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ORIGINAL PAPER

Study on the comprehensive comparative advantages of pig production and development in China based on geographic information system

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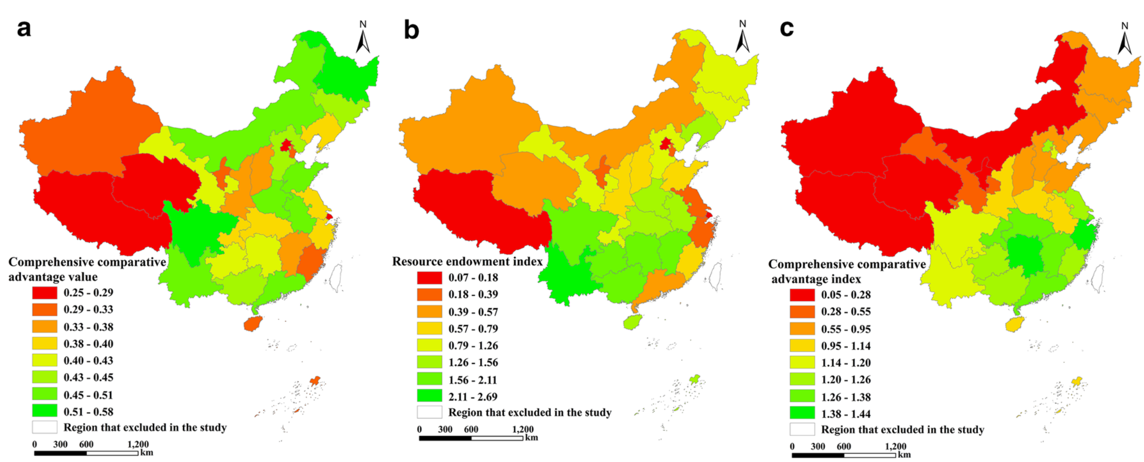
Abstract

China's pig production ranks first in the world. However, keeping a continuous and rapidly sustainable development is difficult due to the dual constraints of environment and resources. To solve this problem, the key regions that have high comprehensive comparative advantage value of pig production and development must be determined. Therefore, this study established a comprehensive comparative advantage index system and a comprehensive comparative advantage model of pig production and development. On this basis, the comprehensive comparative advantage value of pig production and development was calculated, and the key pig production and development regions were selected using (geographic information system) spatial analysis technology. The potential quantity of pig production in the key pig production and development regions were estimated according to the European Union standard for limitation of nutrient load of farmland from livestock manure. Results showed that the largest comprehensive comparative advantage value of pig production and development in China was 0.58 in Heilongjiang, followed by 0.55 in Sichuan, and 0.25 in Beijing, which was the smallest. The 11 provinces selected as the key pig production development regions in China were consistent with the key development regions or potential growth regions defined in the National Pig Production Development Plan 2016–2020. The Inner Mongolia had most potential quantity of pig production, followed by Sichuan. The results of this study could provide support for the spatial layout planning of pig farming and the rational allocation of regional resources.

Graphic abstract



Keywords Coefficient of variation · Comprehensive comparative advantage · Geographic information system · Pig production · Resource endowment index

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Introduction

China is the world's largest producer and consumer of pork (Ren et al. 2018; Wang et al. 2018a, b). Pigs are the main source of meat food in China and guarantee farmers' income. Therefore, improving the production capacity of pigs has great practical importance in stabilizing prices and protecting meat consumption (Chen et al. 2008; Verbeke and Liu 2014). At present, China's pig industry is in a critical period of transformation and upgrading. It also faces environmental pressure caused by pollution of pig manure, disjointed breeding and raising, shortage of land resources, and high dependence of feed raw materials on external resources and constraints (Tang et al. 2017; Kong and Wang 2017). Therefore, guaranteeing the sustained and rapid development of China's pig farming under the dual constraints of resources and environment is the current and future development of animal husbandry that must be addressed (Wang and Xiao 2017). Research on the comparative advantages of pig production and development is conducive to utilizing regional advantages and developing pig farming according to local conditions (Liang et al. 2013).

Moreover, a development mode of pig production that coordinates resources, environment, and economy under the current system framework of ecological civilization construction must be established (Du and Hu 2019). However, the existing traditional comparative advantage methods cannot easily meet the current needs. The summary of relevant literature is shown in Sect. 2. The present work established a comprehensive comparative advantage index (CCAI) system of pig production and development in China, considering resource endowment index, nitrogen load of farmland from livestock manure, phosphorus load of farmland from livestock manure, farmland area per capita, CCAI of maize, CCAI of soybean, and the comprehensive technical production efficiency of large- and medium-scale pig farming, and rural employment and average wage of urban unit employment in animal husbandry. On this basis, the key regions that have high comprehensive comparative advantage value of pig production and development in China can be determined, considering resources, environment, and economy. The potential quantity of pig production in the key pig production and development regions can also be estimated. The results can provide support for spatial layout adjustment of pig production and development and the optimal allocation of regional land resources.

The objectives of this study are as follows: (1) to establish a CCAI system of pig production and development in view of the sustainable development of pig production and environmental protection; (2) to establish a comprehensive comparative advantage model of pig production and development by combining the coefficient of variation method; (3) to determine the key regions that have high comprehensive comparative advantage value of pig production and development; and (4) to calculate the potential quantity of pig production in the key regions according to the European Union (EU) standard for the limitation of nutrient load of farmland from livestock manure.

