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Large-scale production: A possible way to the balance between feed grain security and meat security in China

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ABSTRACT

Food security as a national strategy, closely links to China's economic progress, people's livelihoods and social harmony. The balance between feed grain security and meat security remains a key unresolved issue that significantly impacts China's integral food security goal. In this study, we first apply food security index to demonstrate the efficacy of the self-sufficiency rate as an indicator for evaluating the food security situation, and then evaluate meat security and feed grain security with self-sufficiency rate, as well as explore their production challenges and successful long-term development experiences based on related agricultural data. We find that the burgeoning meat consumption has made feed grains a "rigid demand", among which pork and soybean are critical parts. Pork consumption accounts for over 65% of total meat consumption in 2020, but its self-sufficient rate is waning. Moreover, the self-sufficiency rate of soybean is as low as 0.15, and a great unit yield gap between China and the United States. However, the current production patterns have already reached their attainable potential in production efficiency due to the declining growth rate of unit yield, which also pose challenges for improving production efficiency and domestic supply of soybean. According to the projection by FAO-OECD, the growth rate of unit yield of soybean will remain stagnant from 2020 to 2030. Furthermore, the percentage of medium-scale and large-scale pig farms is remarkably low, accounting for only 0.578% and 0.013%, respectively. Further analysis indicates that large-scale production in soybean and pig industry offers notable advantages in improving production efficiency and reducing feed consumption. Finally, based on factors such as soybean sowing area, regions with high pig slaughter and scale farms, farm size and the pig regional development planning, we propose the integration of soybean-pig in large-scale production in selected possible provinces, which has the potential to improve the production efficiency of soybean and pig, to strike a balance between feed grain security and meat security. This study has practical significance in optimizing the production space of feed grains and livestock products, to improve production capability and ensure China's food security.

1. Introduction

Food security holds paramount importance in national development and human well-being [1,2]. Achieving food security and food system sustainability is one of the greatest challenges in China [3]. Benefiting from high unit yield of grains and substantial agricultural output, Chinese diets have leapt from "eat enough" to "eat well" [4]. Despite significant progress made in increasing food production to ensure national food security over the past decades [5], there are still some new challenges needed to be addressed. Rapid economic growth and urbanisation have prompted a shift in residents' dietary structures and nutritional

preferences, with a greater inclination towards protein-based foods and dairy products [6,7], which requires more grains that are used as feed to meet the need of meat production [8]. The competition for grains used as human food or livestock feed has emerged as a new concern for China's food security [2]. The No.1 Central Document in 2022 explicitly highlights China's focus and concern regarding food security is mainly reflected in the continued growth of demand for feed grains. China's emphasis has thus shifted from grain security to feed grain security [9]. Maize and soybean are the primary feed grains in China, with 189.64 million tons of maize and 95.52 million tons of soybean used for feed purposes in 2020 [2,10]. China's grain demand has been steadily

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growing, reaching approximately 610 million tons in 2020, of which feed grain demand will reach 298 million tons [11]. Furthermore, it is expected that the supply-demand gap will reach 109.20 million tons and 179.40 million tons in 2030 [12]. However, the current feed grain supply gap remains substantial, resulting in significant import dependence and a rapid expansion of feed raw material imports [13]. China stands as the world's largest consumer of soybean, with imports witnessing substantial growth since the 2000s [14]. In 2020, China's soybean imports have reached 100.33 million tons, and it is predicted that China will continue to import 85% of the world's soybeans until 2028 [15,16]. Meat are also the major import items, accounting for 40.88% of China's total agricultural imports from European Union in 2020, marking a 29.92% increase in the structure of agricultural imports compared to 2020 [6]. In 2021, meat consumption reached 90.59 million tons, resulting in a 9.2million tons supply-demand gap. The "14 Five-Year Plan for Promoting Agricultural and Rural Modernization" set a target for China's total meat production to reach 89 million tons by 2025, which will increase pressure on meat production and imports. Consequently, a critical issue emerges: how to strike a balance between feed grain security and meat security simultaneously [17,18]. If China increase feed grain imports, China could ensure sufficient feed for meat production and achieve near self-sufficiency in meats. Conversely, limiting feed grains import would increase its purchase prices, leading to higher costs of meat production. There is no enough feed for meat production, and meat imports may increase to meet domestic consumption, which will decline meat security [19]. In practice, the Chinese government prioritizes the importation of feed grains over meats [20], because of frequent animal epidemics and stringent food quarantine. However, the international trade market is extremely unstable and unpredictable, such as trade wars and changes in international relations. The global COVID-19 outbreak further exacerbates uncertainties in international food markets and food supply; thus, most governments have recognized the significance of ensuring the domestic food supply and partly reduced food export to other countries [19]. Therefore, relying solely on feed grain imports is not a sustainable long-term solution to China's feed grain security and meat security, and maintaining a certain domestic supply capacity is essential to cope with fluctuations in international trade. Instead, alternative approaches are either to improve feed grains production efficiency to meet the needs of meat production and ensure feed grains security, or to improve livestock production efficiency to ensure meat supply while conserving feed grains.

China's agricultural production are primarily dominated by smallholder farms [21], which faces significant pressure to provide an adequate food supply for 18% of the global population with less than 9% of the world's arable land [22]. There are currently more than 200 million smallholder farms across the country, with an average farm size of less than 1 ha [23]. Based on data from 2017, over 70% of cropland is managed by farmers with a farm size smaller than 0.6 ha, over 90% of farms are smaller than 16 ha, with farms larger than 16 ha identified as large-scale farms [24]. The number of large-scale farms is obviously less, primarily distributed in Heilongjiang in the northeast and Xinjiang in the northwest of China. Smallholder farms misuse and overuse fertilizers in China, while large-scale farming has been recognized as a feasible way to achieve both production efficiency and environmental management [25]. According to the China Animal Husbandry and Veterinary Yearbook, pig farms with over 50 slaughtered pigs are considered as scale farms. Chinese smallholder pig producers, typically have low pig output per year [26]. Moreover, approximately 90% of all farmed pigs in China are still produced on small-scale farms. These traditional pig farming practices often neglect the importance of geographical location in the appropriate farm construction, and farmers tend to raise pigs in close proximity, resulting in low space utilization and generally poor infrastructure [27]. These farms are more vulnerable to the impact of animal-borne diseases, making it difficult to track and control epidemics [28]. Traditional backyard farming (less than 50 pigs) also consume substantial natural resources [29]. Large-scale pig farming is seen as a

promising strategy to improve farmers' income and enhance farming productivity [30,31]. Nowadays, grain production is increasingly becoming an integrated component of the agricultural industry chain for many large-scale farms, which often cooperate with planting, livestock, and renewable energy production together [32]. Compared to smallholders, large-scale farms have advantages in adopting advanced technology, responding to market volatility, and implementing sustainable farming managements [33,34].

As for how to measure the security situation in food system, food security assessment may be an effective way. Food security is a multi-concept that aims to ensure people's survival and health, and then gradually to food accessibility, availability, utilization, and stability [35], which include ration security, feed grain security, meat security and so on. There is no consensus on indicators or variables that best represent food security [36]. It can only be identified when a specific objective is clearly demonstrated [37]. According to studies, there are two common methods to assess food security. One of them is the analysis of food supply and demand. For example, Lu (2022) evaluated the output and per capita consumption of grains, meats and other foods from 2013 to 2020 to examine China's food security practices. Self-Sufficiency Rate (SSR) is the well-known empirical coefficient that reflects food supply and demand [38]. Several studies have investigated China's food self-sufficiency in its current situation and for the future in the national level [39] and provincial level [40]. [38] measured the food self-sufficiency rate in China under rapid urbanisation. [41] used grain self-sufficiency rates to assess food security in China as a whole. The another method is to calculate the food security index from availability, accessibility, stability and utilization, proposed by FAO [42,43]. Taking [44] as an example, this study pointed out that food security in China experienced three phases "stable-slightly increasing-rapidly increasing" according to the food security index. The positive projections of China's food security often underestimated the rising demand for meats and feed grains [39]. Although many studies have assessed food security in China from different perspectives and methods and have provided useful general quantitative and qualitative results, few studies focus on feed grains and meats [45]. There are some studies examine the production and consumption of feed grains from a specific point in time, lacking a comprehensive analysis of the long-term supply and demand dynamics and future projections [12]. Therefore, this study aims to address these gaps by specifically measuring feed grain security and meat security, analyzing their production situation (challenges and experiences), and finally proposed a practical way to improve their production efficiency.

