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Satisfying meat demand while avoiding excess manure: Studying the trade-off in eastern regions of China with a nitrogen approach

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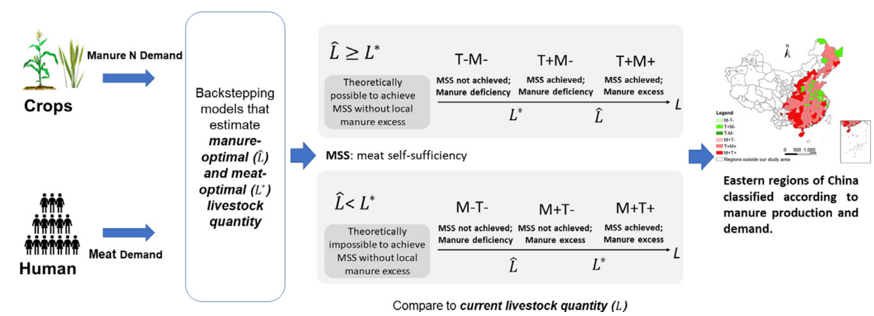
HIGHLIGHTS

- One evaluation procedure for excess/deficiency of manure and meat is proposed.
- The excess/deficiency of manure and meat in eastern regions of China were assessed.
- Meat self-sufficiency was met without manure excess only in ~15% of the regions.
- GDP and arable land per capita affected the excess/deficiency of manure and meat.

GRAPHICAL ABSTRACT



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ABSTRACT

Due to the rising incomes and rapid urbanization, China is facing a challenge in producing more meat while avoiding excess manure. These objectives might be in contrast: if excess manure is avoided, meat self-sufficiency might not be met; in contrast, meeting meat self-sufficiency might cause severe excess manure. Our study (1) characterizes the eastern regions of China according to the deficiency/excess of manure nitrogen and meat production, and investigates their relationships with natural resources and social economic indicators; (2) analyzes how the trade-off changes with increasing proportion of chemical nitrogen substituted with manure nitrogen (*PCSM*). Elaborating on data, we divided eastern regions of China into types according to satisfaction/unsatisfaction of meat demand and deficiency/excess of manure. We then re-calculated the number of regions in each type simulating the effect of increasing values of *PCSM*. In ~15% of the regions, meat self-sufficiency was met without manure excess, but in ~76% of the regions, manure excess occurred where meat self-sufficiency was met. In ~2% of the regions, meat self-sufficiency was not met and manure excess was absent; in ~7% of the regions, meat self-sufficiency was not met and excess manure was observed. The higher the regions' GDP (gross domestic product) per capita, the lower their ability to satisfy meat demand; the more arable land per capita in the regions, the higher their ability to satisfy meat demand and avoid excess manure. For the scenarios of increasing *PCSM*, our results show that some regions still cannot avoid excess manure with unchanged livestock quantity, although manure fertilizer completely replaced chemical fertilizer. Our study suggests that the regions of eastern China need to advocate a healthy diet and strengthen the management of food waste and livestock manures. The study is significant for policymakers to achieve sustainable agricultural production.

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1. Introduction

The livestock sector is linked with the United Nations Sustainable Development Goals, and balancing both the costs and benefits of the livestock sector is important to achieve a sustainable agri-food system (Mehrabi et al., 2020). China is the largest developing country worldwide, and its livestock sector is dealing with the challenge of increasing meat production in the face of rapid economic growth and population increase (Gandhi and Zhou, 2014; Shimokawa, 2015). According to statistics, China's meat production increased by approximately three times from 1988 to 2018 (NBS, n.d.) as a result of a number of policies, such as the Shopping Basket Program (Zhang et al., 2019), supporting the development of a feed-milling industry, and subsidizing imports of more productive animal breeds (Hansen and Gale, 2014). The livestock rearing model in China has been transformed from traditional household production to intensive industrial production (Qian et al., 2018; Wang et al., 2016), and some studies have pointed out that the current intensive and specialized livestock production is not sustainable (FAO, 2006) because, through manure excess nutrient accumulation, it can cause negative environmental effects, such as biodiversity loss, climate change (e.g., CH_4 emission), soil erosion, and air and water pollution (e.g., eutrophication) (Peyraud et al., 2014; Ryschawy et al., 2017; Tang et al., 2012; Xia et al., 2017).