Literature review

On the basis of the comparative analysis of the advantages of pig production and development in China, relevant scholars have conducted notable research. The research on comparative advantages of pig production and development has mainly concentrated on the following aspects. The resource endowment index, including the output of pig product and gross domestic product, was used as CCAI of pig production and development (Hu et al. 2009; Xie et al. 2019). Hu et al. (2009) studied regional comparative advantage of pig production and development using a resource endowment index and corroborated that pork production conforms to the principle of comparative advantages in China. The efficiency and scale advantage indices, which mainly consider the number and output of pigs, respectively, are usually taken as CCAI of pig production and development (Hu et al. 2005; Li and Qin 2009; Jiang et al. 2014; Wang et al. 2018a, b). Jiang et al. (2014) studied the comparative advantages of pig production in Heilongjiang using an efficiency advantage index. In view of efficiency and scale advantage indices as CCAI, Li and Qin (2009) and Wang et al. (2018a, b) calculated the CCAI of the main livestock products in 31 provinces in China and pig production in Heilongjiang, respectively. Yue et al. (2018) used the resource endowment, efficiency advantage, and scale advantage indices to make a comparative analysis of 21 cities in Sichuan Province and proposed policy recommendations on the regional differences of pig production in the province. Industrial concentration has also been used as an index for estimating comprehensive comparative advantage of pig production and development in some studies (Qiao et al. 2015).

Liang et al. (2013) evaluated the comprehensive production capacity of pig farming from seven aspects, namely, natural resource conditions, feed supply capacity, pig production status, breeding costs and benefits, agricultural foundation support, and ecological environment. From the evaluation, the researchers determined the suitable and unsuitable areas for pig farming and analyzed the comparative advantages of pig farming in 31 provinces and cities.

In sum, the current research on the comprehensive comparative advantage of pig production has mainly emphasized on resources and economic factors, such as number and output of pigs. Although a few studies have considered feed supply capacity, agricultural foundation support, and ecological environment, few have considered the environmental pollution from pig farming using the CCAI of maize or soybean on the comprehensive comparative advantage of pig production. The environmental pollution of pig farming has been seriously regarded by governments and scholars (Zhou et al. 2018; Yu et al. 2019) in recent years. The nutrient load of farmlands from livestock manure is an effective indicator for characterizing the environmental pollution from livestock farming (Yan et al. 2017a). Pig farming is a food-consuming animal husbandry in view of animal husbandry economics, which requires the consumption of a large number of corns, beans, and other feed resources (Wang and Qiao 2017). Wu et al. (2013) showed that pig production areas are gradually moving to the main grain production areas in China. Furthermore, pig production status and foundation of agriculture (Liang et al. 2013), market conditions and output of pigs (Zhou et al. 2018), ethical issues (Rozeboom et al. 2014), and land resources (Zhao et al. 2019) are also affected by pig production.

Data and methods

Study area

Data on pork production, total meat production, statistical data of livestock and poultry, GDP, cultivated land and grassland data, sown area of crops, crop yield per unit area, and population data were obtained from China Agricultural Yearbook 2017, China Statistical Yearbook 2017, China Labor Statistics Yearbook 2017, and China Animal Husbandry and Veterinary Yearbook 2017. The average wage of urban unit employment in animal husbandry was obtained from China Labor Statistics Yearbook 2017.

The rural employment of the provinces or municipalities in China was obtained from Statistical Yearbook of Provinces or Municipalities 2017. The weight of piglet, cost of concentrate feed, cost of green and coarse fodder, water fee, fuel and energy fee, cost of medical quarantine, employment quantity per head, and output of main products were collected from the National Compilation of Cost–Benefit Data of Agricultural Products 2017. The feeding period of cows, beef cattle, draft cattle, sheep, horses, donkeys, and mules was calculated as 365 days; and the feeding periods of pigs, poultry, and rabbits were calculated as 199, 210, and 90 days, respectively (Geng et al. 2013; Zhu et al. 2014; Yan et al. 2017a). As cattle, sheep, and other large livestock in Sichuan, Xinjiang, Inner Mongolia, Tibet, and Qinghai graze on grasslands, most livestock manure is disposed in grasslands beside the farmlands (Zhu et al. 2014). Therefore, the nitrogen or phosphorus load of farmland from the livestock manure was calculated using the cultivated land and grassland areas in Sichuan, Xinjiang, Inner Mongolia, Tibet, and Qinghai. The daily excretion of nitrogen or phosphorus from livestock manure was determined by referring to the literature (Geng et al. 2013; Zhu et al. 2014; Yan et al. 2017a). Table 1 presents the results.

Table 1 Daily excretion of nitrogen or phosphorus from livestock manure

Livestock type	Nitrogen or phosphorus	North China region	Northeast China region	Northwest China region	Southwest China region	South central region	East China region
Pig	Nitrogen/(g d^{-1})	29.00	47.25	31.73	16.85	36.51	20.76
	Phosphorus/(g d^{-1})	5.21	5.13	4.22	3.88	4.84	2.63
Beef cattle	Nitrogen/(g d^{-1})	72.74	150.81	104.10	104.10	65.93	153.47
	Phosphorus/(g d^{-1})	13.69	17.06	10.17	10.17	10.52	19.85
Cow	Nitrogen/(g d^{-1})	274.23	257.70	185.89	214.51	353.41	214.51
	Phosphorus/(g d^{-1})	38.27	54.55	17.92	38.47	62.46	38.47
Draft cattle	Nitrogen/(g d^{-1})	121.68	110.95	108.03	107.77	139.76	107.77
	Phosphorus/(g d^{-1})	14.31	24.06	9.54	12.48	25.99	12.48
Sheep	Nitrogen/(g d^{-1})	2.15	2.15	2.15	2.15	2.15	2.15
	Phosphorus/(g d^{-1})	0.46	0.46	0.46	0.46	0.46	0.46
Poultry	Nitrogen/(g d^{-1})	1.27	1.85	1.85	0.71	0.71	1.02
	Phosphorus/(g d^{-1})	0.30	0.48	0.48	0.06	0.06	0.50
rabbit	Nitrogen/(g d^{-1})	1.16	1.16	1.16	1.16	1.16	1.16
	Phosphorus/(g d^{-1})	0.24	0.24	0.24	0.24	0.24	0.24
Horse, donkey and mule	Nitrogen/(g d^{-1})	12.40	12.40	12.40	12.40	12.40	12.40
	Phosphorus/(g d^{-1})	1.60	1.60	1.60	1.60	1.60	1.60

The spatial data of provinces and regions in China were obtained by the vectorization and projection transformation of the administrative map of China using ArcGIS 10.1 software. The spatial data of provinces and regions in China were correlated with pork production, total meat production, statistical data of livestock and poultry, daily nitrogen and phosphorus excretion from livestock manure, GDP, sown area of crops, crop yield per unit area, and population data.

