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Spatial distribution and driving factors determining local food and feed self-sufficiency in the eastern regions of China

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Abstract

Achieving food and feed self-sufficiency is important for both China and the world. While China's food self-sufficiency has been examined at the national and provincial levels, few studies consider lower administrative levels or different food and feed items. This study quantifies self-sufficiency in the eastern regions of China and examines correlations with agronomic (arable area, yield, fertilizer input, and machinery power) and socioeconomic (population density, gross domestic product [GDP]) variables at the local level, which are related to the interactions of the Sustainable Development Goals. We calculated food and feed balances, and checked correlations across and within regions grouped by population density levels between production, balance indices, and other agronomic and socioeconomic variables. The results showed that most regions can achieve self-sufficiency in cereals, vegetables, and meat. Regarding eggs and maize, there was self-sufficiency in the north but deficiency in the south. Nearly all regions demonstrated extreme shortages of milk and soybeans. The results also showed a positive correlation between the production of some food commodities and the population in eastern regions of China, demonstrating that the aim of achieving food self-sufficiency at the local level is pursued. For cereals, vegetables, and maize, the yield and arable land per capita were positive factors for self-sufficiency, while GDP per capita was a negative factor for cereals, meat, and maize. Various factors have different impacts on the food and feed self-sufficiency of regions based on population density. Protecting arable land by rural revitalization and mitigating urban sprawl can retain food and feed self-sufficiency in large cities. This study outlines important implications for policymakers seeking to achieve food and feed self-sufficiency in China.

KEYWORDS
China, food self-sufficiency, feed self-sufficiency, GDP, local level

1 | INTRODUCTION

Ending hunger, achieving food security, improving nutrition, and promoting sustainable agriculture, which are the aims of the second Sustainable Development Goal (SDG-2) (Gil et al., 2019), constitute challenges both today and in the future. Many countries have promoted a policy to achieve food self-sufficiency (Austin, 2019; Barker & Hayami, 1976; Diagne et al., 2013), attempting to satisfy internal food needs from domestic production (Coates, 2013; Noromiarilanto et al., 2016). These policy decisions were triggered by multiple factors, such as volatile prices in international trade (Clapp, 2017) and adverse effects on the environment for both importing and exporting countries (DeFries et al., 2010; Galloway et al., 2007; Lenzen et al., 2012; Sun et al., 2018). For China, achieving food self-sufficiency is particularly challenging: (1) the population is projected to increase to 1.45 billion by 2030 (CSC, China State Council, 2016), and (2) increasing wealth and urbanization has shifted consumer preferences toward more resource-demanding diets (Yuneng et al., 2020). Investigating the main determinants and degree of achievement of food self-sufficiency is of utmost relevance for China and food security worldwide (Brown, 1996).

Several studies have investigated China's food self-sufficiency in its current situation and for the future at both the national level (Anderson & Strutt, 2014; Deng et al., 2019; Huang et al., 2017) and provincial level (He et al., 2017; Huang et al., 2019; Qi et al., 2015; Simelton, 2011). According to these studies, China will probably achieve food self-sufficiency nationally or maybe in local regions today and in the future. However, there is concern regarding the impact on the available resources (e.g., water, soil, nonrenewable fertilizer, and plastics) and on the environment (e.g., greenhouse gas [GHG] emissions).

There are several reasons for studying food self-sufficiency below the provincial level in China. In the context of food security, achieving food self-sufficiency can increase resilience to adverse events. For example, the recent COVID-19 pandemic has caused lockdowns and regional isolation (Anderson et al., 2020), supply chain disruptions, and trade restrictions (Laborde et al., 2020). For China, to ensure that residents have sufficient non-staple food all year round, the "shopping basket program" (Zhong, Si, et al., 2020) has established central and local production bases for meat, eggs, milk, aquatic products, and vegetables. In contrast, long-distance domestic transportation can cause a certain loss due to inadequate preservation techniques or other reasons (Sasaki et al., 2021) and can cause adverse environmental effects (Kriewald et al., 2019; Pradhan et al., 2020). For policymaking, analysis of local-level food self-sufficiency helps to better understand its dependence on and vulnerability to the food system (Dubbeling et al., 2017) and helps to weigh the benefits and limitations of local versus global food sourcing through comparative studies of agricultural capacity and food flows (Schreiber et al., 2021). To the best of our knowledge, no studies have addressed food self-sufficiency below the provincial level in China, and few studies have addressed local-level food self-sufficiency in other countries (Pradhan et al., 2014).

In studying food self-sufficiency, we highlight the importance of distinguishing between different food groups (Monteiro et al., 2012; Pradhan & Kropp, 2020). For China, most attention has been dedicated to both policymaking and research on grain self-sufficiency. In addition, some studies have focused on energy (Baer-Nawrocka & Sadowski, 2019; Pradhan et al., 2014), using metrics in which total food production and total food demand were expressed in calories. However, energy aggregates of all food groups would conceal the details, whereby a country or region could be self-sufficient in one food commodity but not in another. More than 820 million people have insufficient food, and many consume low-quality diets that cause micronutrient deficiencies and contribute to a substantial rise in the incidence of diet-related obesity and diet-related non-communicable diseases (Willett et al., 2019). Additionally, it is paramount to address feed self-sufficiency along with food self-sufficiency. Feed is essential for livestock production, and we argue that self-sufficiency is not achieved for animal-sourced food if feed self-sufficiency is not achieved (Pradhan et al., 2013). Indeed, China is largely non-self-sufficient in soybean and is the world's largest soybean importer (Ghose, 2014).

Investigating the relationship between food and feed self-sufficiency and other biophysical, economic, and social factors can further explore the interactions among different SDGs (e.g., SDG1 ["No Poverty"], SDG2 ["Zero Hunger"], SDG8 ["Decent Work and Economic Growth"], and SDG10 ["Reduced Inequalities"]). Crop production is driven by factors such as arable land, soil quality (Ito & Ni, 2013; Jayne et al., 2014; Lam et al., 2013), and agricultural inputs (Gao, 2010; Moraine et al., 2017). Crucial drivers on the demand side are socioeconomic aspects, including population size and gross domestic product (GDP) (Bai et al., 2018; Li et al., 2008). While studies have investigated the relationships between food self-sufficiency and economic variables such as GDP (Luan et al., 2013), no studies have been conducted at the regional level in China linking local food self-sufficiency with biophysical and socioeconomic variables.

This study has two objectives: (1) to analyze how indicators of food and feed self-sufficiency are distributed among these regions for different crop-sourced food types (cereals and vegetables), animal-sourced food types (meat, eggs, and milk), and feed types (maize and soybeans); and (2) to investigate the correlations between food and feed self-sufficiency indicators at the regional level with biophysical and socioeconomic factors. This study investigates the eastern regions of China because this area contains the majority of the Chinese population, and the basic unit of investigation is the region, which is the administrative level below the province; this could provide scientific insights regarding food sovereignty, which is on the agenda of many countries. The demand for food and the food groups considered are based on the recommendation for a healthy diet of the Chinese Nutrition Associations, and the demand for feed by livestock is based on surveys. The results will provide deep insights for policymakers to achieve food and feed self-sufficiency at the local level.

