, which can be explained by the large input. The desired output at the medium scale was higher than that at the large scale, while the cost of inputs was less than that at the large scale except for the total feeding cost and labor cost. This shows that the return to scale is not fixed, and, to a certain extent, this reflects the validity of the model in this paper.
Empirical results

Eco-efficiency estimates

The scores of eco-efficiency based on the SE-SBM model are reported in Table 2. In most regions, the eco-efficiency was significantly lower than the TFP; however, the eco-efficiency of East, South Central, and Southwest China rose, which may be attributable to regional differences in the average level of the undesired output. The negative externalities of eco-efficiency were strengthened by the increase in undesired output, and the higher the impact of undesired output, the stronger the negative impact of eco-efficiency. We tested the impact of the undesired output on the eco-efficiency by using the proportion of undesired output/desired output to measure the differences of the undesired output across provinces (the results are reported in Fig. 2). As Fig. 2 shows, the average undesired output in East, South Central, and Southwest China was the lowest and much lower than the national level, while other regions were higher than the national level. This implies that a higher undesired output leads to the decrease in eco-efficiency relative to the TFP, and a lower undesired output below the average level leads to the increase in eco-efficiency relative to the TFP.

Table 1 Summary statistics of variables (per hog)

|                          | Unit | Small scale | Medium scale | Large scale | Total Mean | SD |
|--------------------------|------|-------------|--------------|-------------|------------|----|
| Total feeding cost       | CNY  | 425.726     | 74.085       | 434.507     | 70.592     | 412.494 | 63.41 | 424.2086 | 69.931 |
| Labor cost               | CNY  | 123.811     | 66.577       | 85.266      | 48.132     | 15.453  | 5.172  | 58.092    | 34.432 |
| Fixed capital cost       | CNY  | 15.392      | 5.502        | 15.453      | 5.172      | 17.305  | 7.8    | 16.07     | 6.345  |
| Other inputs             | CNY  | 27.741      | 30.617       | 29.746      | 5.022      | 39.185  | 57.532 | 32.194    | 22.146 |
| Desired output           | CNY  | 651.755     | 97.196       | 646.151     | 90.579     | 606.17  | 97.19  | 634.277   | 97.063 |
| Undesired output         | kg   | 20.247      | 5.211        | 19.746      | 5.022      | 26.674  | 12.584 | 22.27     | 9.023  |

Table 2 Eco-efficiency/total factor productivity (TFP) scores from SE-SBM model across regions, 2004–2018

| Areas in China               | 2004     | 2006     | 2008     | 2010     | 2012     | 2014     | 2016     | 2018     |
|-----------------------------|----------|----------|----------|----------|----------|----------|----------|----------|
| North                       | 0.891/0.945 | 0.79/0.839 | 1.004/1.032 | 0.925/0.96 | 0.874/0.941 | 0.978/0.993 | 0.937/0.996 | 0.861/0.903 |
| Northeast                   | 0.754/0.792 | 0.834/0.792 | 0.815/0.909 | 0.674/0.899 | 0.703/0.77 | 0.799/0.747 | 0.751/0.827 | 0.701/0.762 |
| East                        | 1.117/0.995 | 1.085/0.992 | 1.059/0.961 | 1.052/0.892 | 1.077/0.926 | 1.038/0.912 | 1.052/0.874 | 1.087/1.01 |
| South Central               | 0.941/0.877 | 0.843/0.839 | 0.839/0.817 | 0.903/0.841 | 0.899/0.853 | 1.026/0.961 | 0.904/0.878 | 0.983/0.977 |
| Southwest                   | 0.79/0.846 | 1.043/1.039 | 0.933/0.915 | 1.036/1.025 | 1.044/1.057 | 1.032/1.039 | 1.024/1.033 | 1.048/1.058 |
| Northwest                   | 0.974/0.993 | 1.145/1.172 | 0.919/0.933 | 0.841/0.829 | 0.873/0.869 | 0.766/0.738 | 0.883/0.868 | 0.89/0.896 |
| Average                     | 0.908/0.9 | 0.927/0.929 | 0.93/0.92 | 0.905/0.874 | 0.918/0.887 | 0.943/0.903 | 0.927/0.889 | 0.937/0.936 |

Main hog breeding production provinces in China (2018)

| Henan                      | 0.802/0.732 | 0.712/0.719 | 0.665/0.659 | 0.827/0.673 | 0.791/0.619 | 1.021/0.8 | 0.709/0.677 | 0.809/0.813 |
| Hubei                      | 0.672/0.607 | 0.696/0.734 | 0.719/0.762 | 0.842/0.81 | 0.786/0.776 | 0.852/0.801 | 0.85/0.845 | 0.843/0.8 |
| Hunan                      | 1.249/1.247 | 0.918/0.919 | 0.94/0.979 | 0.906/0.931 | 1.038/1.066 | 1.222/1.249 | 1.142/1.186 | 1.136/1.192 |
| Guangdong                  | 0.911/0.772 | 0.868/0.872 | 0.811/0.835 | 0.758/0.752 | 0.785/0.747 | 0.908/0.824 | 0.74/0.701 | 0.926/0.898 |
| Sichuan                    | 0.896/0.865 | 1.055/1.032 | 1.071/1.06 | 1.101/1.07 | 1.064/1.061 | 0.963/0.966 | 0.951/0.976 | 1.03/1.025 |
| Yunnan                     | 0.804/0.885 | 0.955/0.98 | 0.788/0.822 | 0.997/1.017 | 1.066/0.10 | 0.986/0.99 | 0.98/0.997 | 0.997/0.999 |
| Hebei                      | 0.836/0.885 | 0.793/0.852 | 1.054/1.053 | 1.075/1.077 | 1.049/1.048 | 1.044/1.044 | 0.968/1 | 1.03/1.03 |
| Shandong                   | 0.904/0.843 | 1.026/0.981 | 1.152/0.941 | 1.079/0.813 | 1.124/0.863 | 1.115/0.816 | 1.194/1.016 | 1.339/1.028 |