Resource endowment index method

The resource endowment index was used to reflect the relative richness of resources in a country or region. The resource endowment index can be calculated as follows (Pan and Cao 2011; Bai et al. 2014; Tan et al. 2018):

$$\mathrm{EF}_i = \frac{R_i/R}{G_i/G} \tag{1}$$

where EF_i is the resource endowment index, R_i is pork production in i province, R is total meat production in China, G_i is gross national product in i province, and G is national gross national product. If $0 < \mathrm{EF}_i < 1$, it indicates that the pig production resources in this region are lack or have no comparative advantage of resource endowment. If $1 < \mathrm{EF}_i < 2$, it shows that the pig production resources in this region have a certain comparative advantage of resource endowment. If $\mathrm{EF}_i > 2$, it shows that the pig production resources in this region have a strong comparative advantage of resource endowment.

Calculation of nitrogen or phosphorus load of farmland from livestock manure

The nitrogen or phosphorus load of farmland from livestock manure could indirectly measure the environmental pollution caused by local livestock and poultry farming (Zhang et al. 2007; Zhu et al. 2014). Therefore, the potential environment pollution caused by livestock and poultry farming was characterized by livestock manure nitrogen or phosphorus load of farmland. The livestock manure nitrogen or phosphorus load of farmland can be calculated as follows (Zhu et al. 2014; Yang et al. 2016; Yan et al. 2017b):

$$Q = \frac{\sum_{i=0}^{m} (A_i \times t_i \times h_i)}{S} \tag{2}$$

where Q is the nitrogen or phosphorus load of farmland from livestock manure, kg/hm^2, A_i is the number of livestock and poultry, head, S is farmland area, hm^2, t_i is feeding period, d, and h_i is daily excretion of nitrogen or phosphorus from livestock manure, g d^{-1}.

Calculation of CCAI

The CCAI combines the scale dominance index and the efficiency dominance index. It can comprehensively reflect the dominance degree of a certain crop production in a region and can be calculated as follows (Tan and Gao 2018; Ding et al. 2018):

$$\mathrm{SAI}_{ij} = \frac{P_{ij}/P_i}{P_j/P}, \tag{3}$$

$$\mathrm{EAI}_{ij} = \frac{V_{ij}/V_i}{V_j/V}, \tag{4}$$

$$\mathrm{CCAI}_{ij} = \sqrt{\mathrm{SAI}_{ij} \times \mathrm{EAI}_{ij}}. \tag{5}$$

where CCAI_{ij} is comprehensive comparative advantage index, SAI_{ij} is scale advantage index, EAI_{ij} is efficiency advantage index, P_{ij} is planting area of j crops in region i, P_i is planting area of all crops in region i, P_j is planting area of j crops in China, P is planting area of all crops in China, V_{ij} is the crop yield of j crops in region i, V_i is the average crop yield of all crops in region i, V_j is the average crop yield of j crops in China, V is the average crop yield of all crops in China.

Comprehensive comparative advantage model of pig production and development

For a highly comprehensive comparative advantage of pig production and development in different regions, a CCAI system for pig production and development was proposed; this system includes resource endowment index, nitrogen load of farmland from livestock manure, phosphorus load of farmland from livestock manure, farmland area per capita, CCAI of maize, CCAI of soybean, and the comprehensive technical production efficiency of large- and medium-scale pig farming, and rural employment and average wage of urban unit employment in animal husbandry (Hu et al. 2005; Stern et al. 2005; Liang et al. 2013; Wu et al. 2013; Zhang and Sun 2014; Rozeboom et al. 2014; Gutiérrez et al. 2016; Fu 2016; Liao et al. 2017; Zhou et al. 2018; Reyes et al. 2019). On this basis, the comprehensive comparative advantage model of pig production and development was established by combining the coefficient of variation method. The comprehensive advantage value was a comprehensive index that includes factors affecting the comparative advantages of pig production and development. It could reflect the comparative advantages of pig production and development comprehensively.

The calculation process and method are as follows:

1. Dimensionalization of factors (Yao and Zhao 2014; Yan et al. 2017a):

① Positive indicators: $$A_n^i = \frac{C_n^i - C_{\min(n)}}{C_{\max(n)} - C_{\min(n)}}, \quad (6)$$

② Negative index: $$A_n^i = \frac{C_{\max(n)} - C_n^i}{C_{\max(n)} - C_{\min(n)}}. \quad (7)$$

2. The weight calculation method is as follows (Yao and Zhao 2014; Yan et al. 2017a):

$$W_n = \frac{P_n/\bar{A}_n^i}{\sum_{n=1}^{6}\left(P_n/\bar{A}_n^i\right)} \quad (8)$$

3. The comprehensive comparative advantage model of pig production and development is as follows:

$$F_n = W_n \times A_n^i \quad (9)$$

where $C_{\max(m)}$ and $C_{\min(m)}$ are the maximum and minimum value of a certain index, respectively, n is number of factors, i is number of region, P_n is standard deviation of A_n^i, $\bar{A}_n^i$ is mean value of A_n^i, W_n is weights of different indicators, and Z_m is comprehensive comparative advantage value.