Achieving meat self-sufficiency while avoiding excess manure is an important objective set by China (MARAPRC and MEEPRC, 2020; MARAPRC, 1988). Meat is recognized as a valuable food of animal origin because of its high nutrient content (e.g., protein and micronutrients) (Mullen et al., 2017). Many countries have targeted meat self-sufficiency by promoting a series of measures and policy decisions (Metelkova et al., 2019; Nugroho et al., 2013). These policy decisions were based on multiple factors, such as the risk of volatile prices in the international market (Clapp, 2017), food supply chain disruptions and trade restrictions due to the prevailing COVID-19 pandemic (Laborde et al., 2020), and global warming caused by greenhouse gas emissions through transportation (Pradhan et al., 2020). However, a trade-off might occur: achieving meat self-sufficiency might lead to excess manure; on the contrary, avoiding excess manure might not ensure meat self-sufficiency. The increasing and alarming levels of pollution caused by excess manure have been recognized in previous studies (Chadwick et al., 2015; Bai et al., 2018). Although manure constitutes an organic source of nutrients for crops, if not managed properly, it could be a source of pollution when its amount exceeds the crop demand (Bai et al., 2018). Improving manure management is an effective way to reduce environmental impacts (Leinonen, 2019).

To quantify and analyze the trade-off between meat self-sufficiency and manure excess avoidance, it is important to calculate, for a region, the manure need and the meat demand. One condition to avoid manure pollution in a region is that the nutrient supply from livestock manure does not exceed the appropriate quantity of nutrients needed by the crops in the region. Some studies have analyzed manure nutrient production and consumption at the local level to check whether the livestock manure in a region was excessive (see Barker and Zublena (1995) for North Carolina; Bateman et al. (2011) for England; Gerber et al. (2005) for Asia; Peng and Bai (2013) for China). All these studies mainly focused on the environmental carrying capacity of livestock manure but did not consider it in relation to the satisfaction of local meat self-sufficiency.

Increasing the use of manure in fields as a substitution for mineral fertilizer is an effective strategy to reduce excess manure. Previous studies have shown that increasing the use of manure nitrogen (N) for fertilization decreases not only the manure excess close to livestock production systems but also the use of mineral fertilizer, which is another severe source of eutrophication (Cai et al., 2015; Savci, 2012; Tang et al., 2012). The application of organic manure combined with chemical fertilizers can help maintain crop yield and improve soil fertility (Xie et al., 2016; Zhou et al., 2019). Besides, substituting livestock manure for synthetic N fertilizer significantly decreased reactive N losses via NH_3 emission, N leaching, and N runoff (Xia et al., 2017). Therefore, increasing manure application for crops per arable land is one of the optimal ways to avoid/reduce excess manure. Theoretically, other strategies can also reduce excess manure. One strategy would be to increase the crop-cultivated areas or increase the number of crops in the same land per year. However, rapid urbanization and industrialization in China have caused a drastic loss of arable land (Liu et al., 2010). In addition, multiple cropping (i.e., the practice of growing crops for two or more rotations in the same piece of land during one growing season) is mainly affected by climate, including temperature, precipitation, and light, which are difficult to control. Another strategy would be to transport excess manure to other regions where manure is required. Nevertheless, transferring manure to other regions might be expensive (Asai et al., 2014; Dagnall et al., 2000; Wilkins, 2008).

In this study, we analyzed the trade-off between meat self-sufficiency and excess manure in the regions of eastern China with the following specific objectives: (1) characterizing regions in eastern China according to the excess or deficit of manure nitrogen (according to crop requirements) and their capacity to satisfy local meat ideal demand (according to healthy diet recommendations) and investigating their relationships with natural resources and socio-economic indicators; (2) analyzing how the trade-off changes with increasing proportion of chemical fertilizer N substituted with manure N (*PCSM*). We acknowledge that in China there is also consumption of imported meat, or of meat produced in some internal regions and transported to other regions, however in this study we target the specific question of regional self-sufficiency. We focused on N because it is one of the most important nutrients for agricultural production (Dimkpa et al., 2020; Pinsard et al., 2021; Lassaletta et al., 2016), and crops with chemical fertilizer N currently accounted for over 50% of the food production (Zhang et al., 2015). Within China, we chose the eastern regions as our study area for two reasons. First, in terms of socio-economic aspects, the GDP per capita and the urbanization level of eastern China are higher than that of western China (Deng and Bai, 2014), and meat consumption is likely to be higher in these richer regions (Bai et al., 2018). In addition, the population density of eastern China is much larger than that of western China (Deng et al., 2015). For these reasons, eastern China faces more challenges in meeting the meat demand and needs to raise more livestock. Second, intensive and specialized agricultural production dominates in eastern China. Generally, the risk of excess manure is higher in intensive livestock than in grassland regions. It is essential for eastern regions of China to ensure that manure is integrated with crop nutrients using a coupling crop-livestock system (Bai et al., 2018; Chadwick et al., 2015; Gerber et al., 2005), which is a sustainable development approach for agriculture (Moraine et al., 2017; Russelle et al., 2007; Ryschawy et al., 2012).