Complete provincial data are shown in Table 6.
From the perspective of provinces, the eco-efficiency fluctuated and the environmental performance was improved. Among the eight main hog production provinces in 2018, only Hunan’s eco-efficiency ranked the top in the whole country (as no. 3). According to the regional production, the possible reason is that the hog production in the other seven provinces was far beyond the optimal scale, which leads to a decrease in eco-efficiency.

**Decomposition of eco-efficiency growth**

From 2004 to 2018, the eco-efficiency of hog production in China showed a slight upward trend, and the increase in technical efficiency was the main reason for the increase in eco-efficiency. As Table 3 shows, the average growth rate of the eco-efficiency was about 1.1%, while the TFP increased about 1.2% on average. The technical efficiency index (MLEFFCH) of eco-efficiency and TFP were increased about 1.9% and 2% on average, respectively, while the technical progress index (MLTECH) were both increased about only 0.7%.

Combined with the dynamic changes over years, this can be explained by the increased investment in hog production in certain provinces (include the increase in labor costs due to wage increases, the production input for expanding the production scale, etc.), the increase in input improves the output efficiency of the next period since there is a long time cycle in pig breeding, which improves the technical efficiency. However, the inputs cannot translate into revenue completely, which increases the total cost accordingly and restricts the improvement of technological progress. An important factor contributing to the increase in investment in hog farming is the cyclical change in farmer decision behavior around market price changes. As shown in Table 7, the price of pork had a positive effect on the technical efficiency (MLEFFCH) that was statistically significant at the 1% significance level. When the price of pork went up, the profit of breeding was increased, farmers tended to increase their investment in order to obtain more profit, and the technical efficiency was improved. However, the increased input cost cannot fully translate into the current income return, which restricted the current technical progress to a certain extent (the regression coefficient was negative but not statistically significant).

In all six regions of China, as shown in Table 8, the average growth of eco-efficiency of Southwest and South Central China from 2004 to 2018 was 5.56% and 1.56%, respectively, and they were the regions with the highest eco-efficiency growth rate. Southwest China is located in the upper reaches of the Yangtze River, and that makes it become one of the main producing areas of maize in China. Cost advantages of labor, land, and other factors and moderate geographical advantages of temperature and humidity make the southwest area more conducive to hog breeding. Moreover, Southwest China has a suitable breeding density (average breeding density is 4.7755, as shown in Fig. 3), with the highest growth of technical efficiency and technical progress (4.28% and 2.67%, respectively), which drives the rapid growth of eco-efficiency. South Central China was a new rising dominant hog breeding region and with the most increase in pork

| Year  | Eco-efficiency | TFP             |
|-------|----------------|-----------------|
|       | ML  | MLEFFCH | MLTECH |       | Malmquist | MLEFFCH | MLTECH |
| 2004–2005 | 0.861 | 0.938 | 0.942 |       | 0.887 | 0.943 | 0.964 |
| 2005–2006 | 1.195 | 1.153 | 1.082 |       | 1.166 | 1.167 | 1.042 |
| 2006–2007 | 1.084 | 1.010 | 1.088 |       | 1.074 | 1.001 | 1.082 |
| 2007–2008 | 0.740 | 1.054 | 0.719 |       | 0.736 | 1.046 | 0.718 |
| 2008–2009 | 0.990 | 0.969 | 1.049 |       | 0.995 | 0.961 | 1.055 |
| 2009–2010 | 1.207 | 1.051 | 1.161 |       | 1.213 | 1.026 | 1.192 |
| 2010–2011 | 1.038 | 0.993 | 1.053 |       | 1.038 | 1.012 | 1.032 |
| 2011–2012 | 0.831 | 1.031 | 0.810 |       | 0.833 | 1.016 | 0.823 |
| 2012–2013 | 1.058 | 0.999 | 1.064 |       | 1.048 | 0.989 | 1.065 |
| 2013–2014 | 1.007 | 1.045 | 0.972 |       | 1.006 | 1.041 | 0.971 |
| 2014–2015 | 1.126 | 0.978 | 1.156 |       | 1.152 | 0.999 | 1.157 |
| 2015–2016 | 0.909 | 1.005 | 0.910 |       | 0.914 | 0.984 | 0.938 |
| 2016–2017 | 0.951 | 1.035 | 0.925 |       | 0.934 | 1.073 | 0.882 |
| 2017–2018 | 1.150 | 1.006 | 1.161 |       | 1.178 | 1.020 | 1.171 |
| Average | 1.011 | 1.019 | 1.007 |       | 1.012 | 1.020 | 1.007 |

ML is an acronym for Malmquist–Luenberger index
production. It is adjacent to Eastern China, which makes it good for it to introduce new breeding technologies. Henan in South Central China was rich in some of the main feed supplies such as corn and green feed. However, South Central has the highest hog breeding density (average 5.3291 head/km²). Intensive hog breeding operations have a large effect on the marginal cost of production because more land is needed and transportation costs for manure spreading are higher with increased distance. The increase in the cost of manure treatment reduced the growth of ecological efficiency caused by the decrease in feed cost.