Calculation of potential pig production

Potential pig production was obtained by multiplying the difference between the limit value of nitrogen (phosphorus) load of farmland from livestock and existing nitrogen (phosphorus) load of farmland from livestock and farmland area and then divided by pig feeding cycle and nitrogen (phosphorus) from pig manure. The potential pig production is calculated as follows:

$$A_{\text{pig}} = (Q_{\text{limit}} - Q) \times S/(t_{\text{pig}} \times h_{\text{pig}}) \quad (10)$$

where Q_{limit} is the limit value of nitrogen (phosphorus) load of farmland from livestock manure, kg/hm^2; Q is the nitrogen (phosphorus) load of farmland from livestock manure, kg/hm^2; A_{pig} is potential pig, head, S is farmland area, hm^2, t_{pig} is feeding period, d, and h_{pig} is daily excretion of nitrogen or phosphorus from livestock manure, g d^{-1}.

Results and discussion

Results of each factor of the comprehensive comparative advantages of pig production and development in China

On the basis of pork production, total meat production, and formulae (1)–(5), the spatial distribution results of resource endowment index, farmland area per capita, CCAI of maize, CCAI of soybean, nitrogen load of farmland from livestock manure, phosphorus load of farmland from livestock manure, total yield of feed production, pig sale rate, and pork consumption per capita were obtained by combining with the GIS spatial analysis technology. The comprehensive technical production efficiency of large- and medium-scale pig farming in China was calculated using data envelopment analysis with DEAP2.1 software. Several factors were considered for this analysis, including the weight of piglet, cost of concentrate feed, cost of green and coarse fodder, water fee, fuel and energy fee, cost of medical quarantine, employment quantity per head, and output of main products (Kang 2014; Fu 2016). The results were graded by a threshold method or an equal interval method (Fig. 1 and Table 2).

In 2016, more than half of the provinces or municipalities in China lacked or did not have comparative advantages of resource endowment. However, the 13 provinces or cities, including Hebei, Chongqing, Jilin, Heilongjiang, and Liaoning, had comparative advantages value of resource endowment. The highest comparative advantage value of resource endowment was 2.69 in Yunnan. The result is shown in Fig. 1a. Maize production in most provinces or municipalities in 2016 had no comparative advantage against the national average level. Maize production in the 11 provinces or municipalities (i.e., Hebei, Shanxi, Jilin, Heilongjiang, Liaoning, Anhui, Qinghai, Guizhou, Henan, Yunnan, and Xinjiang) had comparative advantages, among which the greatest advantage was 2.14 in Jilin. The results are shown in Fig. 1b. Soybean production in most provinces or municipalities in 2016 had no comparative advantage against the national average level. Soybean production in Shanxi, Jilin, Heilongjiang, Liaoning, and Anhui had comparative advantages, among which the greatest advantage was 3.03 in Jilin. The results are shown in Fig. 1c. In 2016, the average farmland area per capita of all provinces or municipalities in China was only 0.11 ha. The maximum and minimum farmland areas per capita were 0.42 ha and 0.01 ha in Heilongjiang and Shanghai, respectively. The results are shown in Fig. 1. In 2016, the nitrogen load of farmland from livestock manure in most provinces or municipalities, except for Beijing, Fujian, and Guangdong, did not exceed the limit value of