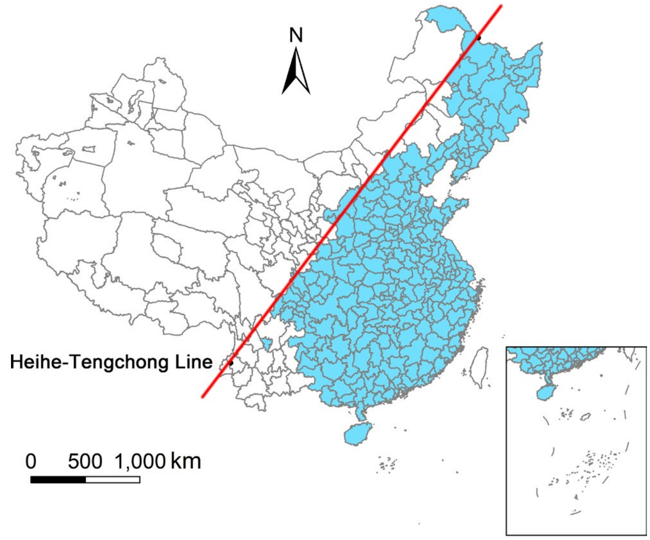

FIGURE 1 Chinese regions considered in the study (in blue) and the Heihe–Tengchong line

2 | MATERIALS AND METHODS

2.1 | Study area

This study considers the eastern part of China for two main reasons. First, this area is formed by regions with higher population densities and less agricultural land, and therefore faces the most difficult challenges of food and feed self-sufficiency achievement. Second, the livestock sector in these regions is not based on grassland, which is not considered in this study due to missing data and consequent difficulty in calculating indicators of feed self-sufficiency. The area considered is east of the Heihe–Tengchong line (Figure 1), a famous geographic demarcation line (Hu, 1935). This area accounts for approximately 94% of the Chinese resident population and comprises approximately 36% of the country's area (Chen et al., 2016; Guo et al., 2017). Some regions east of the Heihe–Tengchong line (in the southwest part of the area) were excluded from consideration due to the high presence of grasslands. In total, 261 regions are considered, with an average surface of 1.39×10^4 km^2 and a population density ranging from 6.78 person·km^{-2} to 6448.60 person·km^{-2}. The climate in the eastern regions of China is mainly monsoon, ranging from temperate (in the north) to subtropical (in the south) and tropical (southernmost areas, e.g., Hainan Province).

2.2 | Definition of food and feed balance indices

In the literature, there are several metrics of feed and food self-sufficiency. At the national level, some metrics consider both trade and production (Clapp, 2017; FAO, Food, 2001). At the local level, some metrics consist of dividing annual production by annual demand (Leonardo et al., 2015; Noromiarilanto et al., 2016). This study defines a metric for highlighting the feed or food surplus or deficit divided by demand. We quantified the feed or food self-sufficiency for food or feed group i and region j as the balance index BI_{ij}, defined by the following equation:

$$BI_{ij} = \frac{P_{ij} - D_{ij}}{D_{ij}} \tag{1}$$

where P_{ij} and D_{ij} are the annual production and annual demand ([tons · yr^{-1}]) of food or feed group i in region j, respectively. We expressed production and demand in a weight-per-year unit, following Simelton (2011). Negative values of BI_{ij} indicate a deficit, while positive values indicate a surplus for food or feed group i in region j. According to Clapp (2017), dietary energy production should be 95% ~ 105% of what is necessary for an adequate diet in caloric terms. Therefore, we account for a possible error of 5%: If $BI_{ij} > 0.05$, there is a surplus; if $-0.05 \le BI_{ij} \le 0.05$, there is a balance; and if $BI_{ij} < -0.05$, there is a deficit. Overall, we state that feed or food self-sufficiency is achieved when $BI_{ij} \ge -0.05$. When feed or food self-sufficiency is achieved, a higher positive value of the balance index indicates higher robustness of self-sufficiency, including the possibility of storing or exporting; conversely, when feed or food is deficient, lower negative values of the balance index indicate higher severity of the deficit.

The data for the production of food and feed groups were directly accessible, and some assumptions concerning food and feed demand were required to calculate food balance indices in Eq. (1). The demand for food items depended mostly on the human population and dietary requirements, while demand for feed items depended on livestock quantity.

$$D_{ij} = \begin{cases} d_{ij} \times R_j & \text{if } i \text{ is a food item} \\ \sum_k f_{ijk} \times L_{jk} & \text{if } i \text{ is a feed item} \end{cases} \tag{2}$$

In the first branch of Eq. (2) (calculation of demand for food items), R_j is the total resident population (person) in region j, while d_{ij} is the individual demand of food group i in region j. The demand for feed items is obtained by adding the feed needs of different livestock categories. In the second branch of Eq. (2) (calculation of demand for feed items), L_{jk} is the quantity of livestock (head) in region j belonging to species k, while f_{ijk} is the feed requirement (tons·head^{-1}·yr^{-1}) of group i in region j by livestock species k.

2.3 | Data

The data (unless otherwise specified) came from the national, provincial, and municipal Statistical Yearbook of China, which is accessible at the China Economic and Social Big Data Research platform (https://data.cnki.net/) and the Statistics Bureau website of various regions. We used data from 2017, which was the most recent year for which information in all regions was available. Missing data were filled in using information from neighboring years (2016 or 2018). We made some assumptions when estimating the food and feed groups' self-sufficiency. First, we considered cereals and vegetables as crop-sourced food items for people. We assumed that cereals only included wheat and rice, while other types of cereals (e.g., maize, millet, and barley) for human consumption were negligible. Second, we assumed only maize and soybeans as feed items. According to the NBS, National Bureau of Statistics (2018), the proportion of total production of wheat, rice, and maize accounted for 98.5% of the total cereal production at the national level, while other cereals (e.g., millet and barley) accounted for only 1.5%. In 2017, only 3.5% of maize and 5.1% of soybeans were used as food for people in China (Chen & Lu, 2019).

2.3.1 | Feed and food production

The data on the production of the different crop-sourced and animal-sourced food and feed items were directly available from the Statistical Yearbook of China. Cereal production was calculated by adding the production of wheat and rice. Meat production was calculated by adding all meat produced from main livestock, including cattle, pigs, sheep, and poultry.