Because of the urban planning requirements and environmental protection of water resources, North and East China have relatively high levels of economic development and environmental regulation. Therefore, although the hog breeding industry was showing a certain agglomeration advantage (with the breeding density of 5.1947 and 5.28 head/km², respectively, and higher than the national average), the eco-efficiency grows slowly. On the one hand, Beijing, Tianjin, and Hebei in North China were the administrative centers and border provinces. And Shanghai, Jiangsu, Zhejiang, Anhui, and Jiangxi in East China belong to the southern water network area. Furthermore, Shanxi in North China belongs to moderate and severe ecologically fragile areas. These regions were the main areas where the banning policy of livestock breeding was implemented. On the other hand, the per capita GDP of Beijing, Shanghai, Jiangsu, Fujian, Tianjin, and Zhejiang were among the top 6 in China. According to the environmental Kuznets curve (EKC), the higher the regional per capita GDP is, the stricter the environmental regulation is (Dasgupta et al. 2001; Antweiler et al. 2001). Meanwhile, these provinces are economically developed areas, where abundant capital makes it easier to access advanced breeding technology. But this area also bears the highest cost of labor and capital.

The average growth of eco-efficiency in Northwest China was 0.85%, while the average technological progress rate is lower than the frontier level, indicating that if breeding technology improves, there is a possibility of a 1.2% increase in hog production with the current technical efficiency and with factor inputs remaining constant. This result could be attributable to the regional characteristic. Qinghai, Xinjiang, and Gansu in the northwest are the main pastoral areas in China and are rich in grazing. But the lack of a main feed supply of hogs makes the breeding cost increased. Notably, most parts of Ningxia and Shanxi in the northwest belong to the severe ecological fragile area, and Qinghai belongs to the moderate ecological fragile area. Hence, compared to other regions, breeding density in Northwest China is found to be the lowest.

Northeast is another main producing area of maize in China. Accordingly, it is rich in feed resources, which brings low production costs. It is a region with a higher degree of scale and organization in hog production. That makes the northeast become the only one among six regions that the variation of eco-efficiency is primarily determined by technological progress. Technological improvement overcomes the problem of temperature for hog breeding and alleviates pollution emissions. The average growth of technical efficiency is only 1.36%, indicating that the utilization of input factors is still inefficient. In addition, the average breeding density in the northeast is 4.5064, properly expanding the scale of breeding can improve the eco-efficiency.

In view of the aforementioned analysis, we found that the growth of eco-efficiency has a significant difference in different regions or provinces of China, while environmental regulation, breeding density, regional industry, and economic characteristics are the main reasons for the differences. Adjusting the distribution of hog breeding based on the regional characteristics is conducive to the improvement of eco-efficiency.

**Dynamic rank of eco-efficiency across provinces**

Based on the results of Table 6, we compared the eco-efficiency changes across provinces with respect to three types of scale in 2004, 2011, and 2018. As shown in Table 4, (1) small scale: the ranking of Liaoning and Guangdong remained unchanged; 14 provinces rose in the rankings, with Shandong (+11), Chongqing (+15), Sichuan (+17), Guizhou (+17), and Gansu (+17) with the largest increases; and 8 provinces fell in the rankings, including Inner Mongolia (−19), Anhui (−10), and Qinghai (−9) with the largest decreases. (2) Medium scale: the ranking of Guizhou remained unchanged; 7 provinces rose in the rankings, with Beijing (+13), Shandong (+12), Yunnan (+13), and Qinghai (+9) showing a large increase; and 18 provinces fell in the rankings, with Tianjin (−13), Inner Mongolia (−9), Zhejiang (−9), Hainan (−18), and Xinjiang (−9) as the five provinces with the largest decreases. (3) Large scale: the ranking of Jiangsu and Henan remained unchanged; 11 provinces rose in the rankings, among them, Jiangxi (+12), Shandong (+10), Hubei (+9), Hunan (+24), Guangxi (+19), Chongqing (+19), Guizhou (+22), and Xinjiang (+10) with a significant increase; while 16 provinces fell in the rankings, and Tianjin (−20), Shanxi (−10), Jilin (−10), Heilongjiang (−13), Sichuan (−14), and Qinghai (−23) had the largest declines.