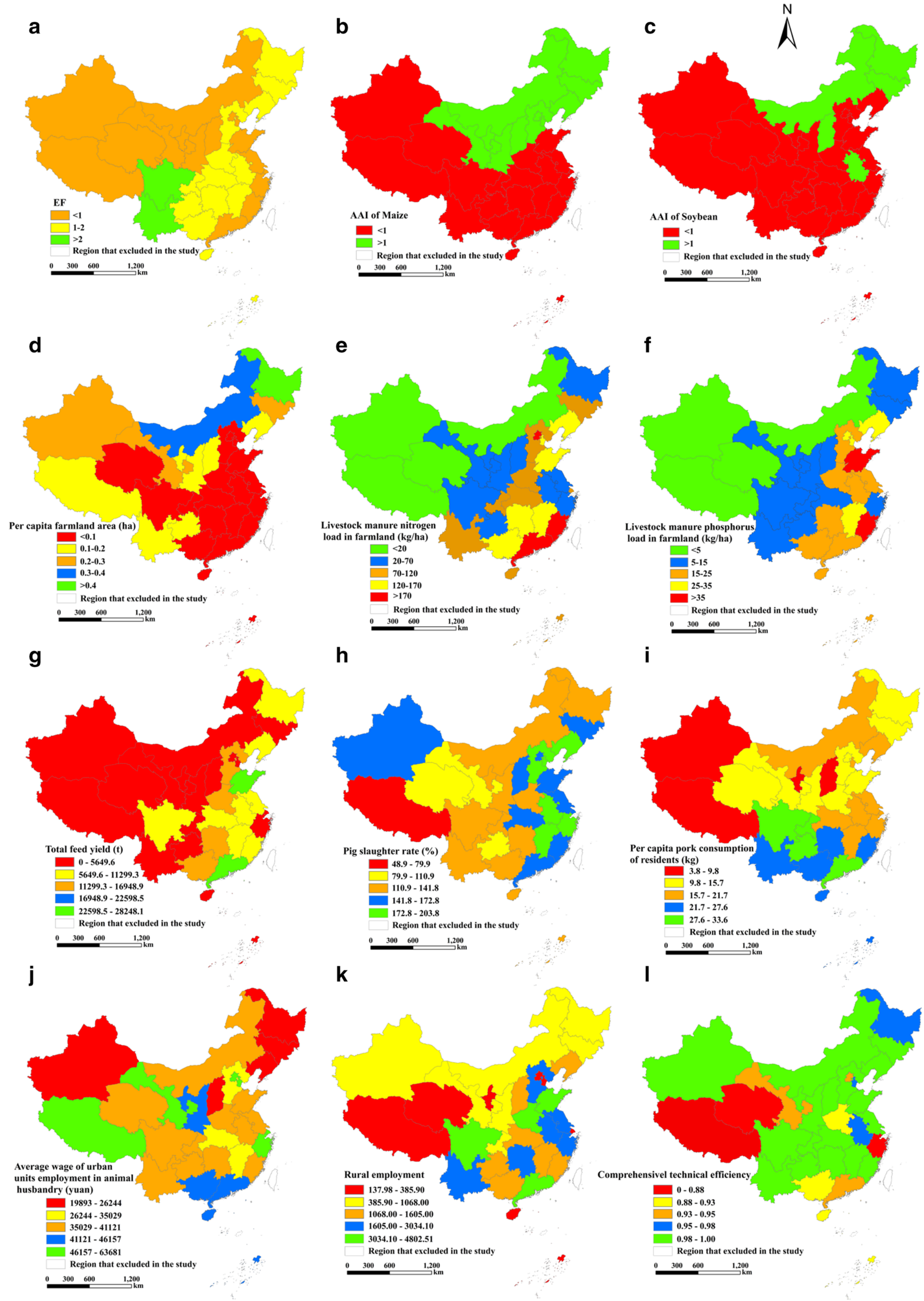

Fig. 1 Spatial distribution results of each factors and comprehensive comparative value of comprehensive comparative advantage of pig production and development in China

Table 2 The index, weight and result of comprehensive comparative advantage of pig production and development in China

Region	Resource endowment index	Farmland area per capita	Livestock manure nitrogen load of farmland	Livestock manure phosphorus load of farmland	CCAI of maize	CCAI of soybean	Total yield of feed production	Pig sell rate	Pork consumption per capita	Average wage of urban units employment in animal husbandry	Rural employment	Comprehensive technical efficiency of production efficiency	Comprehensive comparative advantage value
Shanxi	0.62	0.11	34.24	6.05	1.59	1.07	2856.58	166.53	9.00	1.99	1160.56	1	0.36
Shanxi	0.62	0.10	42.17	5.75	1.10	0.82	3012.17	138.05	10.00	4.62	1068	1	0.37
Ningxia	0.33	0.19	53.54	6.32	1.14	0.48	282.34	139.40	6.70	4.24	214.7	1	0.32
Gansu	0.96	0.21	48.15	5.81	1.09	0.70	926.75	115.53	11.90	6.20	957.73	0.95	0.42
Xinjiang	0.49	0.22	7.80	1.00	0.99	0.61	1907.86	158.37	3.80	2.02	607.97	0.99	0.33
Tibet	0.18	0.13	3.68	0.42	0.32	0.16	0	48.93	9.30	6.37	137.98	0	0.27
Qinghai	0.57	0.10	5.18	0.55	0.62	0	111.55	111.89	12.30	4.11	163.4	0.85	0.29
Inner Mongolia	0.56	0.37	7.79	1.32	1.77	1.58	2786.04	142.06	16.50	3.60	753.3	1	0.51
Heilongjiang	1.26	0.48	38.22	6.13	1.83	3.03	5828.54	144.57	14.20	2.62	955.3	0.97	0.58
Jilin	1.24	0.26	80.74	12.82	2.14	1.05	3213.70	170.79	14.20	2.58	752.26	1	0.45
Liaoning	1.38	0.11	169.60	30.29	1.57	0.90	10738.79	185.48	18.30	2.62	1218.6	1	0.40
Yunnan	2.69	0.13	75.56	10.16	0.96	0.81	3662.47	131.19	26.20	3.76	2203.1	1	0.49
Guizhou	1.85	0.13	62.21	8.17	0.82	0.79	1233.97	117.43	28.00	3.98	1190.56	1	0.43
Beijing	0.12	0.01	182.05	33.42	1.13	0.47	2622.17	166.55	13.10	5.63	385.9	0.95	0.25
Tianjin	0.23	0.03	142.03	26.98	1.16	0.46	2110.55	196.64	16.10	5.87	185.12	0.98	0.30
Shanghai	0.07	0.01	78.91	18.18	0.18	0.28	1622.20	170.93	20.20	6.13	158.26	1	0.28
Guangdong	0.46	0.02	188.59	23.84	0.30	0.56	28248.13	170.12	29.10	4.57	3466.41	0.95	0.47
Hunan	1.94	0.06	156.28	21.42	0.42	0.58	11732.86	150.41	25.10	4.00	2186.86	1	0.42
Hubei	1.39	0.09	97.41	13.20	0.56	0.61	8761.19	173.65	20.80	3.16	1559	1	0.39
Anhui	1.41	0.09	65.91	18.92	0.73	1.56	5981.80	195.76	17.80	3.72	3034.1	0.98	0.47
Jiangxi	1.84	0.07	130.64	29.55	0.16	0.89	9020.05	191.89	19.90	3.50	1559.59	1	0.38
Jiangsu	0.39	0.06	65.42	20.77	0.43	0.80	11232.28	168.42	19.10	3.96	2594.78	1	0.4
Zhejiang	0.27	0.04	45.81	11.84	0.28	0.97	4194.76	203.76	21.50	5.47	2360.2	0.88	0.40
Fujian	0.66	0.03	172.26	55.36	0.24	0.91	8824.77	174.99	25.80	3.74	1436.48	1	0.31
Hebei	1.16	0.09	95.68	17.39	1.04	0.51	13420.40	188.78	12.10	3.08	2914.73	1	0.43
Henan	1.56	0.09	118.03	16.76	0.95	0.66	11371.08	140.16	10.80	3.71	4802.51	0.93	0.47
Shandong	0.79	0.08	120.90	35.56	1.00	0.54	25872.24	168.66	12.80	3.79	3371.4	1	0.48
Chongqing	1.20	0.08	71.05	11.02	0.78	0.91	2309.63	146.73	33.60	4.04	695.76	1	0.40
Guangxi	1.92	0.09	126.77	17.70	0.40	0.38	12164.07	148.01	27.00	4.50	1605	0.92	0.43
Sichuan	2.11	0.08	42.78	6.32	0.84	0.90	10701.05	148.11	33.00	3.68	3257	1	0.55

Table 2 (continued)