The paper' structure and research framework are as follow (Fig. 1). Section 2 outlines the research design, including the data, materials, and methods about food security index, self-sufficiency rate and the degree of scale farming in the pig industry. In Section 3, we first compare two assessment methods, namely the food security index and self-sufficiency rate, to demonstrate the effect of the self-sufficiency rate for evaluating food security. Then the self-sufficiency rate is applied to evaluate meat security and feed grain security, while also analyzing the production challenges and experiences associated feed grain and meat. Section 4 offers a comprehensive discussion about soybean production problems and policies, pig production and its environmental problems, the linkage between crop and livestock, proposing to integrate soybean-pig in large-scale production as a potential means of achieving a balance between feed grain security and meat security. Finally, Section 5 concludes the research, highlighting its limitations and suggesting for future development.

2. Materials and methods

Achieve feed grain security and meat security holds significance for China. feed grains play a crucial role in meat production, and achieving self-sufficiency in meat is mostly contingent upon availability of feed grains [45]. Quantitative and detailed assessment of feed grains and meat security, as well as production challenges and experiences are

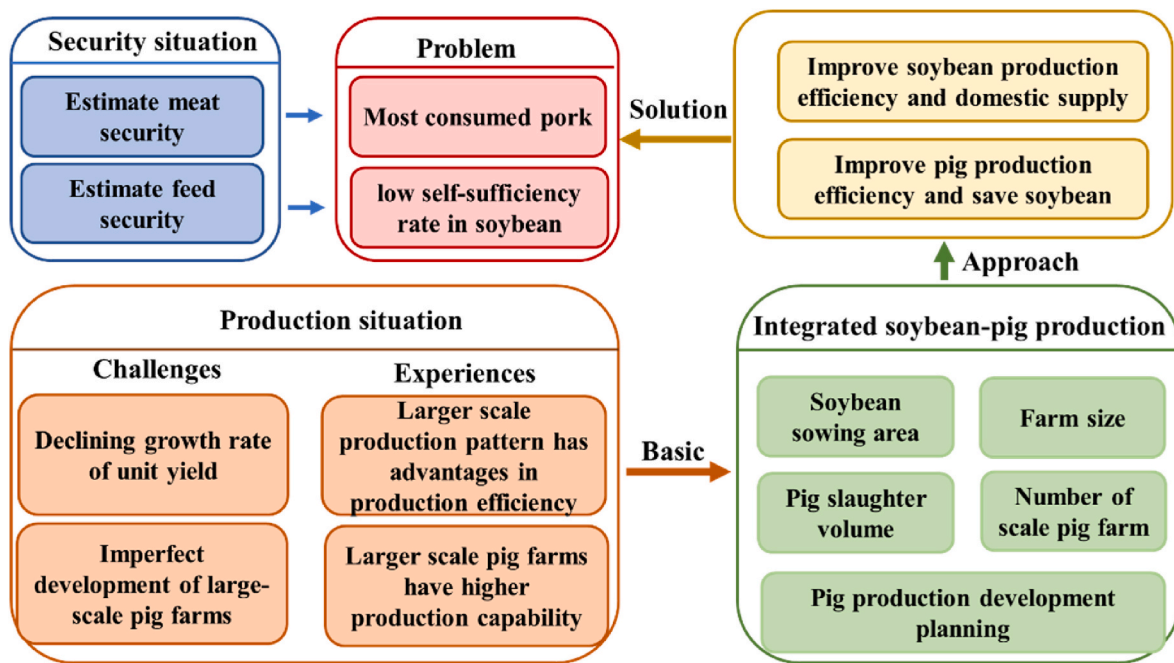


Fig. 1. Research framework.

necessary, which also provide a comprehensive understanding of the key issue related to the overall food security. As one of the critical aspect of evaluating food security, self-sufficiency focuses on a region or country's capacity to satisfy its domestic food demand [46,47], especially in the international environment uncertainties [48]. We will elaborate data used in this study. Data is used for not only calculating the self-sufficiency rate and food security index, but also the analysis of production challenges and experiences.

2.1. Data description and source

The time and source of all data in this paper are listed in Table 1. The historical data of yield, import, export, supply, demand, and unit yield of crops from 1961 to 2020 were collected from China National Bureau of Statistics, United States of America are from United States Department of Agriculture and Food and Food and Agricultural Organization of the

Table 1
The list of data and their sources.

Name	Time	Source and website
Yield, import, export, supply, demand, unit yield of crops and meats in China	1961–2020	China National Bureau of Statistics (https://data.stats.gov.cn/easyquery.htm?cn=E0103)
Yield, import, export, supply, demand, unit yield of crops in United States of America	1961–2020	United States Department of Agriculture (https://quickstats.nass.usda.gov); Food and Agricultural Organization of the United Nations-FAOSTAT (https://www.fao.org/faostat/en/#data)
Unit yield	2021–2031	Organization for economic Co-Operation and Development-OECD. Stat (https://stats.oecd.org/)
Rate of scale feed, net profit of pig production	1995–2020	China Animal Husbandry and Veterinary Yearbook (https://navi.cnki.net/knavi/yearbooks/YZGX/detail?uniplatform=NZKPT&language=chs)
Feed cost, feed grain consumption, feed days, epidemic medical investment of different degree pig farms	2012–2020	Ministry of agriculture and rural affairs of the people's republic of china-database (http://zdcx.moa.gov.cn:8080/nyb/pc/index.jsp)

United Nations-FAOSTAT. The prediction data of unit yield of crops from 2021 to 2031 were from Organization for economic Co-Operation and Development-OECD.Stat. The data of rate of scale farming and net profit over 31 provinces in pig industry mainly from China Animal Husbandry and Veterinary Yearbook. Feed day, cost, net profit, epidemic medical investment of different pig farms is from the database of the Ministry of Agriculture and Rural Affairs of the People's Republic of China. The websites of all data sources are presented in the table.

2.2. Food security index

Indicator selection According to the endorsed definition by FAO, food security is defined as “the state in which all people, at all times have physical and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences, ensuring an active and healthy life” [49]. This comprehensive definition encompasses four key dimensions: availability (ensuring an adequate food supply), accessibility (ensuring adequate resources and means to obtain food), utilization (promoting nutritious and safe diets, and clean water) and stability (maintaining consistent food security over time) [50]. Among four dimensions, food security is not only the quantity of food available, but also the physical and financial ability to access it, along with the capacity to utilize food effectively through proper processing and preparation practices. To measure the four pillars of food security, specific indicators have been selected based on previous studies and practical food production in China. These indicators are not only relevant to food production and food security within China but also have broad applicability across different regions and periods. The pillars, sub-pillars and indicators are presented in Table 2.

Normalisation is achieved with a min-max function that transforms each indicator into a value from zero to one.

$$x' = \frac{X - X_{\min}}{X_{\max} - X_{\min}} \quad (1)$$

where X is the actual value of indicators and X_{\min} and X_{\max} represent its minimum and maximum, respectively.

Weighting First of all, it is important to note that the four pillars of food security carry equal weight in the assessment, as they are equally important to food security. Determining the weights is a subjective

Table 2

Pillars and indicators of the food security index [45,51].