From a regional perspective, the eco-efficiency ranking of North China dropped significantly, and except for the medium-scale ranking, both the small-scale (−2) and the large-scale (−3) ranking dropped, and the large-scale eco-efficiency ranking dropped from first in 2004 to fourth in 2018. At the same time, the eco-efficiency rankings of South Central China and Southwest China rose sharply. Among them, although the eco-efficiency ranking of small-scale (−1) and medium-scale (−2) farms in South Central China declined, the large-scale (+5) eco-efficiency ranking rose sharply, from sixth in 2004 to first in 2018. The eco-efficiency of small-scale
medium-scale (+2), and large-scale (+2) farms in southwest China all increased. In Southwest China, the eco-efficiency of small-scale farms increased from fifth in 2004 to first in 2018, and the medium-scale farms in 2018 also ranked first. Thus, from 2004 to 2018, there was not only a shift in hog production from north to south central but also an increasing trend of breeding eco-efficiency.

The common explanation for the aforementioned situation can be explained as follows: due to overall strategic positioning adjustments, increased production costs, and changes in resource endowments, the total production of hogs was reduced in North China. The decrease in total production mainly came from the decrease in large-scale production, in the case of a large amount of fixed investment, the reduction of production led to the insufficiency of scale benefits and the decrease in productivity. At the same time, the total production of hogs in South Central and Southwest China increased significantly (as shown in Fig. 1). The increase in large-scale

| Province          | Small scale  | Medium scale | Larger scale  |
|-------------------|--------------|--------------|---------------|
| Beijing           | 11           | -            | 25            |
| Tianjin           | -            | -            | 6             |
| Hebei             | 15           | 9 (6)        | 16            |
| Shanxi            | 19           | 16 (4)       | 20            |
| Inner Mongolia    | 6            | 3 (25)       | 9             |
| North             | 3 (2)        | 5 (9)        | 5             |
| Liaoning          | 24           | 24 (0)       | 23            |
| Jilin             | 26           | 25 (3)       | 24            |
| Heilongjiang      | 20           | 23 (16)      | 10            |
| Northeast         | 6 (6)        | 6 (6)        | 6             |
| Shanghai          | -            | -            | -             |
| Jiangsu           | 1 (10)       | 2 (-1)       | 1             |
| Zhejiang          | 4 (4)        | 1 (+3)       | 7             |
| Anhui             | 10           | 21 (20)      | 12            |
| Fujian            | 3            | -            | -             |
| Jiangxi           | -            | 13 (9)       | -             |
| Shandong          | 14           | 13 (11)      | 15            |
| East              | 1 (3)        | 2 (-1)       | 1             |
| Henan             | 17           | 26 (21)      | 19            |
| Hubei             | 25           | 17 (22)      | 22            |
| Hunan             | 2            | 7 (8)        | 2             |
| Guangdong         | 13           | 15 (13)      | 18            |
| Guangxi           | 7            | 6 (5)        | 8             |
| Hainan            | 8            | 19 (12)      | 3             |
| South Central     | 2 (5)        | 3 (-4)       | 2             |
| Chongqing         | 22           | 2 (7)        | -             |
| Sichuan           | 23           | 9 (6)        | 13            |
| Guizhou           | 21           | 5 (4)        | 4             |
| Yunnan            | 16           | 14 (11)      | 21            |
| Southwest         | 5            | 1 (1)        | 3             |
| Shaanxi           | 18           | 12 (17)      | 11            |
| Gansu             | 27           | 20 (10)      | 26            |
| Qinghai           | 9            | 1 (18)       | 14            |
| Ningxia           | 12           | 22 (14)      | 17            |
| Xinjiang          | 5            | 18           | 5             |
| Northwest         | 4            | 4 (4)        | 4             |

**Table 4** The ranking and dynamic changes of eco-efficiency in hog production across provinces

| Province          | Small scale  | Medium scale | Larger scale  |
|-------------------|--------------|--------------|---------------|
| Beijing           | 11           | -            | 25            |
| Tianjin           | -            | -            | 6             |
| Hebei             | 15           | 8 (9)        | 16            |
| Shanxi            | 19           | 16 (15)      | 20            |
| Inner Mongolia    | 6            | 3 (25)       | 9             |
| North             | 3 (2)        | 5 (9)        | 5             |
| Liaoning          | 24           | 24 (0)       | 23            |
| Jilin             | 26           | 25 (3)       | 24            |
| Heilongjiang      | 20           | 23 (16)      | 10            |
| Northeast         | 6 (6)        | 6 (6)        | 6             |
| Shanghai          | -            | -            | -             |
| Jiangsu           | 1 (10)       | 2 (-1)       | 1             |
| Zhejiang          | 4 (4)        | 1 (+3)       | 7             |
| Anhui             | 10           | 21 (20)      | 12            |
| Fujian            | 3            | -            | -             |
| Jiangxi           | -            | 13 (9)       | -             |
| Shandong          | 14           | 13 (11)      | 15            |
| East              | 1 (3)        | 2 (-1)       | 1             |
| Henan             | 17           | 26 (21)      | 19            |
| Hubei             | 25           | 17 (22)      | 22            |
| Hunan             | 2            | 7 (8)        | 2             |
| Guangdong         | 13           | 15 (13)      | 18            |
| Guangxi           | 7            | 6 (5)        | 8             |
| Hainan            | 8            | 19 (12)      | 3             |
| South Central     | 2 (5)        | 3 (-4)       | 2             |
| Chongqing         | 22           | 2 (7)        | -             |
| Sichuan           | 23           | 9 (6)        | 13            |
| Guizhou           | 21           | 5 (4)        | 4             |
| Yunnan            | 16           | 14 (11)      | 21            |
| Southwest         | 5 (1)        | 1 (1)        | 3             |
| Shaanxi           | 18           | 12 (17)      | 11            |
| Gansu             | 27           | 20 (10)      | 26            |
| Qinghai           | 9            | 1 (18)       | 14            |
| Ningxia           | 12           | 22 (14)      | 17            |
| Xinjiang          | 5            | 18           | 5             |
| Northwest         | 4 (4)        | 4 (0)        | 4             |

“—” indicates no data. The absence of statistical data in some provinces results in the absence of efficiency values.
breeding improved the scale benefit of breeding and promoted eco-efficiency.