Region	Resource endowment index	Farmland area per capita	Livestock manure nitrogen load of farmland	Livestock manure phosphorus load of farmland	CCAI of maize	CCAI of soybean	Total yield of feed production	Pig sell rate	Pork consumption per capita	Average wage of urban units employment in animal husbandry	Rural employment	Comprehensive technical efficiency of production efficiency	Comprehensive comparative advantage value
Hainan	1.49	0.08	118.28	15.46	0	0.27	2425.25	137.38	27.00	4.29	317.69	0.90	0.31
Weight	0.10	0.12	0.07	0.04	0.09	0.10	0.14	0.04	0.08	0.08	0.12	0.03	

170 kg/ha. The maximum, minimum, and average nitrogen loads of farmland from livestock manure were 188.59 kg/ha in Guangdong, 3.68 kg/ha in Tibet, and 85.41 kg/ha, respectively. The results are shown in Fig. 1c.

In 2016, the phosphorus load of farmland from livestock manure in most provinces or municipalities, except for Shandong and Fujian, did not exceed the limit value of 35 kg/ha. The maximum, minimum, and average livestock manure phosphorus loads of farmland were 55.36 kg/ha in Fujian, 0.42 kg/ha in Tibet, and 15.76 kg/ha, respectively (Fig. 1d) The maximum, minimum, and average total yields from feed production were 28,248,133.00 kg in Guangdong, 0 in Tibet, and 6,747,588.48 kg, respectively (Fig. 1g). The maximum, minimum, and average pig sale rates were 203.80% in Zhejiang, 48.90% in Tibet, and 155.20%, respectively (Fig. 1h). The maximum, minimum, and average pork consumption per capita was 33.60 kg in Chongqing, 3.80 kg in Xinjiang, and 18.20 kg, respectively (Fig. 1i). The maximum, minimum, and average wage of urban unit employment in animal husbandry was 63,681.00 in Tibet, 19,893.00 in Shanxi, and 40,507.16, respectively (Fig. 1j). The maximum, minimum, and average rural employment was 48,025,100 in Henan, 1,379,785 in Tibet, and 15,249,757, respectively (Fig. 1k). Ultimately, the comprehensive technical efficiency of most provinces or municipalities was 1.00, and that of other provinces or municipalities exceeded 0.80. However, the comprehensive technical efficiency of Tibet was 0 due to lack of data. The results are shown in Fig. 1l.

Results of comprehensive comparative advantage of pig production and development in China

The spatial distribution results were obtained using formulae (6)–(9) and GIS spatial analysis techniques based on results of each factor of the comprehensive comparative advantages of pig production and development in China. The results were graded by the Natural Breaks (Jenks) method (Table 2 and Fig. 2a).

Heilongjiang and Sichuan had high comprehensive comparative advantage values of pig production and development, which had evident comprehensive advantages and were highly suitable for pig production. Henan, Hebei, Shandong, Anhui, Guangdong, Yunnan, Jilin, Inner Mongolia, and Guangxi had relatively evident comprehensive advantages in pig production, which were suitable for the development of pig production. The comprehensive comparative advantage values of pig production and development in Chongqing, Jiangxi, Gansu, Hubei, Jiangsu, Guizhou, Hunan, Zhejiang, and Liaoning were average, as well as their respective pig production capacities.

The comprehensive comparative advantage values of pig production development in Shanxi, Shanxi, Hainan, Ningxia, Xinjiang, and Fujian were weak, whereas those in Beijing,

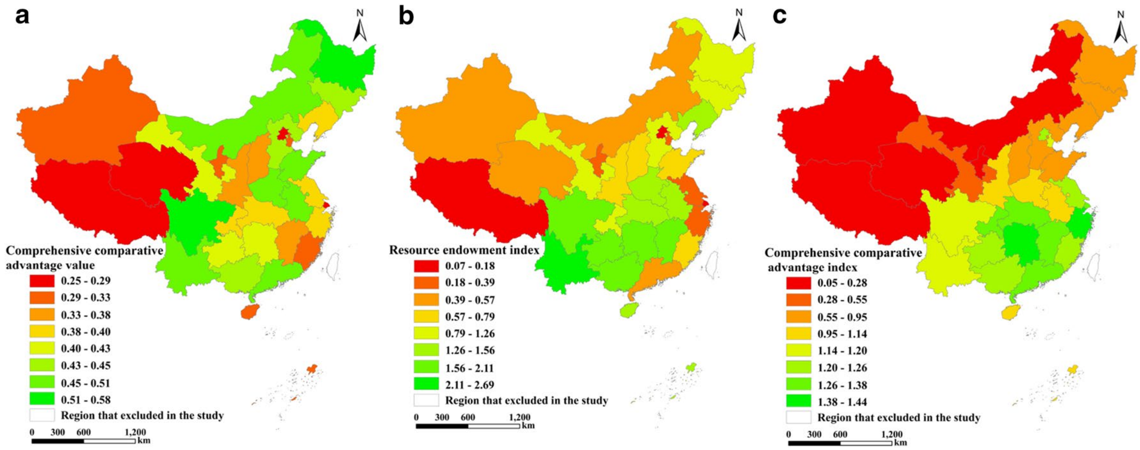

Fig. 2 Spatial distribution results of resource endowment index, comprehensive comparative advantage index and comprehensive comparative advantage value of pig production and development in China

Tianjin, Tibet, Qinghai, and Shanghai were extremely weak; both results were unsuitable for the development of pig production. Moreover, pig production in these places should be restricted. In view of the statistical data, the maximum comprehensive comparative advantage value of China's pig production and development was 0.58 in Heilongjiang, followed by 0.55 in Sichuan, and a minimum of 0.25 in Beijing.