Pillar	Sub-pillar	Indicator	Description and implication
Availability		Average dietary energy supply adequacy Average protein supply	Measure in kilocalories and protein per capita per day in a region, indicating the variety and nutritional quality of average diets, as well as the safety of food
Accessibility	Physical	Length of railroad lines in service Length of highway lines in service Length of inland waterway lines in service Length of aviation lines in service	Measure the ability of a region to access food in physical conditions and the ability of consumer to purchase food, how consumer can afford to the price shocks, it indicates resident's economic ability
	Economic	GDP, per capita Household consumption level	
Utilization		Using at least basic drinking water	The ability to utilize food well through good processing and preparation
Stability	Social	Agricultural employed population, share of total population	Measure the capability of agricultural production and food supply, assess a region's expose to the nature risks affecting food production and provision
	Natural hazard	Affected by disaster areas, shared of total population	

process [52], but assigning equal weights is a commonly accepted approach that minimize subjectivity [53]. However, some subjectivity may still exist in determining the weights when calculating the food security index. It is worth noting that this might affects the absolute value of the index, but it does not change the overall time trend and scale difference of food security [54]. The weight assigned to each indicator and sub-pillar varies based on the number of indicators selected in each dimension. The weight of pillar N , sub-pillar S and indicator V is as follows [53]:

$$W_s = \frac{1}{N} \times \frac{1}{S} \text{ and } W_v = \frac{1}{N} \times \frac{1}{S} \times \frac{1}{V} \quad (2)$$

where N , S , and V are the number of pillars, sub-pillars within a pillar and indicators within a sub-pillar, respectively.

Aggregation is the final step in calculating the food security index, which different pillars are combined to create a composite index. Compensatory or non-compensatory technique can be applied in it, depending on how far food security needs to be balanced between different indicators. A recommendation approach by Casadio Tarabusi and Guarini (2013) is the “mean-min” aggregation function, which is compatible with both compensatory and non-compensatory frameworks. This function can be expressed as a weighted arithmetic mean and a minimum function, where the composite index falls between the mean and the lowest normalized value of the indicators within a sub-pillar. The former reflects perfect compensability, and the latter represents the maximum penalization for imbalances between indicators. The function returns different scores based on a penalization factor α and a complementarity factor β . This approach considers the extent to which a country's performance requires trade-offs between indicators using compensatory or non-compensatory methods is considered. The function is as follow:

$$y_{c,t}^s = \mu_{c,t}^s - \alpha \left(\sqrt{\left(\mu_{c,t}^s - \min(x'_{c,t,v}) \right)^2 + \beta^2} - \beta \right) \quad (3)$$

where y is the composite index by sub-pillar S . μ and $\min(x')$ represent

the weighted mean and the minimum value of the normalized indicators within the sub-pillar S , respectively. t is the time scale, and c is the location. A similar equation is used to aggregate the sub-pillar scores in to pillars and ultimately into the composite index. According to the existing researches, $\alpha = 0.5$ allows for partial compensability between indicators, as achieving food security needs a balanced approach across all dimensions, however, some level of imbalance between indicators is acceptable, as long as food security can be achieved by prioritizing different policies [55]. The complementarity factor β is set $\beta = 0.5$ to balance the tends and outcomes of aggregation function [53].

2.3. Self-sufficiency rate

A comprehensive and quantitative assessment of self-sufficiency rate of feed grain and meat is crucial to gain a deeper understanding of key issue related to the overall food security [46]. Studies that evaluate self-sufficiency over time at various spatial scales, offers valuable insights into regional and national variations [51]. The basic concept of self-sufficiency means the extent to which an area can meet its food needs through domestic production; in the second understanding, it also can consider the trade when defining self-sufficiency as the ratio of food production to food consumption (production/(production + imports - exports) [51]. In this study, we analyze the self-sufficient rate in China based on the basic concept and trade. The food Self-Sufficiency Rate (SSR) is calculated using an empirical coefficient method to measure the production and consumption of a specific region, as follows [56]:

$$SSR_t = \frac{P}{P + I - E} \times 100\%$$

where SSR is the self-sufficiency rate in year t . P is the total production, which can be feed grains, meats. I and E represent the value of import and export in China, and the $P + I - E$ indicates the consumption in a region or country [38].

2.4. The degree of scale farming in pig industry

According to the China Animal Husbandry and Veterinary Yearbook, the degree of scale farming in pig industry is defined with the number of slaughtered pigs. There are two types of pig production. One of them is backyard pig production, which the number of slaughtered pigs is less than 50. The other is scale farming, which the number of slaughtered pigs is more than 50. In a more specific definition, scale farms are classified into three types: small-scale farms (50–499 pigs slaughtered), medium-scale farms (500–9999 pigs slaughtered) and large-scale farms (over 10,000 pigs slaughtered). The degree of scale farming D of the pig industry is calculated as follow:

$$D = \frac{S}{T}$$

where S is the number of pigs slaughtered on the scale farms, and T represents the total number of pigs slaughtered in all farms.

3. Results

3.1. The effect of two methods in estimating food security

Feed grain security and meat security are the two important parts of food security in China. Self-sufficiency and food security index are two main methods in estimating food security from different aspects and dimensions. Because of the data limitations, we mainly use self-sufficiency to assess their security situation, here we use food security index to test the effect of self-sufficiency in estimating food security. Here we compare the effects of two methods, as shown in Fig. 2. The food security index increased from 0.1 to 0.32. Especially after 2000, it accelerated and was significantly higher than before. A similar trend can

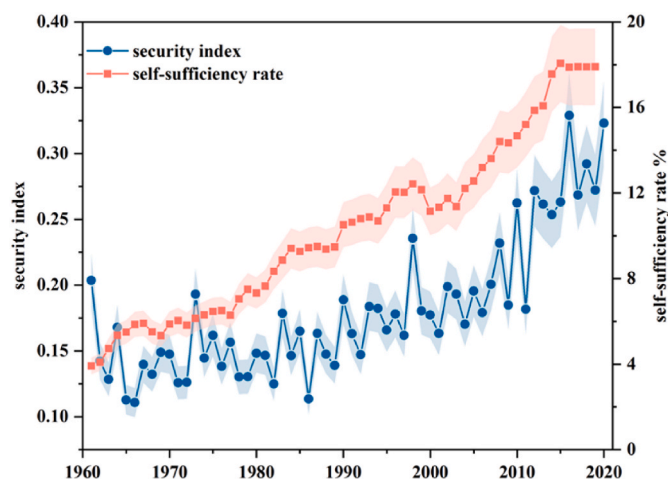


Fig. 2. Food security index and self-sufficiency rate in China.

also be observed in the self-sufficiency rate, which is another index reflecting the balance of food supply and demand. China's food self-sufficiency rate increased from 4% to 18%, indicating an improvement in food security during this period, which was smoother than the food security index. This is because the self-sufficiency rate is affected by food production, import and export, and changes linearly over time. The food security index was calculated by several indicators that do not have completely similar tendency. For example, average dietary energy supply adequacy, average protein supply and GDP increase during this period, but the share of employment in agriculture decrease gradually. The proportion of people affected by natural disasters is influenced by

extreme weather events, such as heat waves, flooding, and droughts. Therefore, the food security index varies greatly. From what has been discussed, the trend of the self-sufficiency rate is similar with that of the food security index. Self-sufficiency rate can reflect food security circumstances in China to some extent. As one of the critical dimensions of food security, self-sufficiency focuses on the ability of a region or country to meet its domestic food needs, reflecting its specific security circumstances [46]. In the following section, we will use self-sufficiency to estimate the feed grain security and meat security.