**Determinants of eco-efficiency**

To further find out the determinants for the variance of hog farm’s eco-efficiency, we also conduct a Tobit function to analyze the effects of different determinants of eco-efficiency in three dimensions as environmental regulation factors, development of hog industry factors, and regional development factors.

Environmental regulation factors. The literature has emphasized two different impacts of environmental regulation on the eco-efficiency of the hog breeding industry: decrease and improvement. The neoclassical economic theory suggests that environmental regulation will decrease the breeding eco-efficiency by reducing production and increase the hog breeding cost. On the other hand, the Porter hypothesis asserts that environmental regulation will improve breeding eco-efficiency by stimulating technological innovation. The compensation effect from innovation will make up for the increased hog breeding cost. Nevertheless, the government’s investment in environmental control will reduce the cost of innovation both directly and indirectly as a subsidy. The environmental regulation factors include data on the forbidden policy (FP) is a dummy variable, according to the forbidden policy for livestock cultivation in certain areas, when province i completely implements the forbidden breeding policy at year t, then the FP equals 1, and, before year t, the FP equals 0. The government’s investment in environmental control (GIEC) is measured by the ratio of the government’s total investment in environmental pollution control to regional GDP.

Development of hog industry factors. Based on the analysis of differences in ecological efficiency of regions earlier, we already found that high breeding density will lead to the increase of breeding cost and hinders the growth of eco-efficiency. And feed supplies will lead to the increase of eco-efficiency by stimulating technological innovation. The compensation effect from innovation will make up for the increased hog breeding cost. Moreover, the government’s investment in environmental control will reduce the cost of innovation both directly and indirectly as a subsidy. The environmental regulation factors include data on the forbidden policy (FP) is a dummy variable, according to the forbidden policy for livestock cultivation in certain areas, when province i completely implements the forbidden breeding policy at year t, then the FP equals 1, and, before year t, the FP equals 0. The government’s investment in environmental control (GIEC) is measured by the ratio of the government’s total investment in environmental pollution control to regional GDP.

Rural economic development factors. The impact of regional economic growth level increases the environmental regulation degree (Magnani 2000), which increases the cost such as build more environmentally compliant lagoon to store manure or get a siting permit. Convenient transportation improves regional feed supply and reduces feed costs and so on. Therefore, the following variables are chosen as the regional development factors: Rural economic development (RED) is measured by the per capita net income of rural households. Rural economic development is ultimately reflected in the increase in the income of rural households, benefit to the adoption of advanced breeding technology, and the rational use of resources. Urbanization rate (UR) is measured by the proportion of the urban population to the total population. Urbanization promotes the transformation of the agricultural population into the urban population, which affects the structure and quantity of the rural labor force and then affects the labor inputs of hog
breeding. Transportation conditions (TC) are expressed for each province per square kilometer of road and railway geometric mean value. The better the transportation conditions, the more conducive to the decrease in transport costs (Wu 2008; Yuan and Xie 2016). Rural human capital (RHC) is measured by the average educational level in rural areas, and we used the following formula to calculate it: RHC = \( \frac{\sum_{i=1}^{5} w_i \cdot edui}{\text{rural population over 6 years old}} \), where \( edui \) denotes the educational level and \( w_i \) is the corresponding weight, with \( i = 1, 2, 3, 4, \) and \( 5 \). This indicates not attending school, primary school education, junior middle school education, high school education, and junior college education and above education, respectively, with \( w_i \) equal to 1, 6, 9, 12, and 16 correspondingly. Hence, the Tobit regression equation is constructed as follows:

\[
ML_{it} = \beta_0 + \sum_{n=1}^{12} \beta_n X_{nit} + \gamma_{it} \quad (9)
\]

where \( ML_{it} \) is the eco-efficiency; \( X_{nit} \) denotes the influence factors (the density of slaughtered fattened hogs, prices of hogs, rural economic development, and transportation conditions are all expressed in logarithmic form, and all the price indexes are expressed in 2003 constant prices); \( \beta_n \) is a coefficient; and \( \gamma_{it} \) is the random error. In particular, we used the consumer price index (CPI) to deflate all the price indicators. The results are reported in Table 5.