In comparison with the current research results (Hu et al. 2009; Li and Qin 2009; Zhu et al. 2014; Yue et al. 2018; Wang et al. 2018a, b), this study focused on environmental pollution factors, maize and soybean feed supply factors, and land resource factors in pig production because the pig production industry faces environmental pressure and land resource shortage; these problems are caused by pig manure pollution, disjointed breeding and farming, and the high dependency of feed raw materials on the outside world (Tang et al. 2017; Kong and Wang 2017). This study combined the nitrogen (phosphorus) load of farmland from livestock manure and the CCAI of maize and soybean to perform the comprehensive comparative advantages of pig production and development in China and analyze the potential quantity of pig production in China, in accordance with the requirement of Document No. 1 in 2016 (that is, "adjusting regional breeding layout and optimizing livestock and poultry breeding structure according to environmental capacity"; Huang 2017). This study is also performed in accordance with the Central Document No. 1 in 2017; this document recommends the stabilization of pig production, the optimization of pig production regions, and guidance of the transfer of pig production capacity to regions with large environmental capacity and major maize production regions (Wang 2017).

The comprehensive comparative advantages of pig production and development with resource endowment index (Hu et al. 2009; Xie et al. 2019) and CCAI from geometric mean of efficiency and scale advantage indices (Li and Qin 2009; Wang et al. 2018a, b) were also calculated, respectively. The results were graded by the Natural Breaks (Jenks) method (Fig. 2b, c).

On the basis of the results using resource endowment index, Yunnan, Sichuan, Guizhou, Guangxi, Hunan, Anhui, Liaoning, Hainan, Henan, Hubei, and Jiangxi had comprehensive advantages of pig production and development. In light of the results with CCAI, Hunan, Zhejiang, Guangdong, Chongqing, Hubei, Fujian, Beijing, Guangxi, Guizhou, Jiangsu, Shanghai, and Jiangxi had comprehensive advantages of pig production and development. In comparison with the results of resource endowment index and CCAI in China (Fig. 2b, c), the results in this study were more in accordance with the key development or potential growth regions defined in the National Pig Production Development Plan 2016–2020.

Results from the analysis of potential quantity of pig production in key pig production and development regions in China

On the basis of the results, 11 provinces or municipalities (i.e., Heilongjiang, Sichuan, Henan, Hebei, Shandong, Anhui, Guangdong, Yunnan, Jilin, Inner Mongolia, and Guangxi) with high comprehensive comparative advantage values of pig production and development were selected as the key regions in China.

Given the EU standard for the limitation of nitrogen (phosphorus) load of farmland from livestock manure as criteria (nitrogen: 170 kg/ha, phosphorus: 35 kg/ha) (Schröder et al. 2003; Oenema et al. 2004), the result from the analysis of potential quantity of pig production in the key regions in China was obtained using formula (8) and GIS spatial analysis techniques from the perspective of sustainable

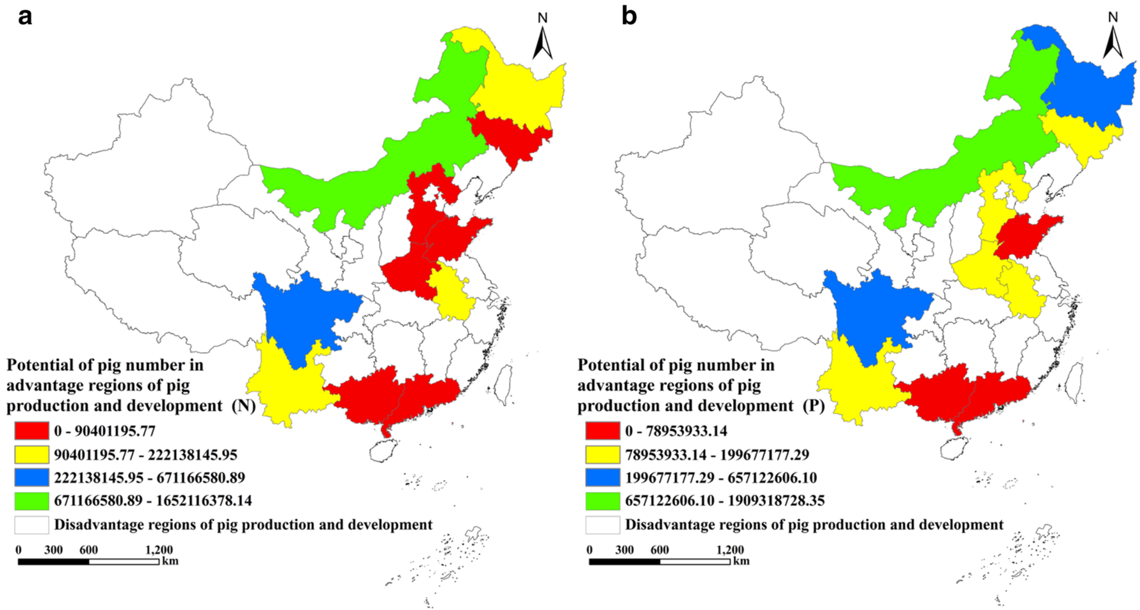

Fig. 3 The potential quantity of pig production analysis result in key pig production and development regions in China

environmental development. The results were graded by the Natural Breaks (Jenks) method (Fig. 3a, b).

The result from the analysis of potential quantity of pig production in key regions in China was different when the EU standard for the limitation of nitrogen (phosphorus) load of farmland from livestock was considered.

According to the EU standard for the limitation of nitrogen load of farmland from livestock, Inner Mongolia and Sichuan had a great potential quantity of pig production; Anhui, Yunnan, and Heilongjiang had an average potential quantity; Jilin, Shandong, Guangdong, Guangxi, Henan, and Hebei had a small potential quantity.

In view of the statistical data, the total, average, maximum, and minimum potential quantities of pig production in the 11 key regions in China were 3,193,033,418.55, 290,275,765.32 and 1,652,116,378.14 in Inner Mongolia, and 0 in Guangdong, respectively. The nitrogen load of farmland from livestock manure in Guangdong Province exceeded the EU limit. Therefore, the potential quantity of pig production in Guangdong was 0.