3.2. The changes in meat security and feed security

3.2.1. Changes in meat security

As shown in Fig. 3a, Before 2000, except beef, the self-sufficiency rate of pork, mutton and poultry were relatively stable and fluctuated around 1, which were nearly self-sufficiency. However, especially after 2010, meats' self-sufficiency rate showed a decreasing trend, which were not so optimistic. Meanwhile, total meat consumption increased from 2.477 million tons to 99.809 million tons in 2020, an increase of more than 40 times, with the population growth and socio-economic development. Pork consumption increased from 0.002 million tons to 0.059 million tons, a 30-fold increase, whose proportion reached its peak in 1985, accounting for approximately 84.4% of Chinese meat consumption (Fig. 3b). Pork dominated the meat consumption market in the long term. Affected by African swine fever in 2019–2020, a considerable number of pigs died, causing a sharp decline in domestic pork supply and consumption. Because of the “Enhanced Pig Circle”, declining pork consumption also has led to a low meat consumption in 2020. In addition, with the development of the social economy after 1985, per capita GDP grew rapidly. Residents were able to afford more

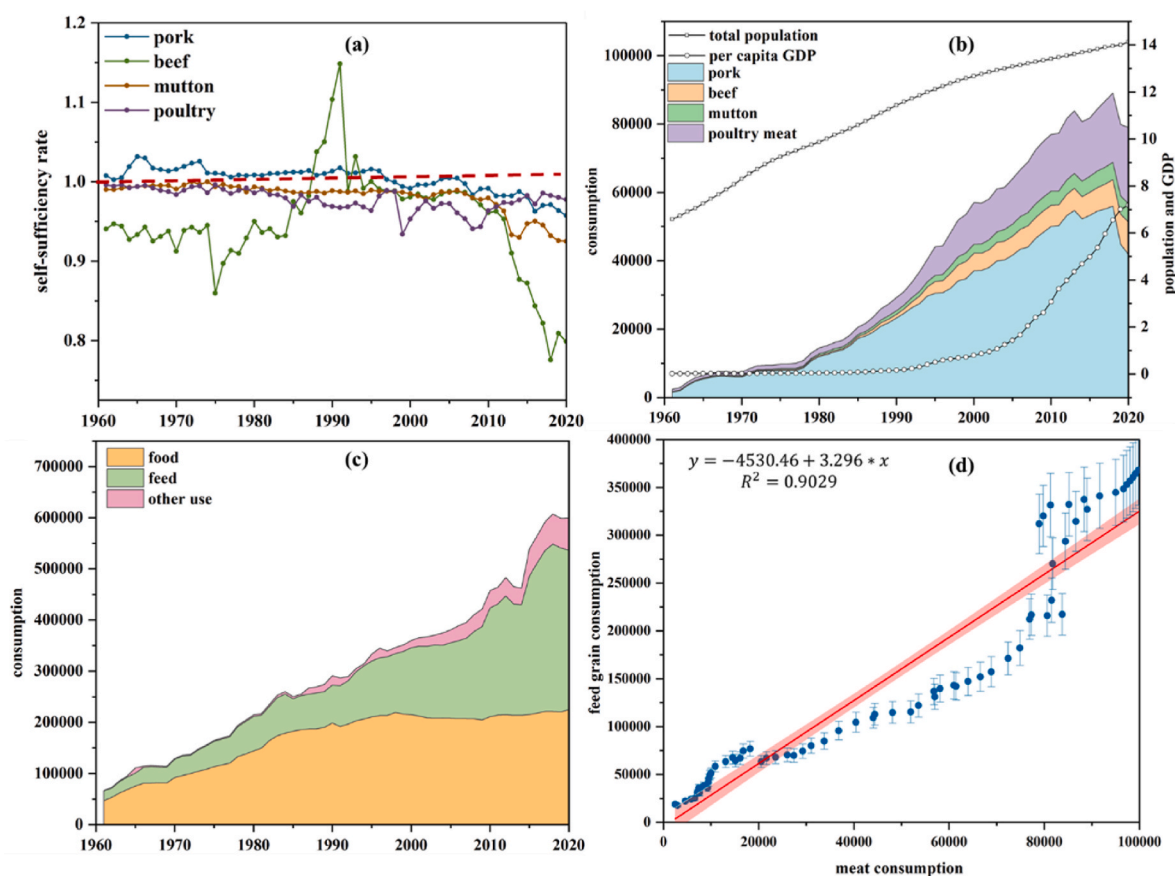


Fig. 3. (a) Self-sufficiency rate of meats; (b) Changes in meat consumption and population, GDP; (c) Grains used for feed and food; (d) The relationship of meat production and feed grain consumption.

diversified, richer and healthier meat, leading to an increase consumption of poultry meat, beef and mutton, but pork is still the main types of meat consumption. The surges in meat consumption has put enormous stress on feed grains. Although the proportion of grains used for food was greater than feed at first, because the growing population needed large quantities of rice, wheat, maize and other grains to solve the problem of food and clothing, increased meat consumption necessarily required more feed grains to meet the needs of animal-derived food production. After 2010, the growth rate of feed grains accelerated significantly and surpassing the food ratio, accounting for 56.6% of the total grain consumption (Fig. 3c). Moreover, it can be observed in Fig. 3d that meat consumption has a strong linear relationship with feed grains consumption ($R^2 = 0.9029$). We can reasonably infer that ensuring the feed grains supply is key to satisfying the demand for protein products. Besides, processed feed is used for pig production, while cow and sheep are fed on pasture.

3.2.2. Changes in feed grain security

From the perspective of feed grains production and consumption, domestic production was higher than consumption from 1961 to 2015. However, consumption gradually surpassed production, and the gap between them increased after 2015, indicating that the domestic supply of feed grains did not meet the needs for domestic livestock production. In general, international trade is an important way to address supply gap. The total import of feed grains was quite low from 1961 to 1997, mainly for maize. However, it increased sharply after 1997, and soybean accounted for over 90%. In 2020, China's soybean imports have reached about 100.33 million tons, which mainly came from Brazil, the United States, Argentina and other American countries [15,16]. An unstable and unpredictable international market will not be sustainable for the soybean supply if soybean heavily relies on import (Fig. 4).

As for the feed grains domestic production, the unit yield of maize production increased rapidly, from 1.18 t/hm² in 1961 to 6.32 t/hm² in 2020, an approximately 5.4 times increase. Except for some special years, the self-sufficiency rate of maize remains above 0.9, even over 1 in some years. Domestic maize was basically self-sufficient. However, there was a large difference compared to the United States, whose unit yield was twice that of China, and the gap is growing. Its self-sufficiency rate was more than 1 and even up to 2, making American soybeans have a strong advantage in both domestic meat production and international trade (Fig. 5a). We also observed that soybean was completely different from maize. The self-sufficiency rate of soybean showed a declining trend and dropped sharply from 0.9 to 0.15 in 2020, due to the low domestic soybean production efficiency and enormous domestic demand. The unit yield of soybean was 0.626 t/hm² in 1961 and then increased to 1.98 t/hm² in 2020, while in the United States it was 3.43 t/hm² in 2020, and its self-sufficiency rate was steadily exceeded 1.4. The

gap of the unit yield and the self-sufficiency rate between China and the US shows an expanding trend (Fig. 5b). Because of lower production efficiency and profits, farmers are not enthusiastic about planting; therefore, the domestic supply of soybean is overwhelmingly negative.

Pigs and poultry are primarily raised for protein feed, while cattle and sheep are herbivores. Pork plays a dominant role in the meat consumption. Ensuring meat security needs to stabilize pork domestic supply, which in turn relies on improving availability of feed grains such as maize and soybean. Although maize production is relatively sufficient domestically, feed grain security is still not positive owing to soybean. Because soybean is at low self-sufficiency rate, the unsustainable and scarce soybean domestic supply likely fails to meet such a huge feed demand [17]. To strike a balance between feed grain security and meat security, it is necessary to analyze the challenges and experiences associated with soybean and pork production, aiming at finding a potential strategy to improve soybean production efficiency to meet the need of pig production, or improve pig production efficiency to alleviate the strain on soybean.