The regression results provide evidence for different correlations of eco-efficiency and influencing factors. In environment regulation factors, the forbidden policy for livestock cultivation in certain areas was correlated only with the large-scale eco-efficiency, and the coefficient was \(-0.0966\) and was statistically significant at the 10% significance level. This indicates that the policy decreased the large-scale eco-efficiency by 0.0966. After the implementation of the forbidden policy for livestock cultivation, the farms in the forbidden breeding areas were closed down, and there was a limit on the scale of the farms in the restricted breeding areas, which, to a certain extent, reduced the scale benefit of the farms and, therefore, had a negative effect on large-scale farms. The government’s investment in environmental control was correlated only with the medium-scale eco-efficiency, and the coefficient was 4.2643 and was statistically significant at the 10% significance level. Improving the environmental control investment, therefore, remains an important measure to improve the eco-efficiency of China’s livestock sector.

The development of hog industry factors also had different positive effects on eco-efficiency. The structure of the hog breeding industry and density of slaughtered fattened hogs had a statistically significant negative effect on eco-efficiency. According to the regression results, a larger proportion of the hog industry and density of hog production led to an increase in the undesired output, which inhibited the eco-efficiency. Due to the cross-regional feed procurement, the effect of the local feed supply conditions on the eco-efficiency was not significant. Each additional 1% of hog prices decreased the eco-efficiency of large-, medium-, and small-scale farms by \(-0.0291\), \(-0.0342\), and \(-0.0144\), respectively. The negative effect of the previous price on the average co-efficiency was greater. The stable market price of agricultural products is an important factor to promote the growth of production efficiency. Hog production in high market advantage regions had greater eco-efficiency.

In regional development factors, the development of the rural economy promoted technical progress and environment improvements, especially in medium- and small-scale farms. The eco-efficiency of hog production in regions with food transportation conditions was slightly higher than in those with lower traffic conditions. Neither the urbanization rate nor rural human capital had a significant effect on any scale of farms’ eco-efficiency.

Conclusions and implications

In this paper, we utilized an analytical framework taking environmentally detrimental emissions as the undesired output and using data from IEDA and NIES (2009), NDRC (2005–2019), NBSC (2005–2020), and CAAA (2021). We conducted an empirical analysis of the environmental efficiency of hog production for 30 provinces (excluding Tibet) in China from 2004 to 2018. The empirical results showed that the eco-efficiency increased, and the increase was mainly by the improvement of the technical efficiency. The hog production in China gradually shifted to South Central China from North China, and the high eco-efficiency region concentrated in South Central China and spread to the surrounding areas while showing a marked difference between the north and the south of China. More specifically, the medium- and small-scale predominant production areas were transferred from Eastern China to Southwestern China, and the large-scale predominant areas transferred from Northern China to South Central China. In addition, we found that only Hunan’s eco-efficiency ranked in the top 5 of the eight main production areas, which reflects that there may be excessive scale in the main production areas.

We analyzed the influence factors for eco-efficiency using a Tobit model and found that the government’s investment in environmental control, the rural economic development, the market advantage index, and the transportation conditions had positive effects on the eco-efficiency, while the forbidden breeding policy, the structure of the hog breeding industry,
the density of slaughtered fattened hogs, and the prices of hogs had negative effects on the eco-efficiency.

Based on the aforementioned findings, several suggestions are proposed: First, although the eco-efficiency of hog production in China demonstrated an increasing trend, the government should pay increased attention to the excessively expanding hog farm scales and encourage farmers to adopt technology and equipment for the recycling and harm reduction treatment of livestock and poultry manure. Second, optimize the layout of the hog industry according to the eco-efficiency and regional characteristics. We argue that hog production should be appropriately transferred from South Central China to Southwest and Northeast China, while hog production in North and East China could be appropriately transferred to Inner Mongolia and Shandong, respectively. Northwest China would be better to maintain. Third, the government could increase investment in environmental control and support technological innovation of hog breeding farms through subsidies to offset the cost increase brought by environmental regulations. And then, the government should take measures to stabilize hog prices and to guarantee feed input and control the regional breeding density to a suitable range. Furthermore, advocate for ecological cycles in hog production and promote regional rural economic growth level, and improving the transport conditions will help to the growth of eco-efficiency.

Table 5 Regression results of factors affecting the eco-efficiency based on a Tobit model

| Variables                        | ML      | Large scale | Medium scale | Small scale |
|----------------------------------|---------|-------------|--------------|-------------|
| Environment regulation factors   |         |             |              |             |
| FP                               | −0.008  | −0.0966*    | −0.0228      | −0.0373     |
|                                  | (0.0369)| (0.0537)    | (0.0494)     | (0.0534)    |
| GIEC                             | 1.3235  | 0.2274 (2.92)| 4.2643*     | 0.9884      |
|                                  | (1.9234)| (2.547)     | (2.7278)     |             |
| Development of hog industry factors |       |             |              |             |
| SHI                              | −0.4848*| −0.5382     | −0.6495*     | −0.2004     |
|                                  | (0.2888)| (0.4171)    | (0.3844)     | (0.4389)    |
| DSFG                             | −0.0648***| −0.0725**  | −0.056*      | −0.0659***  |
|                                  | (0.0231)| (0.0399)    | (0.0309)     | (0.0312)    |
| CLFS                             | 0.0111 (0.0074) | 0.0109   | 0.0124      | 0.0145      |
|                                  | (0.0112)| (0.0101)    | (0.0107)     |             |
| PRICE                            | −0.0239***| −0.0291*** | −0.0342***   | −0.0144*    |
|                                  | (0.0059)| (0.0089)    | (0.008)      | (0.0083)    |
| LI. PRICE                        | −0.0338***| −0.0158*   | −0.027***    | −0.0192**   |
|                                  | (0.0056)| (0.0084)    | (0.0075)     | (0.0077)    |
| Regional development factors     |         |             |              |             |
| RED                              | 0.0616**| 0.0437      | 0.0716**     | 0.0664*     |
|                                  | (0.0261)| (0.0374)    | (0.0343)     | (0.0345)    |
| UR                               | −0.0294 | −0.1432     | 0.0623       | 0.0701      |
|                                  | (0.1417)| (0.2076)    | (0.1923)     | (0.2066)    |
| TC                               | 0.0696* | 0.1172*     | 0.0362       | 0.0431      |
|                                  | (0.0398)| (0.061)     | (0.0531)     | (0.0551)    |
| RHC                              | 0.0012  | 0.0024      | 0.0108       | −0.0011     |
|                                  | (0.0239)| (0.0369)    | (0.0324)     | (0.0335)    |
| Constant                         | 0.6733***| 0.5543      | 0.6238*      | 0.4722      |
|                                  | (0.2427)| (0.3608)    | (0.3276)     | (0.3349)    |