2. Material and methods

2.1. Study area

We considered the Chinese regions east of the Heihe-Tengchong line (Fig. 1), excluding those characterized by a high presence of grasslands. In the regions that west of the Heihe-Tengchong line, there is an important quantity of grassland and pasture, which makes it difficult to account for the livestock manure that effectively can reach the crops. In total, 261 regions were considered, with an average surface area of 1.39×10^4 km^2 and a GDP per capita ranging from 18,134 Yuan$\cdot$person^{-1} to 177,033 Yuan$\cdot$person^{-1} (average value: 51,379 Yuan$\cdot$person^{-1}) in 2017. The eastern regions of China are mainly monsoon climate, which ranges from temperate monsoon climate (in the north) to subtropical monsoon climate (in the south) and tropical monsoon climate (southernmost areas, e.g., Hainan Province).

2.2. Definition of notable livestock quantities

To analyze whether meat production was sufficient for people and whether manure N was excessive for the crops in a region, we defined

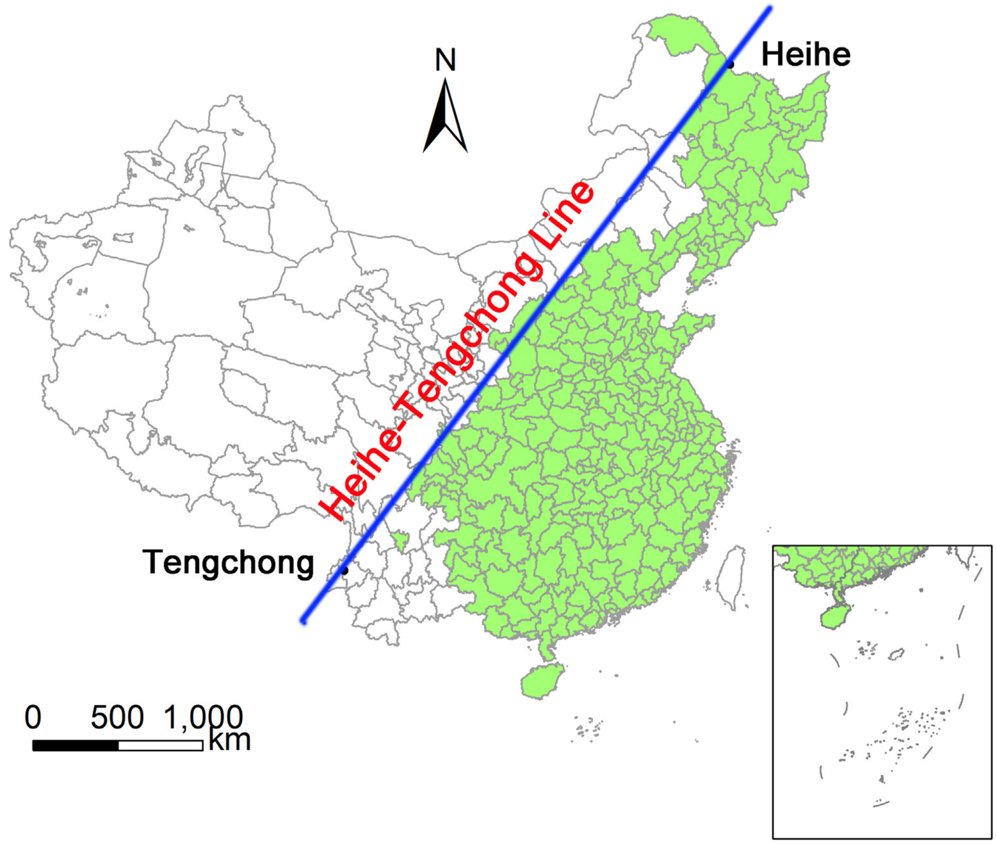

Fig. 1. Chinese regions considered in the study area (in green) and Heihe-Tengchong line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