2.3.2 | Feed and food demand

Regarding individual food demand (d_{ij} in Eq. (2)), we referred to the dietary guidelines for Chinese residents. While this does not correspond to the effective food consumed by the population, obtaining such consumption data might be quite challenging and might require surveys. Therefore, the balance indices for food self-sufficiency are referred to as ideal diets. This approach of using healthy diets follows that of previous studies (Brink et al., 2019; Diethelm et al., 2012). The Food and Agriculture Organization of the United Nations (FAO) has helped more than 100 countries to develop food-based dietary guidelines that are adapted to the nutrition situation, food availability, culinary cultures, and eating habits (http://www.fao.org/nutrition/education/food-dietary-guidelines/home/en). According to FAO principles, experts proposed dietary guidelines for the Chinese population based on nutrition science, food resources, dietary characteristics, traditions, and nutrient needs. Referring to the 2016 version (CNS, The Chinese Nutrition Society, 2016), we considered the average values of daily intake of each food (Table S1), adjusted in time and weight dimensions to fit Eq. (2).

Regarding the feed demand per head for each livestock species (f_{ijk} in Eq. (2)), we used the survey data (Table S2), adjusted in time and weight dimensions to fit Eq. (2). The resident population and livestock quantity in each region were retrieved from the Statistical Yearbook. The livestock species considered were cattle, pigs, sheep, broiler poultry, and layer poultry. To avoid replicated calculation of livestock quantity, we used stock quantities for livestock species with a production cycle greater than 1 year (i.e., cattle, sheep, and layer poultry), and we used marketable quantities for livestock species with a production cycle of less than 1 year (i.e., pigs and broiler poultry). In this case, the feed demand was adjusted by the length of the production cycle.

2.3.3 | Factors influencing feed and food self-sufficiency

We considered factors that could influence feed and food self-sufficiency in Chinese regions to test correlations available from the Chinese Yearbook of the regions. We considered agronomic factors (arable land per capita [ha·capita^{-1}], chemical fertilizer input per arable land [ton·ha^{-1}], machinery power per arable land [kW·ha^{-1}]), and socioeconomic factors (population [persons], population density [person·km^{-2}], and GDP per capita [10^4 Yuan·person^{-1}]). Arable land refers to the total land occupied by crops; chemical fertilizer input includes nitrogen, phosphorous, potassium application, and compound fertilizers; machinery power refers to the total rated power of all agricultural machinery. Yield calculation is only for crops, and the yield ($kg \cdot ha^{-1}$), including cereals, vegetables, maize, and soybean, is calculated by dividing production by cultivated area. The yield of cereals was calculated by dividing the total production of wheat and rice by the total cultivated area of wheat and rice.

2.4 | Analysis

After calculating the balance indices for all food or feed items in the 261 regions considered, we performed a sensitivity analysis of the proportion of food and feed self-sufficiency regions by varying the threshold of the balance index within the range (−0.1 ~ 0.1) to test the robustness of our methodology. The details are provided in the Supporting Information. The analysis followed the objectives of this study. For the first objective (how food and feed self-sufficiency indicators are distributed in the regions of eastern China), we mapped the calculated balance indices and analyzed the distribution for each item. For the second objective (correlations of food and feed self-sufficiency indicators at the regional level with biophysical and socioeconomic factors), we proceeded in two steps. First, we explored pairwise correlations (using the Spearman correlation index) between the productions, balance indices, factors, and other derivate quantities obtained by combinations of more factors. Second, we conducted a refined analysis of the groups of regions characterized by different population levels. The first step provided a general, high-level overview of how different factors are mutually related to the local level of eastern China. In the second step, achieving self-sufficiency is challenging in regions with higher population densities and higher demands; therefore, we hypothesized that relationships among factors differ depending on population levels.

We divided the regions into four groups based on the four quartiles of population densities. The group of regions with population density ranging from the minimum (corresponding to 6.78 $person \cdot km^{-2}$) to the 1st quartile (corresponding to 205.59 $person \cdot km^{-2}$) was labeled as *low* population density; the range from 1st quartile to 2nd quartile (corresponding to 384.48 $person \cdot km^{-2}$) was labeled *low-medium* population density; the range from the 2nd quartile to the 3rd quartile (corresponding to 632.16 $person \cdot km^{-2}$) was labeled *medium–high* population density; the range from 3rd quartile to the maximum (corresponding to 6448.60 $person \cdot km^{-2}$) was labeled *high* population density. Within each of the defined groups of regions, we explored (i) correlations between the feed and food balance indices and other factors (or derived) using the Spearman correlation index and (ii) the difference (using one-way ANOVA) in the distribution of factors within self-sufficient and non-self-sufficient regions.

3 | RESULTS

3.1 | Balance indices of food and feed items in the eastern regions of China

The distributions of the balance index values were different for different food and feed items (Figure 2). Specifically, self-sufficiency is largely reached for cereals (72.8% of the regions), vegetables (91.2%), and meat (92.3%), only partially for eggs (53.3%) and maize (30.7%), and only a few regions satisfy the demand for milk (3.8%) and soybeans (3.8%). The spatial distribution of the balance indices for different food and feed items in the regions of eastern China is shown in Figure 3. For the feed and food items that did not attain self-sufficiency in all regions, the spatial distribution was uneven. For cereals, only some coastal regions and developed regions (e.g., Beijing, Shanghai, Guangzhou, and Shenzhen) do not achieve self-sufficiency; for eggs, self-sufficient regions are mostly in the central and northern regions; for maize, the self-sufficient regions are mostly in the north, where the climate is favorable; for soybean, the self-sufficient regions are mostly in the northeast where vast and fertile land is available; for milk, the self-sufficient regions are mostly in the northeast and agricultural and pastoral transition regions. In China, milk production occurs mainly in the western part of the country. As a result of our sensitivity analysis (Table S3), the differences in the proportion of regions that achieved self-sufficiency for each food/feed group were no more than 5% when the threshold of the balance index changed within a range (−0.05 ~ 0.05).

3.2 | Correlations among feed and food balance indices and other factors

Pairwise correlation indices were calculated among production quantities, balance indices and crop yields, population, population density, GDP per capita, arable land per capita, fertilizer input per arable land, and machinery power input per arable land (Figure 4). The correlation index considered (Spearman correlation index r) ranges between −1 and 1, and we considered that values of the index greater than 0.50 indicate strong positive correlations, while values lower than −0.50 indicate strong negative correlations. Only significant correlations with a p-value (p) lower than 0.01 were considered.

Correlations between balance indices and the yield of their respective crops were strongly positive for maize ($r = 0.61$, $p < 0.01$), weakly positive for cereals ($r = 0.35$, $p < 0.01$) and vegetables ($r = 0.19$, $p < 0.01$), but not significant for soybeans, indicating that yield is not the determining factor of soybean self-sufficiency in China. Arable land per capita was strongly correlated with the balance indices for maize ($r = 0.55$, $p < 0.01$) and eggs ($r = 0.50$, $p < 0.01$) and weakly correlated for meat ($r = 0.44$, $p < 0.01$), cereals ($r = 0.39$, $p < 0.01$), milk ($r = 0.32$, $p < 0.01$), soybeans ($r = 0.27$, $p < 0.01$), and vegetables ($r = 0.17$, $p < 0.01$). The balance indices of cereals ($r = -0.24$, $p < 0.01$), meat ($r = -0.31$, $p < 0.01$), and maize ($r = -0.27$, $p < 0.01$) were weakly and negatively correlated with GDP per capita, indicating that more developed regions tend to be less self-sufficient for these three food items. Population was not strongly correlated with any of the balance indices (though weakly for milk, vegetables, and soybean), and population density was not strongly correlated with any of the balance indices (though weakly for meat and vegetables).