3.3. Challenges and experiences of soybean and pork production

3.3.1. The declining growth rate of unit yield in soybean

The significant reduction in food security risk can primarily be attributed to the notable increase in total grain production. In 2022, China achieved a total grain production of approximately 633.24 million tons, representing a substantial 60% increase compared to the production in 1990. This remarkable growth has significantly enhanced China's capacity to meet its grain demands. The increased grain unit yield in cultivated land has played a pivotal role in this achievement [57], which is the result of various factors, including technological progress, variety improvement, increased capital investment, land system reforms [58]. As a component of the overall grain production system, the unit yield of soybean is affected not only by its specific production condition, but also by the dynamics of the entire grain production system.

The unit yield of grains showed significant phase characteristics. The trend of changes in unit yield of rice and wheat was similar and grew at the fastest pace from 1961 to 1985. During this period, a large amount of arable land, labour, chemical fertilizers and pesticides were invested in producing rice and wheat, resulting in a rapid increase in unit yield. Then, it slowed down and fluctuated around zero to near zero in 2020 (Fig. 6a and b). Different from rice and wheat, the growth rate of per unit yield in maize and soybean was higher from 1961 to 2000, which lasted approximately 15 years longer than that in rice and wheat. However, after 2000, they inevitably declined and finally stabilised at approximately zero after 2020. Although the growth rates of maize and soybean also increased slightly, production was lower than that of the previous period (Fig. 6c and d). The OECD has predicted that the growth rate of the unit yield in these four grains would be around zero in the next decade. This means that the production capability has reached a phased peak in the current grain production system, and the "ceiling" of grain production has reached. In these circumstances, it is difficult for soybean to improve production efficiency and capability in the future. With the low unit yield and decreasing growth rate of unit yield, it is difficult for soybean to improve production efficiency to improve domestic supply.

3.3.2. The limitations of pig production

Pork has dominated meat consumption in China, which also accounts for the largest proportion of feed grain consumption. With the implementation of rural renovation and environmental protection policies, a major change has taken place in the pig industry.

As shown in Fig. 7a, from 1995 to 2020, the degree of scale farming of the pig industry increased from 13.6% in 1995 to 82.29% in 2020, indicating that there was a superior output from scale farming, and it is a great improvement in pig production. At the same time, a substantial amount of backyard pig farms withdrew, sharply declining from 104.33

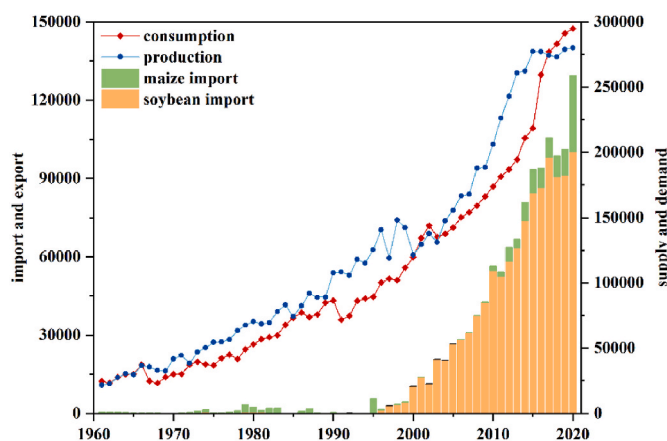


Fig. 4. The supply, demand and trade of feed grain.

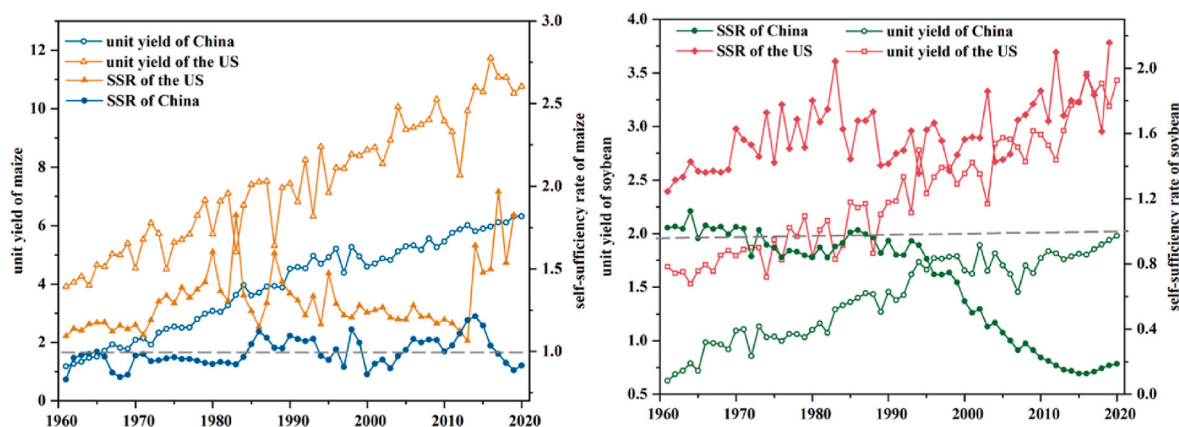


Fig. 5. Production efficiency and self-sufficiency of feed grain. (a) Maize; (b) Soybean.

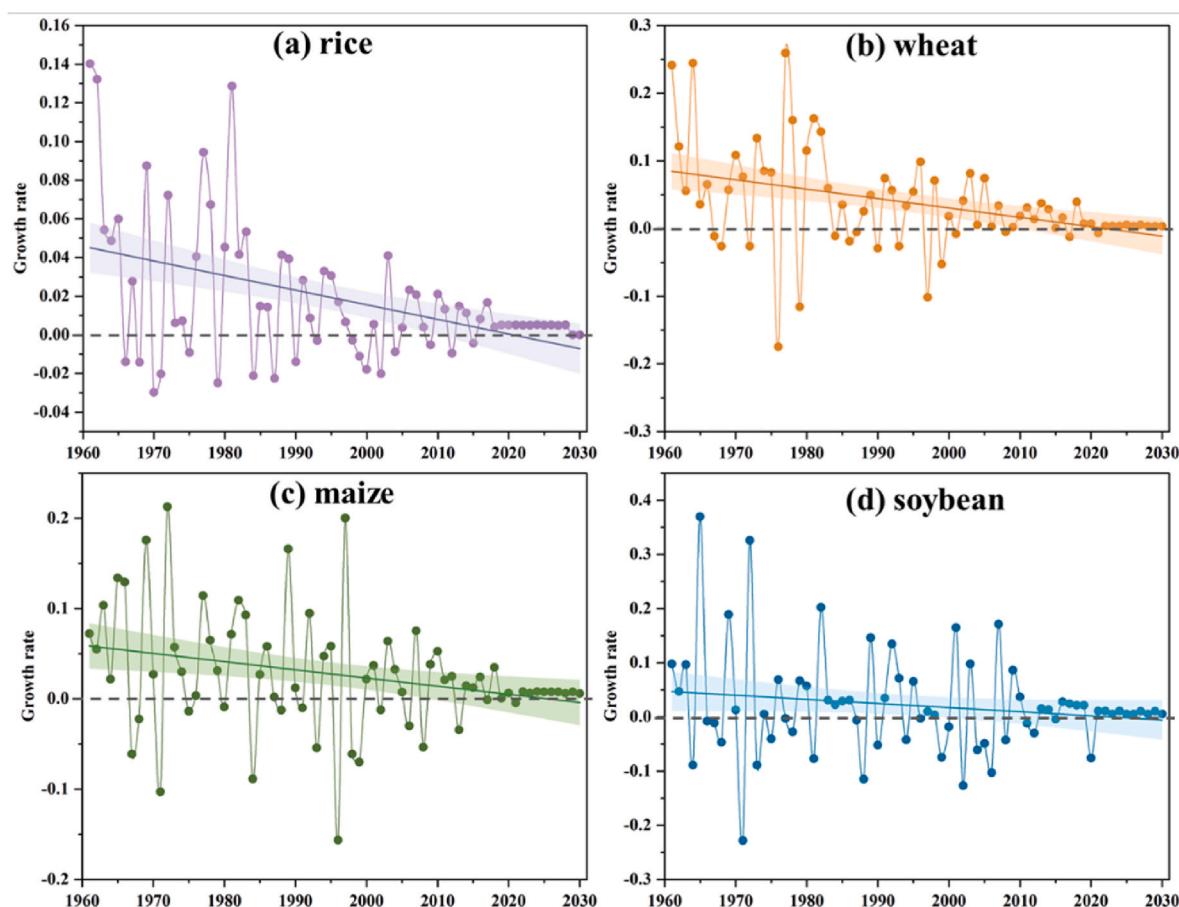


Fig. 6. The changes of growth rate of unit yield of grains.

million to 19.49 million since 1999, over five times. However, there was still a large quantity gap between backyard farms and scale farms. Although both the number and proportion of medium-scale and large-scale farms showed an ascending trend from 2002 to 2020, the proportion of medium-scale farms and large-scale farms were still at a relatively low level, only 0.578% of medium-scale farms and 0.013% of large-scale farms (Fig. 7b). With the prohibition of backyard farming, scale farming has developed rapidly in recent years. However, medium-scale and large-scale farms have not developed fully in China, and there is still a lot of development space for medium-scale and large-scale farms.