*a*Indicates significance at the 10% level

**Indicates significance at the 5% level

***Indicates significance at the 10% level

All regressions control fixed effects. Standard errors are clustered at the region level and appear in parentheses

The statistic description of influence factors is shown in Table 9
Appendix

Fig. 2 The undesired output/desired output in six regions of China

Table 6 The eco-efficiency/TFP scores from the SBM model across 30 provinces in China, 2004–2018

| Province | Year | Ranks |
|----------|------|-------|
| Beijing  | 2004 | 0.657/0.69 | 22/25 |
| Tianjin  | 2005/1.071 | 0.933/0.979 | 10/11 |
| Hebei    | 2006/0.885 | 0.793/0.892 | 27/30 |
| Shanxi   | 2007/0.825 | 0.914/0.931 | 14/16 |
| Inner Mongolia | 2008/1.121/2.126 | 0.783/0.841 | 28/30 |
| Liaoning | 2009/0.634/0.73 | 0.816/0.871 | 13/15 |
| Jilin    | 2010/0.706/0.693 | 0.842/0.928 | 12/14 |
| Heilongjiang | 2011/0.921/0.952 | 0.844/0.929 | 16/18 |
| Shanghai | 2012/1.355/1.138 | 1.206/0.877 | 7/9 |
| Jiangsu | 2013/1.311/1.075 | 1.257/1.148 | 11/13 |
| Zhejiang | 2014/1.078/0.954 | 0.845/0.782 | 17/19 |
| Anhui | 2015/0.971/0.93 | 0.967/0.893 | 19/21 |
| Fujian   | 2016/1.081/1.031 | 1.155/1.136 | 18/20 |
| Jiangxi  | 2017/1.142/1.128 | 1.014/0.93 | 21/23 |
| Shandong | 2018/0.904/0.843 | 1.026/0.981 | 24/26 |
| Henan    | 2019/0.802/0.732 | 0.712/0.719 | 26/28 |
| Hubei   | 2020/0.672/0.607 | 0.696/0.734 | 27/30 |
| Hunan   | 2021/1.249/1.247 | 0.918/0.919 | 28/30 |
| Guangdong | 2022/0.911/0.772 | 0.868/0.872 | 29/31 |
| Guangxi | 2023/0.937/0.844 | 0.928/0.837 | 30/32 |
| Hainan  | 2024/1.077/1.058 | 0.939/0.955 | 31/33 |
| Chongqing | 2025/0.599/0.711 | 0.919/0.821 | 32/34 |
| Sichuan | 2026/0.896/0.865 | 1.055/1.032 | 33/35 |
| Guizhou | 2027/0.859/0.924 | 1.118/1.105 | 34/36 |
| Yunnan | 2028/0.804/0.885 | 0.955/0.98 | 35/37 |
| Shaanxi | 2029/0.905/0.915 | 0.945/0.991 | 36/38 |
| Gansu | 2030/0.538/0.597 | 0.602/0.637 | 37/39 |
| Qinghai | 2031/1.409/1.412 | 2.448/2.448 | 38/40 |
| Ningxia | 2032/0.901/0.932 | 0.877/0.887 | 39/41 |
| Xinjiang | 2033/1.115/1.107 | 0.875/0.895 | 40/42 |
| Average | 2034/0.908/0.9 | 0.927/0.929 | 41/43 |

“—” means no data

The absence of statistical data in some provinces results in the absence of efficiency values.

There is a great variation in eco-efficiency across provinces, ranging from 0.557 to 1.19 with a mean value of 0.937 in 2018. And the overall average eco-efficiency increased from 2004 to 2018.
Table 7 Regression analysis on the price, technical efficiency, and technical progress index of hog production

|       | ML   | MLEFFCH | MLTECH |
|-------|------|---------|--------|
| PRICE | 0.007(0.022) | 0.02*** (0.006) | −0.008 (0.021) |
| R²    | 0.01 | 0.54    | 0.02   |

***Indicates significance at the 1% levels

The standard error is shown in parentheses

The “PRICE” adopts the annual price of pork market, and we deflated it using the price index of the pork market.