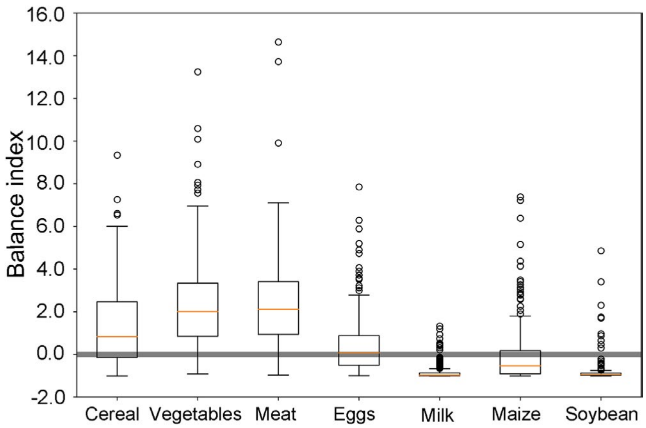

FIGURE 2 Box plots of the balance indices of food and feed items in eastern regions of China. The gray area represents the interval between −0.05 and 0.05

The production of maize ($r = 0.57$, $p < 0.01$) was strongly positively correlated with arable land per capita, while the production of soybeans ($r = 0.48$, $p < 0.01$), eggs ($r = 0.29$, $p < 0.01$), milk ($r = 0.23$, $p < 0.01$), meat ($r = 0.21$, $p < 0.01$), and cereals ($r = 0.19$, $p < 0.01$) was weakly and positively correlated with arable land per capita. Positive correlations with population were found in the production of all items, especially for vegetables ($r = 0.75$, $p < 0.01$), meat ($r = 0.60$, $p < 0.01$), cereals ($r = 0.53$, $p < 0.01$), and eggs ($r = 0.52$, $p < 0.01$). This indicates that, for these food groups, the eastern regions of China locally increase their production as a function of population and eastern China is working to achieve food self-sufficiency at the local level; however, the absence of correlations between population and balance indices indicates that feed and food self-sufficiency are independent of population size.

The balance indices of eggs ($r = 0.52$, $p < 0.01$) and milk ($r = 0.52$, $p < 0.01$) were strongly and positively correlated with the maize balance index. Additionally, the balance

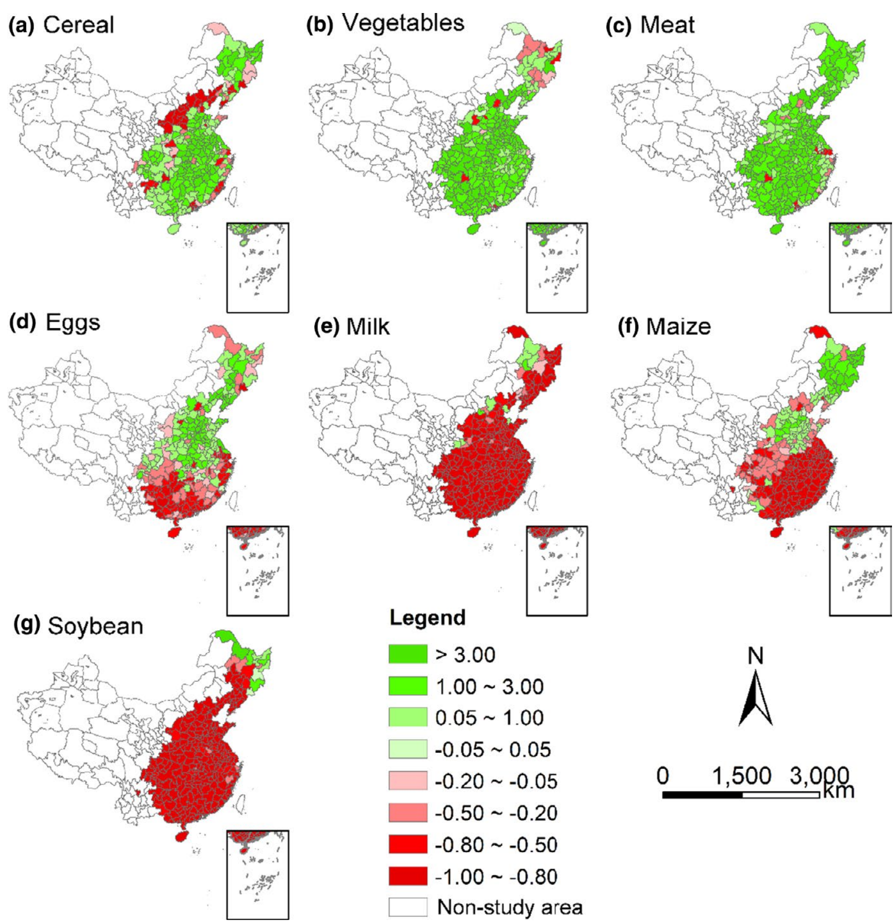

FIGURE 3 Spatial distribution of food and feed balance indices in eastern regions of China. Green regions are self-sufficient and characterized by a balance index greater than −0.05, with increasing color intensity indicating increasing surplus. Red regions are not self-sufficient and characterized by a balance index smaller than −0.05, with increasing color intensity indicating an increasing deficit