3.3.3. The advantages of large-scale production in planting and pig industry

During the long-term development of agricultural production system, both grain production and meat production have undergone transformations in response to changes in production environments, conditions, and market demands. In addition to the smallholder and backyard production, larger-scale production models have also emerged.

Adapting to local agricultural and socio-economic developments, larger scale production pattern of grains played a vital role in improving agricultural production productivity [59]. The Heilongjiang reclamation areas and its state-owned farms are typical cases. According to Fig. 8, unit yield of rice, maize, soybean and grain in Heilongjiang Province was

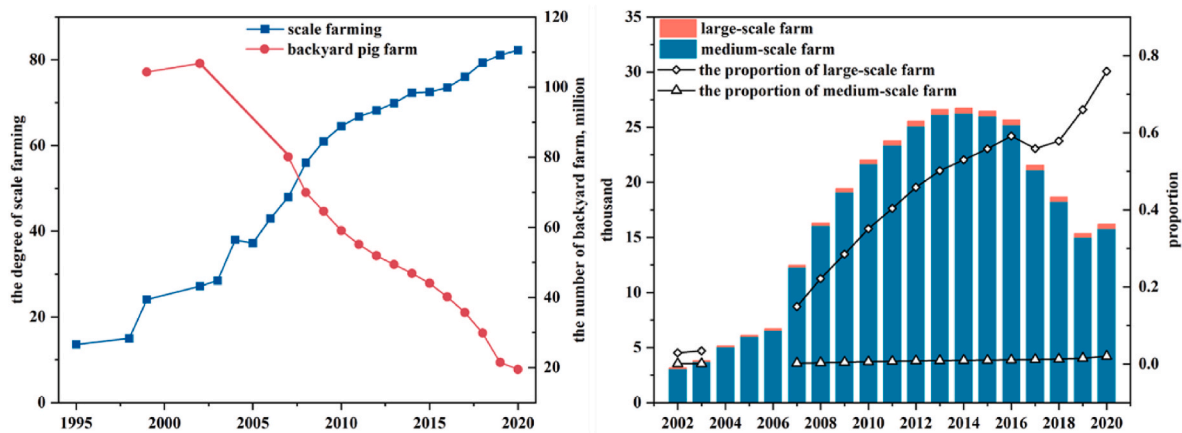


Fig. 7. (a) The changes in the degree of scale farm and backyard pig farm; (b) The number and proportion of medium-scale and large-scale farm.

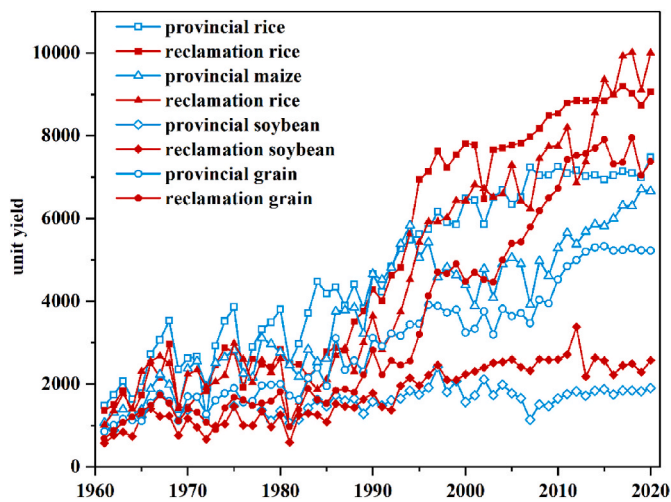


Fig. 8. Comparing the production efficiency of Heilongjiang Province and reclamation.

higher than that in the reclamation area from 1961 to 1990. Afterwards, the unit yield of these grains in the reclamation area surpassed that in Heilongjiang Province. In 2020, the unit yield of soybean in the Heilongjiang province was 1905 kg/ha, while that in the reclamation was higher to 2573 kg/ha, an increase of over 35%. As for the unit yield of total grains, it was 5223 kg/ha in Heilongjiang province but 7375 kg/ha in the reclamation, 40% higher than the whole province. State-owned farms in reclamation areas are usually large-scale, so it is easy to carry out mechanisation, centralised irrigation, unified fertilizer and modern management, which contribute to improving production efficiency. Larger scale production pattern in planting industry is an important supplement to existing agricultural production patterns and a possible way to ensure domestic grains supply and food system sustainability which not only requires an environmental-friendly manner but also pursues certain productivity and risk resistance, rather than by cropland expansion and excessive input of production factors [60]. It is also a vital way for soybean to improve its production efficiency to ensure domestic supply and achieve a higher self-sufficiency rate.

In addition to the planting industry, the pig industry has also witnessed significant advantages in larger-scale farming. Taking feeding time as an example, the average feeding day of backyard pig farms was

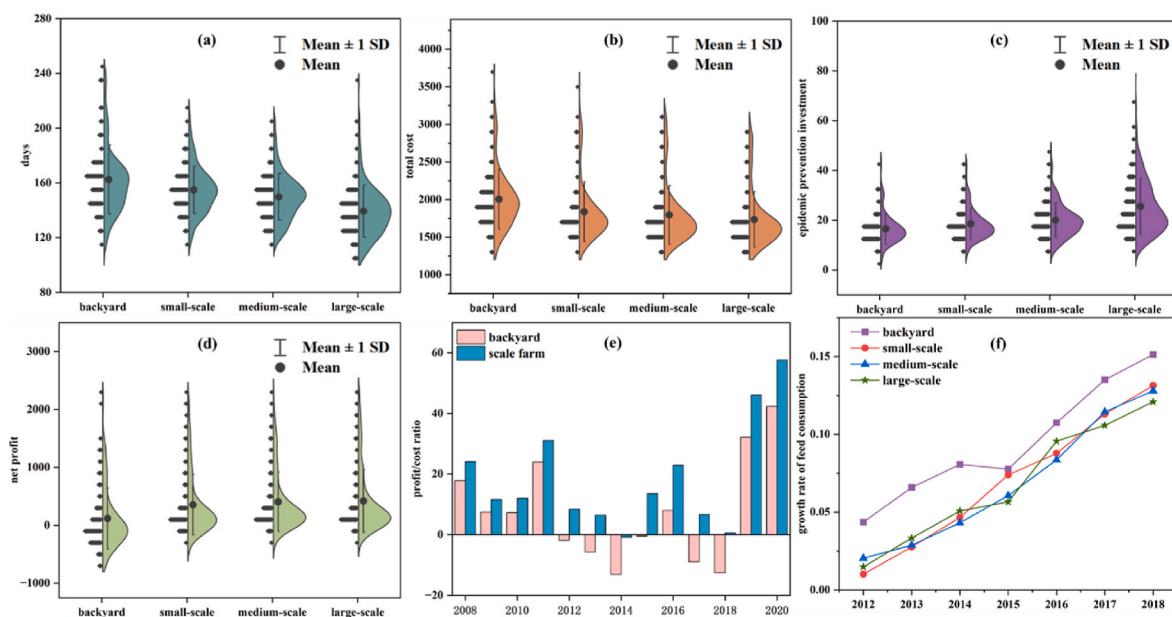


Fig. 9. (a) Average feeding days; (b) Total cost of feeding per pig; (c) Epidemic prevention investment of per pig; (d) Net profit per pig; (e) Profit/cost ratio per pig; (f) Growth rate of feed consumption in different farms.