According to the EU standard for the limitation of phosphorus load of farmland from livestock manure, Inner Mongolia, Heilongjiang, and Sichuan had a great potential quantity of pig production; Anhui, Yunnan, Jilin, Henan, and Hebei had a general potential quantity; and Guangdong, Guangxi, and Shandong had a small potential quantity.

In view of the statistical data, the total, average, maximum, and minimum potential quantities of pig production in the 11 key pig production and development regions in China were 3,920,097,028.50, 356,372,457.14, and 1,909,318,728.35 in Inner Mongolia, and 0 in Shandong. The phosphorus load of farmland from livestock manure in Shandong Province exceeded the EU limit. Therefore, the potential quantity of pig production in Shandong was 0.

The research results by Liang et al. (2013) corroborated that the comprehensive production capacity of pig production ranked in the first level (including Sichuan, Hunan, Heilongjiang, Henan, Jilin, Inner Mongolia, Shandong, and Yunnan). This study affirmed that the high comprehensive comparative advantage value of pig production development includes the provinces of Heilongjiang, Sichuan, Henan, Hebei, Shandong, Anhui, Guangdong, Yunnan, Jilin, Inner Mongolia, and Guangxi.

The results of Liang et al. (2013) and of this study overlap to some extent. However, some differences are also present due to the differences in factors. On the basis of the results of the comprehensive comparative advantages of pig production and development in China, 11 provinces (i.e., Heilongjiang, Sichuan, Henan, Hebei, Shandong, Anhui, Guangdong, Yunnan, Jilin, Inner Mongolia, and Guangxi) were identified as key regions in China (Fig. 4a).

Except for Anhui and Guangdong, the other provinces belonged to the key development or potential growth regions defined in the National Pig Production Development Plan 2016–2020 (Fig. 4b). The comparison results contended that the results in this study had certain scientific rationality.

This study performed the comprehensive comparative advantages of pig production and development in China and the potential quantity of pig production analysis in the country. The work could aid in realizing the visual expression of the results and in making the potential quantity of pig

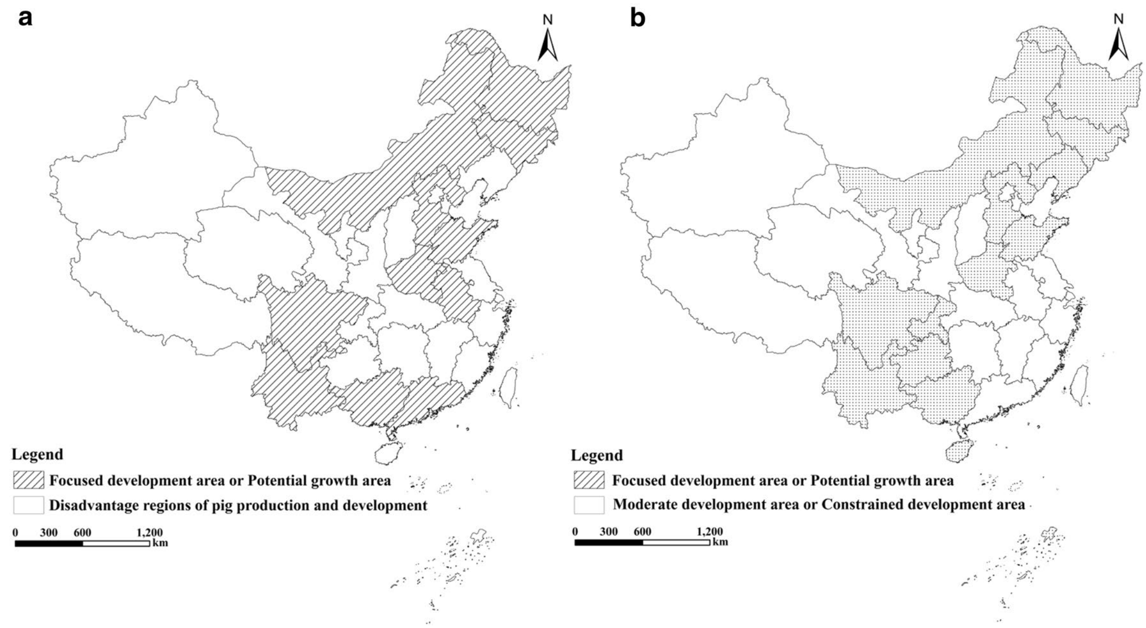

Fig. 4 The key pig production and development regions in China determined by this paper and the key development regions or potential growth regions defined in the National Pig Production Development Plan 2016–2020

production intuitive and visual using the GIS spatial analysis method.

Conclusions

This study calculated each factor of the comprehensive comparative advantage of pig production and development in China. A CCAI system and a comprehensive comparative advantage model of pig production and development were also established. The results of comprehensive comparative advantage values of pig production and development were obtained for the 11 selected key regions in China (e.g., Heilongjiang, Sichuan, Inner Mongolia, and Henan). Moreover, the comprehensive comparative advantages of pig production and development with resource endowment index and CCAI were also calculated and compared with the results in this study. On this basis, the potential quantity of pig production in the 11 key regions was calculated.

The results are of great significance in optimizing the distribution of pig production in China under the dual constraints of environment and resources and in sustaining the rapid development of pig production in the country. The study also had a certain reference value for the strategic adjustment plan of the pig farming industry in China, such as moving from south to north and from east to west.

However, problems must still be addressed in the future study. First, this study considered the potential environment pollution from livestock manure in the key regions on the basis of the EU limit value of the nitrogen (phosphorus) load of farmland from livestock manure. Moreover, other indicators, such as livestock density, alarm value of equivalent pig manure load of farmland, and pollution load index of water body, were not considered. Second, the results would be more accurate at the city, county, or township scale than at the province scale, given the evident spatial differences in the comprehensive comparative advantages of pig production and development in different administrative regions.

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