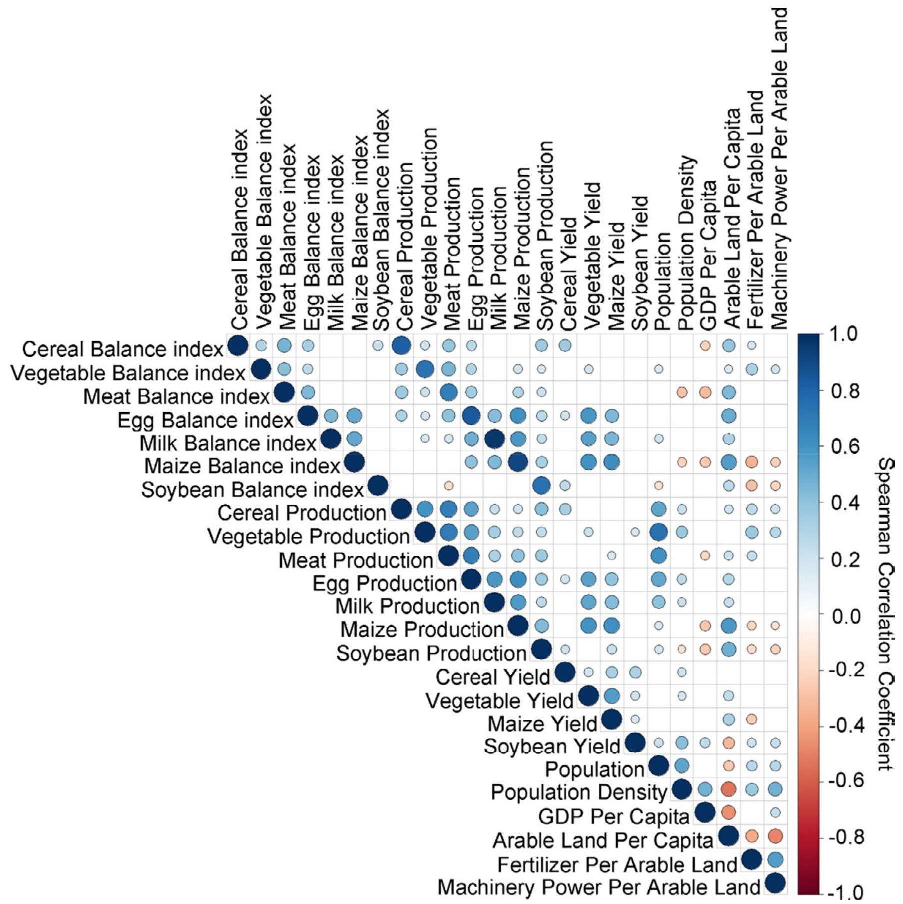

FIGURE 4 Graphical representation of the correlation matrix (using the Spearman correlation coefficient) showing pairwise correlations among feed and food balance indices, productions, and environmental, agronomic, and socioeconomic factors. Blue indicates positive correlations; red indicates negative correlations. The color intensity and circle size indicate the strength of the correlations. Empty cells indicate non-significant correlations ($p > 0.01$)

indices of eggs ($r = 0.60$, $p < 0.01$) and milk ($r = 0.57$, $p < 0.01$) were strongly and positively correlated with maize production. These results showed that, in these regions, the more laying hens and dairy cattle are raised, the more maize feed is produced. However, there was no correlation between meat, eggs, and milk with soybeans. This reflects regions that satisfy maize feed for egg and milk production, but soybean feed for livestock is not suitable.

3.3 | Correlations among balance indices and factors at different population levels

The analysis was performed within different groups of regions, characterized by *low*, *medium-low*, *medium–high*, and *high* population densities (hereafter LPD, MLPD, MHPD, and HPD regions, respectively) and revealed that balance indices are correlated with different factors at different population levels (Table 1). LPD regions (e.g., Hegang, Panzhihua, Sanming) are mainly distributed in the northeast, west, or hilly regions of the study area. The HPD regions (e.g., Beijing, Shanghai, Tianjin, Wuhan, Shenzhen) are mainly distributed in the eastern coastal areas.

Balance indices for vegetables, maize, and meat were found to be negatively correlated with GDP per capita only in highly populated regions (HPD regions and, for cereals, also MHPD regions). However, the same correlation was not found for the LPD and MLPD regions. For soybeans, eggs, and milk, no significant correlations were found in any of the groups. Concerning arable land per capita, different behaviors were observed for different food and feed items. Cereals and vegetable balance indices exhibited strong positive correlations with arable land per capita in the MHPD and HPD regions. For maize and soybeans, positive correlations were found at almost all population levels, but correlations were weaker for soybeans. For meat, strong positive correlations were found within the HPD regions, and weak correlations were found in the MHPD and MLPD regions. Balance indices were strongly and positively correlated with the respective yields for cereals and vegetables in the HPD regions. Concerning feed item yields, the behavior was drastically different for maize and soybeans. For maize, the correlations were positive and significant at all population levels, whereas for soybeans, no significant correlations were found. Concerning fertilizer and machinery power per arable land, the balance index showed only weak positive correlations in MLPD regions for cereals and in LPD regions and MLPD regions for vegetables. For maize and soybeans, correlations were negative for the LPD and LMPD regions.

Within each population density group, we compared the distribution of factors within regions characterized by deficit

TABLE 1 Correlations among balance indices and factors at different population levels

Balance indices	Population density	GDP per capita		Arable land per capita		Yields[a]		Fertilizer per arable land		Machinery power per arable land	
		Correlation	Significance	Correlation	Significance	Correlation	Significance	Correlation	Significance	Correlation	Significance
Cereals	LPD	–	–	–	–	0.39	**	–	–	–	–
	MLPD	–	–	–	–	–	–	0.26	*	0.31	*
	MHPD	−0.34	**	0.70	**	0.47	**	–	–	–	–
	HPD	−0.54	**	0.86	**	0.57	**	–	–	–	–
Vegetables	LPD	–	–	−0.30	*	–	–	0.44	**	0.39	**
	MLPD	–	–	–	–	–	–	0.36	**	0.25	*
	MHPD	–	–	0.50	**	0.35	**	–	–	–	–
	HPD	−0.52	**	0.78	**	0.61	**	–	–	–	–
Maize	LPD	–	–	0.56	**	0.78	**	−0.57	**	−0.42	**
	MLPD	–	–	0.55	**	0.64	**	−0.49	**	−0.45	**
	MHPD	–	–	0.47	**	0.40	**	–	–	–	–
	HPD	−0.54	**	0.75	**	0.63	**	–	–	–	–
Soybean	LPD	–	–	0.39	**	–	–	−0.35	**	−0.33	**
	MLPD	–	–	–	–	–	–	−0.31	*	–	–
	MHPD	–	–	0.30	*	–	–	–	–	–	–
	HPD	–	–	0.43	**	–	–	–	–	−0.33	**
Meat	LPD	–	–	–	–	–	–	–	–	–	–
	MLPD	–	–	0.25	*	–	–	–	–	–	–
	MHPD	–	–	0.38	**	–	–	–	–	–	–
	HPD	−0.66	**	0.86	**	–	–	–	–	–	–
Eggs	LPD	–	–	–	–	–	–	–	–	–	–
	MLPD	–	–	–	–	–	–	–	–	–	–
	MHPD	–	–	–	–	–	–	–	–	–	–
	HPD	–	–	–	–	–	–	–	–	–	–
Milk	LPD	–	–	–	–	–	–	–	–	–	–
	MLPD	–	–	–	–	–	–	–	–	–	–
	MHPD	–	–	0.25	*	–	–	–	–	–	–
	HPD	–	–	–	–	–	–	–	–	–	–

Note: Correlation tests were performed between the balance indices and the yield of the corresponding crop. Population density, LPD = low; MLPD, medium–low; MHLD, medium–high; HLD, high. **correlation significance p-value <0.01; *correlation significance p-value <0.05; – correlation significance p-value >0.05.