In accordance with this study, the price indexes were expressed in 2003 constant prices.

The sample period was 2005–2016 because the “PRICE” index only counts up to 2016.

Table 8 Decomposition of the growth of the eco-efficiency across provinces and areas in China, 2004–2018

| Province/area | ML     | MLEFFCH | MLTECH | Province/area | ML     | MLEFFCH | MLTECH |
|---------------|--------|---------|--------|---------------|--------|---------|--------|
| Beijing       | 1.0131 | 1.0616  | 0.9895 | Henan         | 1.0232 | 1.0244  | 1.0246 |
| Tianjin       | 0.9755 | 1.0000  | 1.0075 | Hubei         | 1.0358 | 1.0336  | 1.0135 |
| Hebei         | 1.0025 | 1.0286  | 0.9913 | Hunan         | 1.0296 | 1.0302  | 1.0264 |
| Shanxi        | 1.0107 | 1.0469  | 1.0236 | Guangdong     | 1.0059 | 1.0236  | 0.9972 |
| Inner Mongolia| 1.0731 | 1.0374  | 1.0845 | Guangxi       | 1.0426 | 1.0314  | 1.0188 |
| North         | 1.0053  | 1.0253  | 1.0133 | Hainan        | 1.0228 | 1.0252  | 1.0279 |
| Liaoning      | 1.0165  | 1.0109  | 1.0346 | South Central | 1.0156 | 1.0206  | 1.0095 |
| Jilin         | 1.0147  | 1.0180  | 1.0181 | Chongqing     | 1.0619 | 1.0391  | 1.0318 |
| Heilongjiang  | 0.9912  | 1.0229  | 1.0148 | Sichuan       | 1.0277 | 1.0317  | 1.0069 |
| Northeast     | 1.0032  | 1.0136  | 1.0155 | Guizhou       | 1.1204 | 1.0602  | 1.0625 |
| Shanghai      | 0.9431  | 0.9847  | 0.9583 | Yunnan        | 1.0793 | 1.0649  | 1.0498 |
| Jiangsu       | 0.9931  | 0.9974  | 0.9978 | Southwest     | 1.0556 | 1.0428  | 1.0267 |
| Zhejiang      | 1.0384  | 1.0147  | 1.0520 | Shaanxi       | 1.0383 | 1.0266  | 1.0293 |
| Anhui         | 1.0210  | 1.0013  | 1.0232 | Gansu         | 1.0342 | 1.0593  | 0.9939 |
| Fujian        | 1.0956  | 1.0399  | 1.0783 | Qinghai       | 1.0373 | 1.0577  | 0.9915 |
| Jiangxi       | 1.0006  | 0.9888  | 1.0140 | Ningxia       | 0.9812 | 1.0042  | 0.9876 |
| Shandong      | 1.0041  | 1.0302  | 0.9791 | Xinjiang      | 0.9954 | 1.0509  | 0.9745 |
| East          | 1.0035  | 1.0046  | 1.0053 | Northwest     | 1.0085 | 1.0297  | 0.9880 |

Here, we report the average growth rate of each index by province/area.

ML is an acronym for Malmquist–Luenberger index.
**Fig. 3** The hog production density in six regions of China, 2004–2018 (the geometric average)

![Boxplot of hog production density](image)

**Table 9** Summary statistics of variables in the Tobit regression

| Variable                        | Obs. | Mean       | SD          | Min       | Max       |
|---------------------------------|------|------------|-------------|-----------|-----------|
| ML                              | 414  | 1.024235   | 0.221187    | 0.446094  | 1.878281  |
| Large scale                     | 392  | 1.045169   | 0.297080    | 0.356202  | 2.528874  |
| Medium scale                    | 392  | 1.041269   | 0.275553    | 0.447445  | 2.298067  |
| Small scale                     | 359  | 1.037703   | 0.263210    | 0.470719  | 1.934931  |
| Environment regulation factors  |      |            |             |           |           |
| FP                              | 420  | 0.161905   | 0.368803    | 0         | 1         |
| GIEC                            | 390  | 0.013439   | 0.006668    | 0.002991  | 0.042314  |
| Development of hog industry factors |      |            |             |           |           |
| SHI                             | 420  | 0.14338    | 0.06121     | 0.016118  | 0.365597  |
| DSFG                            | 420  | 4.501904   | 1.403546    | 0.296976  | 6.090496  |
| CLFS                            | 413  | 5.423296   | 1.870877    | 0.262364  | 8.28959   |
| PRICE                           | 420  | 10.71826   | 5.167272    | 5.920777  | 97.10138  |
| L1 PRICE                        | 420  | 10.84826   | 6.009947    | 5.920777  | 97.10138  |
| Regional development factors    |      |            |             |           |           |
| RED                             | 420  | 8.5748     | 0.624079    | 6.316107  | 9.947689  |
| UR                              | 420  | 0.534867   | 0.139157    | 0.2687    | 0.896     |
| TC                              | 420  | 6.964019   | 0.77028     | 4.369525  | 8.275311  |
| RHC                             | 420  | 7.59258    | 0.643933    | 5.458665  | 9.837992  |
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