163 from 2012 to 2020, whereas in large-scale farms, it was 139 day, approximately 25 days less. This demonstrates that larger-scale farms have a shorter meat production cycle, indicating increased efficiency (Fig. 9a). Moreover, the total cost of small-scale, medium-scale and large-scale pig farms was lower than that of backyard pig farms. The average total cost was 2015 RMB in backyard farms from 2012 to 2020, compared to 1780 RMB in scale pig farms, resulting in a cost savings of approximately 235 RMB per pig. Larger-scale farming allows for better cost control and higher income generation (Fig. 9b). In terms of medical and epidemic prevention investment, there is a negative relationship with scale. From 2012 to 2020, the average investment in medical and epidemic prevention per pig was 17 RMB for backyard pig farms, while large-scale pig farms invested an average of 26 RMB per pig (Fig. 9c). Medical and epidemic prevention investment is crucial in pig production as it effectively prevents pig diseases and reduces pig mortality, such as African swine fever in 2018 and 2019. Furthermore, larger-scale pig farms exhibit greater profitability. The net profit of backyard pig farms in 2020 was 1232.64 RMB, while large-scale pig farms achieved a net profit of 1619 RMB (Fig. 9d). Even during specific years, such as 2012 to 2013 and 2017 to 2018, scale farms maintained a positive profit-to-cost ratio. It is noteworthy that the profit-to-cost ratio of scale farms surpassed that of backyard farms from 2008 to 2020 (Fig. 9e). Another crucial aspect in ensuring pig production is feed consumption. Observing the growth rate of feed consumption, it is evident that the feed consumption rate of backyard pig farms was higher than that of the three scale farms from 2012 to 2018. Particularly after 2016, the growth rate of feed consumption in large-scale farms was lower than that in small-scale and medium-scale farms, contributing to savings and improved utilization of feed grains (Fig. 9f).

4. Discussion

The demand for meat in China is experiencing significant growth, as evident not only from the increased meat imports mentioned earlier but also from the rising imports of feed grains [61]. The government's ongoing support for the livestock industry emphasizes the need for improved efficiency [62]. China as a major producer and consumer of pork, relying solely on soybean imports to meet meat production or importing meat to alleviate domestic pig production intensity presents challenges [63]. Therefore, it is crucial to improve the production efficiency of both soybean and pork to ensure a sustainable supply in the country.

4.1. Supportive policies for soybean production

Ensuring soybean supply in China is a crucial challenge, given that over 80% of soybean demand relies on imports. Any disruption or blockage in the international food supply chain could lead to a decline in soybean imports and a significant increase in soybean prices. This, in turn, would raise the prices of soybean products such as soybean oil and increase the costs of the pig industry, potentially impacting the prices of cereal and other food products. Ultimately, it will have a negative impact on overall food security. In 2020, the soybean sowing area in China was 13.8 million hectares, which accounted for only a quarter of the feed grain required for pork and poultry production. The current planting structure is far from meeting China's consumption demand for animal-based food [7]. Therefore, it is necessary to prevent the reduction of soybean sowing area [64], and improve the soybean productivity to increase domestic soybean supply.

China has implemented a range of policies to simulate soybean production and improve its self-sufficiency. Soybean producer subsidy policy introduced in 2017, has helped stabilize soybean planting areas in Northeast China. In 2020, the "Opinions of the Central Committee of the Communist Party of China and the State Council on Doing a Good Job in Key Work in the Fields of Agriculture, Rural Areas and Farmers to Ensure the Realization of a Well-off Society in an All-round Way" proposed

increasing support for the promotion of high-yielding soybean varieties and new soybean intercropping techniques. In 2022, the "Opinions of the Central Committee of the Communist Party of China and the State Council on Promoting the Key Work of Rural Revitalization in 2022" reiterated the importance of implementing projects to improve soybean production capacity. These initiatives include promoting grain and soybean rotation in Northeast China, piloting rice-to-soybean projects in suitable areas in Heilongjiang and conducting demonstrations of soybean planting in saline-alkali land. Currently, soybean productivity and net profit are lower compared to other staple crops, which contributes to the stagnant soybean planting areas [14]. Therefore, it is necessary to explore ways to enhance soybean production efficiency and increase farmer income [65].

4.2. Environmental problems and supportive policies for pig production

China, as the largest global producer and consumer of pork and the largest pork importer, puts a crucial position of pork in ensuring food security and people's livelihoods [66]. However, the increasing demand for pork presents significant challenges in terms of improving production efficiency while minimizing environmental impact, and some environmental problems are difficult to inevitable [67]. Pig production contributes to greenhouse gas emissions (particularly from manure management (N₂O and CH₄) and enteric fermentation (CH₄), with pig manure accounting for 76% and 32% of national CH₄ and N₂O emissions from livestock manure in China, respectively [68]), higher pressure on land and water resources [69,70], leading to soil acidification and water eutrophication [71]. These environmental challenges may exacerbate by increasing pig densities, decoupling from crop production, and uneven distributions between regions [63], potentially hindering China's progress in achieving Sustainable Development Goals nationwide. To address these concerns, the government has strengthened regulations and policies to mitigate the environmental impacts of pig production and protect natural resources. Such as the first pollution control regulations for industrial livestock production in 2014, the Action Plan for Prevention and Control of Water Pollution in 2015, Action Plan for Recycling of Resources from Livestock Production in 2017, which require provinces to designate non-livestock production regions near vulnerable water bodies, natural scenic areas, and human residential areas [72]. National pig production development plan (2016–2020) also includes the designation of restricted area in the Southern water network region. On the other hand, restructuring the pig production sector is being pursued, including spatial planning of pig production in areas with high availability of feed grains, setting maximum pig production intensity at the farm level, and promoting technology innovation in whole-chain manure management [63]. Nowadays, The government is now focused on strengthening the industrialization of pig production, urging the acceleration of phasing out traditional backyard pig farms and eliminating outdated production capacity [73]. Moving forward, China should adopt a rational spatial layout for pig production based on the availability of feed resources to facilitate the transformation and upgrading of the pig industry.

4.3. Linkage between feed grains and livestock production

Significant initiatives are being undertaken in developing countries to integrate forage crops into crop-livestock systems, aiming to improve farmer livelihoods and mitigate environmental problems [74]. Reestablishing the linkages between specialized crop and livestock farms through local-level cooperation can effectively reduce agricultural greenhouse gas (GHG) emissions, contributing to the agricultural sustainable development [75]. Livestock rearing systems primarily contribute to GHG emissions through enteric fermentation, feed production, and manure management processes [76]. The integration of crop production and livestock rearing systems demonstrates synergistic relationships, as animal manure can be utilized as organic fertilizer for

cropland, while crop residues can serve as fodder for livestock. Consequently, recoupling cropping and livestock systems has emerged as a potential solution to mitigate agricultural GHG emissions. Danish pig farms are typical mixed crop-pig farms, with an average of 3500 pigs, and they also prioritize feed production as an integral component of their operations [77]. Specialized pig farms constitute two-thirds of the total number of pig farms in Denmark, with a significant portion of agricultural land dedicated to growing feed grains. Danish farmers exhibit higher production efficiency by cultivating feed cereals on large holdings. Moreover, Denmark has implemented stringent environmental policies that effectively couple manure production to land area [78]. In line with the Danish implementation of the EU Nitrates Directive, a considerable portion of the manure produced on Danish pig farms is utilized on the farms' own land. Danish regulations stipulate a maximum application rate of 140 kg/ha N for pig manure on agricultural land [79]. As a result of progressively lowering manure and fertilizer application standards, Danish pig farmers demonstrate reduced sensitivity to nutrient policies and feed prices, thereby achieving high self-sufficiency rates for both feed grains and pigs [80]. Scholars such as [81], [82], [83] and [84] also have highlighted the benefits of cooperation between specialized farms, emphasizing improved resource efficiency and production efficiency, mitigation of agricultural pollution, reduction of environmental externalities, and opportunities for sustainable intensification of agriculture. The cooperation between specialized livestock and crop farms is considered a promising approach to alleviate environmental costs in China [75]. Optimizing geographical distribution of crop-livestock systems is key factor in the sustainable operation of these integrated systems, as it impacts economic and environmental profit [85,86]. Consequently, policymakers in China are increasingly recognizing the importance of local-level cooperation between specialized crop and livestock production for the sustainable agricultural development.