[a]The correlation between food balance indices and yield was only tested for crops.

and surplus for cereals and maize, which are the most important crops in China. A comparison was made graphically (Figure 5) and with ANOVA. According to the sensitivity analysis, the regions that achieved self-sufficiency of maize and cereals did not change significantly in number if the threshold of balance indices ranged within (−0.05 ~ 0.05) (Table S3).

Within the MHPD and HPD regions, there was a significant ($p < 0.01$) difference in the distribution of GDP per capita between self-sufficient and non-self-sufficient regions for both kinds of cereals (Figure 5a) and maize (Figure 5d). In addition, Figure 5a,d illustrate (along with ANOVA confirmation, $p < 0.01$) that GDP per capita, on average, increases with the population density level; however, this increase was more accentuated for cereals and maize non-self-sufficient regions.

Concerning arable land per capita, cereals in the MHPD and HPD regions exhibited higher values for self-sufficient regions than for non-self-sufficient regions. The same difference was less marked (and non-significant) for the LPD and MLPD regions. Visually, Figure 5b shows that the average arable land per capita is relatively constant at all population levels for cereal self-sufficient regions, while it shows a decreasing trend for non-self-sufficient regions. For maize, arable land per capita was systematically higher in self-sufficient regions than in non-self-regions at all population levels. Figure 5e shows that the average arable land per capita in the maize self-sufficient regions decreased with the population density level.

The distribution of yields did not show any particular increase or decrease with increasing population levels for both kinds of cereals and maize (Figure 5c,f). The results show a significant difference for cereals between the self-sufficient and non-self-sufficient regions in LPD regions; the yield of maize self-sufficient regions was significantly higher than in non-self-sufficient regions in the LPD, MLPD, and HPD regions (for the MHPD regions, the difference was graphically visual but not significant).

4 | DISCUSSION

In this study, we investigated the food and feed self-sufficiency of eastern China at the regional level and its relationship with possible determinants. Our results showed that although China reaches self-sufficiency at the national level for some crops, this is not the case for all regions. According to the data on imports and production in 2017, China was nearly self-sufficient in cereals, maize, vegetables, meat, eggs, and milk. China imported approximately 8.5×10^6 tons of cereals (wheat and rice), accounting for only 2.4% of its internal production (NBS, National Bureau of Statistics, 2018). China produced approximately 22.3% of the global maize and imported 7.3×10^6 tons of maize

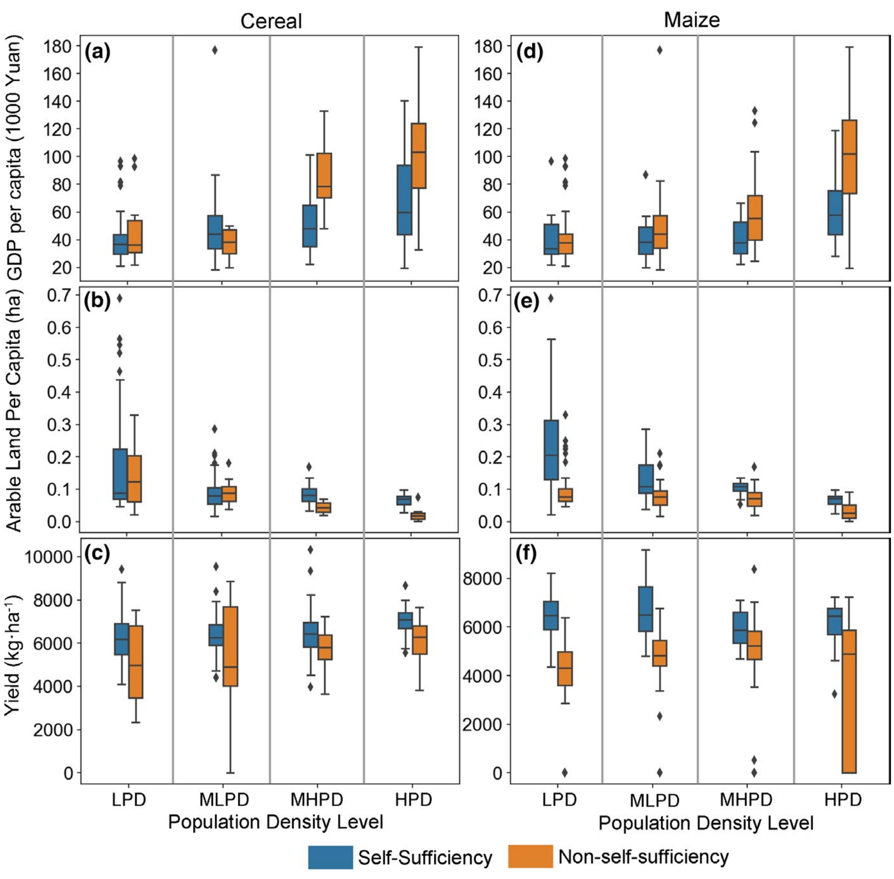

FIGURE 5 The box plot of GDP per capita, arable land per capita, and yield in different self-sufficient and non-self-sufficient regions in different population density degrees. (a–c) show cereal. (d–f) show maize. Red lines split the population density

(Data from FAO, Food and Agriculture Organization of the United Nations, 2018), accounting for 2.8% of the domestic production (NBS, National Bureau of Statistics, 2018). China produced 58.5% of global vegetables (Data from FAO, Food and Agriculture Organization of the United Nations, 2018), covering its internal needs. Meat imports were approximately 4.3×10^6 tons, representing 4.8% of the internal production (GACPRC, General Administration of Customs of the People's Republic of China, 2018). Egg imports were approximately 1.7×10^5 tons (Data from FAO, Food and Agriculture Organization of the United Nations, 2018), comprising 0.5% of the total production. China imported approximately 8.6×10^5 tons of milk, accounting for 2.7% of internal production. This soybean situation is different, as China is not sharply self-sufficient in this area: China imported approximately 9.8×10^7 tons of soybeans, which was 7.5 times its internal production, indicating a severe deficiency in this commodity (Wu et al., 2020). Although most food or feed is basically self-sufficient from the viewpoint of fewer imports from the international market, previous studies have shown that a large proportion of the population, especially in rural areas, experiences a deficiency of nutrients (Huang et al., 2020; Zhang et al., 2016).

In response to this study's first aim (how indicators of food and feed self-sufficiency are distributed among the regions of eastern China), our analysis showed that self-sufficiency is not evenly achieved in all regions of eastern China. For vegetables and meat, self-sufficiency is obtained in almost all regions, except for coastal regions and some regions with highly populated cities. Concerning feed, maize self-sufficiency is mostly clustered in northern regions, likely due to climatic reasons (He & Zhou, 2012), while soybean self-sufficiency is met only in the northeast. According to the NBS, National Bureau of Statistics (2018), soybean production in Heilongjiang Province (in the northeast) alone accounted for 39.1% of the nation's total, which may be why the northeast regions can achieve soybean self-sufficiency. Milk self-sufficiency is achieved in a low percentage of regions; however, milk production regions in western China with a higher presence of cattle and grasslands (Kemp et al., 2020; Zhang, 2007) were not included in this study. The EAT-Lancet Commission proposed the reference healthy diet, which is related to human health and environmental sustainability and benefits sustainable food systems (Willett et al., 2019). Therefore, from a nutritional perspective, the unbalanced food and feed groups' self-sufficiency can be improved through optimized crop-livestock structure based on natural resources, environmental carrying capacity, and socioeconomic factors (Lemaire et al., 2014; Nie et al., 2018).

In response to this study's second aim (investigating the correlations of food and feed self-sufficiency indicators at the regional level with biophysical and socioeconomic factors), our analysis revealed significant and strong correlations between feed and food balance indices and those factors. Although production is correlated with population, the balance indices were independent of population size. Our assessment showed that some less densely populated regions were non-self-sufficient, while some more densely populated regions were self-sufficient. Therefore, we decided to investigate correlations for different population density levels, with the hypothesis that, for different population levels, food and feed self-sufficiency are associated with different factors. The hypothesis was confirmed; if some correlations were absent or weak overall in the eastern regions of China, they were strong for some population density levels (e.g., vegetable balance index and GDP per capita). Indeed, the analysis showed that, for different population density levels, different biophysical and socioeconomic factors are correlated with feed or food balance indices.

4.1 | Effects of arable land and crop yield on food and feed self-sufficiency

Our results showed that arable land per capita and crop yields were correlated with nearly all balance indices, but stronger correlations with cereals, vegetables, and maize were found for regions with medium–high and high population densities. For soybeans, this occurs only for arable land per capita. For cereals, Figure 5b shows that approximately the same level of arable land per capita is necessary to sustain self-sufficiency across all population density levels, while Figure 5c shows that yield is slightly higher in self-sufficient regions with high population density. A reason for higher cereal yields in highly populated regions could be that big cities in China have high investments, such as high technology-based agricultural facilities and factory production (Zhong, Hu, et al., 2020). For example, the peri-urban agriculture in Beijing and other big cities, which is mainly operated by large-scale enterprises, can efficiently use local resources, stimulate innovation in agricultural production, and facilitate a rapid response to information on changes in agricultural operations (Yang et al., 2010).

Arable land per capita and yield are limiting factors for obtaining self-sufficiency in feed and food crop items. However, yields in most regions have already been strongly increased during the second half of the last century, but 24% ~ 39% of the global area has stagnated (Ray et al., 2012). Although some pathways to further increase yields might be possible (e.g., with high-yield breeding technology and other methods, see Cabas et al. (2010); Lobell et al. (2011); Ray et al. (2012); Pradhan et al. (2015)), it seems that increasing yields to achieve local self-sufficiency is challenging. For example, Pradhan et al., (2015) found that many regions in eastern China have already achieved more than 80% of their potential yields. Arable land is becoming increasingly scarce;

notably, the population growth projected for China will decrease arable land per capita (Cao et al., 2014; Liu et al., 2014). Urbanization is also one of the reasons for arable land reduction. Hence, it is important to protect arable land (Kong, 2014), limit urban sprawl (Kumar et al., 2016), and promote urban agriculture (Lovell, 2010; Pearson et al., 2010), where food production coexists with urban land use. The "shopping basket program" proposed in the 1988 initiative required all local regions to produce non-staple food in China (Zhong, Si, et al., 2020), promoting self-sufficiency of vegetables, meat, and eggs at the local level.

4.2 | Effects of fertilizer input and machinery power on food and feed self-sufficiency

A positive correlation was found between cereals and vegetable production and agronomic input factors; that is, fertilizer per arable land and machinery power per arable land. The strongest correlations were found for regions with low and medium–low population densities, meaning that in these regions fertilizer input might be a limiting factor, while it reached its maximal levels in regions with high population density. This hypothesis might be confirmed, as there is a positive correlation between agronomic input factors and population size. In general, increasing inputs to agriculture is relevant for closing yield gaps (McArthur & McCord, 2017), making pathways for sustainable intensification preferable (Pradhan et al., 2014), but this certainly exacerbates environmental stress (Moraine et al., 2017; Nicolopoulou-Stamati et al., 2016).

4.3 | Effects of GPD on food and feed self-sufficiency

Our results show that food and feed self-sufficiency are in contrast to the objectives of economic growth. Clearly, in highly populated regions, balance indices showed a significant negative correlation with GDP for cereals, vegetables, maize, soybeans, and meat. GDP and GDP per capita usually increase with population size and density (Liang & Yang, 2019); however, Figure 5a,d show that such an increase is stronger if (cereals and maize) self-sufficiency is not achieved. When food self-sufficiency is achieved, the increase in GDP with population density is lower. For example, Huang et al. (2019) found that difficulty in achieving grain self-sufficiency mainly occurred in eastern coastal areas, especially the megalopolises of the Yangtze River Delta and Pearl River Delta, regions of China with fast economic growth and higher GDP. Apparently, there are trade-off interactions between SDG1 ["No Poverty"] that related to GDP and SDG2 ["Zero Hunger"] that related to food self-sufficiency, as confirmed in previous studies (Deng & Gibson, 2019; Deng et al., 2015; Huang et al., 2019), and these should be carefully considered when developing policy.

At present, urbanization is the most powerful factor in promoting economic growth in China through the accumulation of physical capital, knowledge capital, and human capital (Bakirtas & Akpolat, 2018; Liang & Yang, 2019). However, rapid urban development and population growth have resulted in the loss of arable land and threaten food self-sufficiency in China (Wei & Ye, 2014). Policies that uncouple economic growth from cities promote better rural vitality in countryside areas (Li et al., 2018; Liu, 2018).

4.4 | Feed non-self-sufficiency in China

China is far from obtaining feed self-sufficiency, especially in soybeans. The situation is better for maize in eastern China, but maize self-sufficiency is largely unreached in many regions. In contrast, meat self-sufficiency has been attained in most of the regions considered. This implies that imports from abroad or internal transport are needed in eastern China to sustain meat production. Although the meat balance index was positive in most regions, meat production cannot be considered self-sufficient at the national or local levels when the whole value chain is considered. In particular, massive soybean imports were largely associated with land displacement and deforestation in exporting countries (Boerema et al., 2016) and increased nitrogen pollution in importing countries, where soybean farmland was converted to nitrogen-demanding crops (e.g., wheat, corn, rice, and vegetables) (Sun et al., 2018).

Table 1 shows that at almost all population density levels, the maize balance index is correlated with arable land per capita and yield, whereas the soybean balance index is correlated only with arable land per capita. For soybeans, it is difficult to increase yield in a short time period for China (Ray et al., 2012), and arable land remains the main limiting factor. From the analysis, China tends to prioritize crop cultivation for direct human consumption. Increasing the cultivation of feed would inevitably increase feed-food competition (Muscat et al., 2019) and harm the country's cereal self-sufficiency. Monogastric livestock (especially pigs and poultry) are the main sources of livestock products in China, accounting for 85.9% of total meat (MARA, 2018). It is challenging to promote solutions that decrease feed-food competition, as suggested by van Zanten et al. (2016), such as feeding livestock with crop residues, food waste, and other feed from marginal land.