4.4. Recommendation for integrating soybean-pig production in China

Pork consumption holds a dominant position in China's meat market, and its production also consumes the largest proportion of soybean due to the herbivorous nature of cattle and sheep. From the above analysis, it is evident that maize production can largely meet domestic feed demands, whereas the domestic supply of soybeans falls short. Consequently, the contradiction between feed grain security and meat security primarily manifests as a conflict between soybean supply and pig production. The growth of China's pork production relies heavily on increased input quantities, particularly in soybean [87]. The available alternatives are either to increase soybean imports to meet pig production needs or to enhance pig production efficiency in order to reduce soybean consumption. Importing soybeans is currently the preferred option; however, it is not a sustainable or long-term solution [17]. Drawing from long-term agricultural production experiences, it becomes evident that larger-scale production in both the planting and pig industries offers significant advantages. In fact, the Chinese government has made several decisions to promote scale production in the agricultural sector. In 2021 China's government work report proposed the construction of a national industrial belt to develop the core agricultural technologies and ensure food supply. In 2022, the 14th Five-Year Plan for Promoting Agricultural and Rural Modernization also suggested optimization of agricultural production space and the designation of functional and protected production zones for key agricultural products, with soybean being a typical example. The crop-livestock production system is also regarded as an effective approach to improve production efficiency. Integrating soybean and pig production at a regional scale has been suggested as a potential strategy to achieve a balance between feed grain security and meat security [60,88].

When integrating soybean and pig production, it is crucial to comprehensively consider various factors, including the conditions for soybean and pig production, farm size [89], the number of scale farms,

and regional development planning for pig production. The protected production zone for soybean aims at enhancing production capability, taking the northeast plain as the focus, supplemented by the Huang-Huai-Hai region. These regions align with the provinces that have higher soybean yields, such as Inner Mongolia Autonomous Region, Heilongjiang, Jilin, Shandong, Henan, Anhui and Hubei. Meanwhile, provinces with higher pig slaughter volumes coincide with the advantageous soybean-producing areas. Apart from the northeast plain and the Huang-Huai-Hai region, Sichuan, Guizhou, and Yunnan are also advantageous provinces for soybean and pig production (Fig. 10 (a)). Furthermore, farms with an average size of over 16 ha are predominantly located in Inner Mongolia Autonomous Region, Heilongjiang, and Xinjiang, while medium-sized farms (over 2.6 ha) are mainly found in the northeast plain, Shandong, Hebei, Henan, and Hubei (Fig. 10 (b)). Therefore, it is advisable to rely on larger farms to implement soybean and pig production. Last but not least, the Ministry of Agriculture and Rural Affairs has also proposed a regional development plan for the pig industry, designating Hebei, Shandong, Sichuan, Chongqing, Guangxi, and Hainan as key development zones, and identifying Heilongjiang, Inner Mongolia Autonomous Region, Guizhou, and Yunnan as potential development zones. Notably, key development zones and the potential development zones resemble to advantageous soybean production areas and high-yield regions of pig industry. The number of scale farms in the key development zones exceeds that of other provinces. In the regional development planning for pig production, environmental carrying capacity and pollution should be also taken into consideration. The restricted development zones are Beijing-Tianjin-Shanghai area and Southern water network area, requiring optimize the layout of pig farms and promote moderate-scale standardization of pig production (Fig. 10 (c)). The theoretical distribution of suitable areas and national planning are basically consistent, suggesting that these superior regions should be considered as potential zones for integrating soybean-pig in large-scale production.

5. Conclusion

Striking a balance between feed grain security and meat security is the key to China's overall food security, and it is also a major issue for sustainable agricultural development. Evaluating the security situation of feed grains and meats, exploring their production challenges and experiences, we drew the following conclusions: (1) Meat consumption showed an upwards trend from 1961 to 2020, dominated by pork. Pork production was mostly dependent on feed grains, which made feed grains a "rigid demand". Although maize can basically achieve self-sufficiency, the domestic supply of soybean was insufficient to meet demand and depended heavily on import. (2) With the changes in agricultural production conditions and resources, the declining growth rate of unit yield in grains indicates that the current production patterns have already reached their attainable potential and that soybean has difficulty improving its production efficiency in the future as the projection by FAO-OECD. In addition, scale farming of the pig industry showed an upwards trend, but the proportion of medium-scale and large-scale farms is remarkably low and developed insufficiently. (3) Scale farming is superior in improving the production efficiency of soybean and pig industry, especially in saving feed grains. (4) Rebuilding linkage between specialized crop and livestock production through local-level cooperation is regarded as an effective way to improve production efficiency and reduce environmental problems. Finally, considering factors such as soybean sowing area, regions with high pig slaughter and scale farms, farm size and the pig regional development planning, we propose the integration of soybean-pig production in selected possible provinces, which has the potential to enhance the production efficiency of soybean and pig, to strike a balance between feed grain security and meat security.

Nevertheless, some problems needed to be explored in the future. One is that large-scale farming in the planting and pig industries needs to

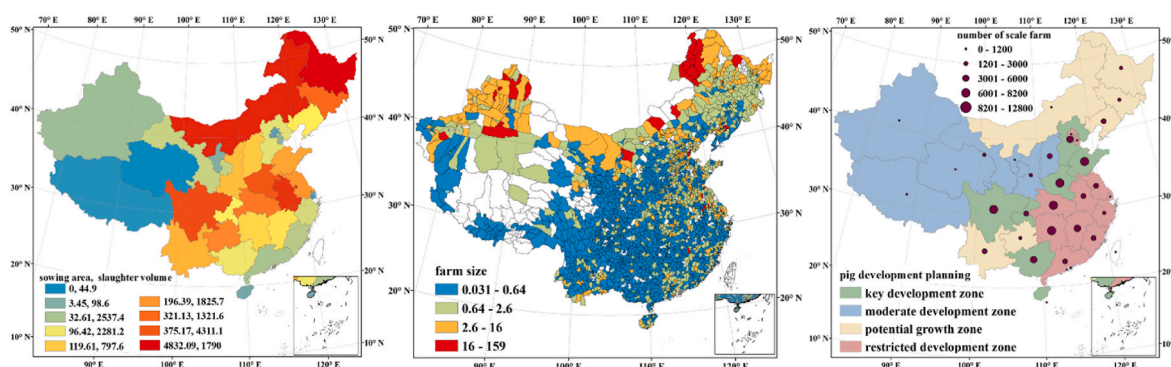


Fig. 10. (a) Sowing area of soybean and slaughter volume of pig; (b) Farm size (c) Regional development planning of pig production and the number of scale farm in each province.

be identified in much higher-resolution data. Combined with remote sensing and GIS, obtaining long-term spatiotemporal data of grains and livestock products is helpful for us to clarify the scientific and practical areas for soybean and pig. Although the Chinese government has proposed specialized production belts and functional production areas for important agricultural products, integrating soybean and pig production is theoretical and systematic. How to put them into practice also requires more analysis and researches, including policy decisions, geographic locations, farmers' willingness and so on.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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