Currently, China is a major importer of soybeans from North and South America (Gale et al., 2019; Wang, 2019), and studies have confirmed that limited land and limited water availability make it difficult and economically disadvantageous for China to increase soybean self-sufficiency. He et al. (2019) suggested that replacing some of the existing maize crops with soybeans would improve soybean self-sufficiency as well as environmental and sustainability performance. This suggests that soybean in China can be promoted through intercropping and crop rotation models. Gao et al. (2020) proposed that China can increase cultivated grasslands in regions with low and medium yields to develop sheep and cattle to produce beef and dairy and, at the same time, improve soil fertility.

4.5 | Future insights for local food self-sufficiency

Aiming at food and feed self-sufficiency does not necessarily imply that regions will need to depend exclusively on their own resources; regions can still depend on other regions' resources. However, considering supply chain disruptions and trade restrictions caused by the current COVID-19 pandemic (Laborde et al., 2020), and GHG emissions caused by long-distance transportation of food (Kriewald et al., 2019; Pradhan et al., 2014, 2020), strengthening food self-sufficiency at the local level increases the resilience of food value chains and mitigates global warming. The degree of local food self-sufficiency can reflect regional food availability, which is one aspect of food security (Pinstrup-Andersen, 2009). It is also important to note that for the future, a mix of self-sufficiency and connectivity among regions will be important (Kinnunen et al., 2020).

Along with economic development (i.e., GDP) and urbanization, the proportion of animal-sourced food in the Chinese diet is gradually increasing (He et al., 2016; Huang & Tian, 2019), while arable land is decreasing (Deng et al., 2015; Liu et al., 2010). Shimokawa (2015) found that the average meat consumption level was 958.3 g per week among adults aged 18 years or older in China by sampling observation, while 70.1% of adults exceeded the proper level of meat consumption. High meat intake can adversely affect health, and rising meat consumption has negative consequences for land and water use and environmental changes (Godfray et al., 2018). The destruction and loss of arable land pose a major challenge to food security (Larson, 2013). According to Wang et al. (2019), arable land in China decreased by 5.92 million hectares from 2000 to 2010. Therefore, advocating a healthy diet and arable land protection is conducive to future environmental benefits and food security.

With climate change in recent years, extreme weather events have become more severe and frequent (Li et al., 2019) and could affect all dimensions of food security (Cogato et al., 2019; De Haen & Hemrich, 2007; Hay, 2007; Lesk et al., 2016). From the viewpoint of agricultural supply, the degree of the effect of disastrous weather on different regions would be different. For regions with a weak level of food self-sufficiency, the occurrence of natural disasters would cause a weak adverse effect on the agricultural supply because these regions usually satisfy food demand through imports from other regions. For regions with strong food self-sufficiency, extreme climatic events would cause a strong unfavorable effect on the agricultural supply, while affecting the regions that imported food from these regions. Therefore, the emergency food reserves policy (Lassa et al., 2019) and trade are still significant in ensuring food security when encountering a sudden incident. In addition, agricultural production systems must adapt to extremes in a changing climate (Lesk et al., 2016) by developing adaptation strategies (De Haen & Hemrich, 2007; Motha, 2011).

4.6 | Limitations and perspectives of the study

This study used data on food production, food demand, and socioeconomics to investigate self-sufficiency at the local level in the eastern regions of China, and there are several limitations and perspectives. First, the demand data were from the Chinese Dietary Guidelines recommended by the Chinese Nutrition Society, and we used the same standard of food demand for all people. However, food demand differs across regions and depends on the age group of the population (Batis et al., 2014; Mullie et al., 2010). In addition, we used meat production data, which totals all meat types, including beef, pork, mutton, and poultry, while some people do not eat pork for customary reasons. Therefore, food demand data should be improved according to the region and types of people, which can be accomplished by conducting a survey. Second, other food groups may have been considered (see, e.g., Pradhan & Kropp, 2020). Considering that more food groups would provide a more complete view of food self-sufficiency, while the data of several other food groups (e.g., fruit and aquatic products) are not easily available at the local level in China, the methodology presented in this paper, based on food balances, can be easily applied in other contexts where data are available. Third, we used production data from 2017, which are the latest available data. However, the production of crops and livestock in China varies by year because of climatic disasters (Simelton, 2011), classical swine fever (Luo et al., 2014), and other policy implications. Therefore, future research should use multi-year data. Fourth, the analysis of food self-sufficiency can use the data of real food consumption to account for food overconsumption and waste. In 2014, 40 million tons of restaurant waste were produced in China (De Clercq et al., 2017), which affects food self-sufficiency and increases GHG emissions (Hiç et al., 2016). In addition, future food consumption should be considered. Fifth, we conducted an analysis of local-level food and feed self-sufficiency in the eastern regions with higher population densities and less agricultural land, facing more challenges in achieving food and feed self-sufficiency. However, a more complete analysis should also include the western region, with the methodology adapted to account for grasslands.

5 | CONCLUSIONS

Food and feed self-sufficiency is a priority strategy for China and is meaningful to global food security. We found that not all regions could achieve food and feed self-sufficiency in the eastern regions of China. Most regions can achieve self-sufficiency of cereals, vegetables, and meat at the local level. Total egg production was sufficient for all eastern regions, but the distribution was uneven, sufficient in northern regions but deficient in southern regions. Maize production as feed for livestock in eastern China was deficient, and maize production was mainly distributed in the northern regions. The results indicate extreme shortages of milk as nutrition for people and soybeans as feed for livestock in eastern China.

For all regions of eastern China, food production and population have a significant positive correlation, indicating that China is trying to achieve self-sufficiency at the local level. The yield and arable land per capita are positive factors for the self-sufficiency of cereals, vegetables, and maize, while GDP per capita is a negative factor for cereals, meat, and maize.

The effect factors are different from food and feed self-sufficiency in regions with different population densities. For regions with high population density, improving food and feed self-sufficiency by protecting arable land is more important than improving crop yield in the short term. Rural revitalization and slowing urban sprawl can maintain food and feed self-sufficiency in large cities. Facing serious conditions of soybean deficiency, optimizing the structure of crops, and utilizing lower yield cropland for cultivated feed are efficient approaches to slow the soybean shortage. The results will help policymakers understand the mechanisms of food and feed self-sufficiency at the local level and to make scientific decisions for food security in China.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTION

Yang Li involved in methodology, software, formal analysis, investigation, data curation, writing–original draft, and visualization. **Zhigang Sun involved in** conceptualization and supervision. **Francesco Accatino involved in** methodology, software, validation, writing–review and editing, visualization, and supervision.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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