two notable livestock quantities corresponding to specific theoretical conditions. The *meat-optimal* livestock quantity (L^*) corresponds to the total livestock quantity that theoretically achieves meat balance, that is, producing the amount of meat equal to the regional demand, according to recommendations for healthy diets. The *manure-optimal* livestock quantity ($\widehat{L}$) corresponds to the total livestock quantity theoretically achieving manure N balance, that is, producing a quantity of manure equal to crop needs. Comparing these two livestock quantities L^* and $\widehat{L}$ informs about the capacity of a region to conciliate (or not) the achievement of meat self-sufficiency and the avoidance of manure excess. The condition $\widehat{L} \geq L^*$ means that the livestock quantity that satisfies meat demand would not provoke manure excess, therefore in that region, it is possible to solve the trade-off between meat demand and excess manure avoidance. On the contrary, the trade-off could not be addressed where $\widehat{L} < L^*$, that is, it was not possible to satisfy the local meat demand without producing excess manure. In the latter case, manure had to be exported, or meat had to be imported.

The meat-optimal and the manure-optimal livestock quantities L^* and $\widehat{L}$ could also be compared with the *current* livestock quantity (L), i.e., the actual total livestock number in the region. We observed that meat self-sufficiency was met in a region where $L \geq L^*$, whereas it was not met where $L < L^*$. The manure N was excessive for crops when $L \geq \widehat{L}$ (possibly causing environmental pollution), whereas it was deficient for crops when $L < \widehat{L}$.

2.3. Assumptions of the methodology

To calculate the livestock quantities L, $\widehat{L}$, and L^*, we need to pose some assumptions which take into account the data availability and the scale addressed. (i) Our focus is on the regional scale: all the species of livestock and crops are summed together and parameters (e.g., meat productivity, excretive coefficient, nitrogen demand) are constant within each species and are averaged (using weights proportional to the species quantities). (ii) Feed composition is assumed to be the same for each livestock species in all the regions. In the eastern regions of China, most of the livestock is raised with intensive practices due to the little grassland in this area. Therefore, the difference in feed composition for the same livestock type in different regions would be negligible. (iii) We only consider the main crops (i.e., rice, wheat, maize, soybean, vegetables), for which the consumption of chemical fertilizer (i.e., nitrogen, phosphorus, potassium, and compound fertilizer) of these main crops accounted for 84% of the total consumption of chemical fertilizer in China in 2017 according to the NCAPCB (2018). Also, we only consider the main livestock species (i.e., cattle [dairy and meat], sheep, pigs, and poultry [broiler and layer hens]), for which the meat production accounted for 99% of the total meat production in China in 2017 according to the CRSY (2018). Dairy cattle and laying hens also produce (in lower quantities) meat when their productivity of dairy and eggs is low. (iv) All the livestock manure produced is fermented to organic fertilizer and then applied to the crops in the local region, which is the efficient and ecological approach as it is more expensive and polluting to transport manure across regions (Asai et al., 2014; Dagnall et al., 2000; Wilkins, 2008). (v) The manure balance is expressed in N quantities. Some other elements are important to consider (e.g., potassium, phosphorous), but for this study, we only focus on N for the following reasons. First, N is considered to be the main nutrient of livestock manure, and the loss of livestock N from manure to air and water would harm the environment, ecosystems, and humans themselves (Galloway et al., 2004; Tamminga, 2003; Pinsard et al., 2021). Second, many governments have implemented measures to use N standards to control livestock quantity (Oenema, 2004). (vi) The N cycle is assumed in an ideal condition and N loss is not considered, which is an issue that needs to be solved through various agronomic measures to avoid environmental pollution in the future. (vii) The meat demand used in our paper refers to the healthy dietary guidelines.

2.4. Calculation of the notable livestock quantities

Fig. 2 represents the workflow leading from available data to the calculation of the notable livestock quantities.

Two methodological issues were addressed to calculate the three livestock quantities (L, L^*, and $\hat{L}$). First, the quantities L, L^*, and $\hat{L}$ were obtained by summing different livestock species. Second, we assumed that the proportion of each type of livestock in a region was considered constant within a year. There are two types of terms used to describe the livestock quantity: marketable (*LM*) and stock (*LS*) quantity. The marketable quantity is defined as the number of livestock sold in the market for one year. The stock quantity is defined as the number of livestock at the end of the year. For meat production estimation, we can use the marketable quantity to multiply the meat productivity of unit livestock directly. For manure production estimation, the choice of stock quantity or marketable quantity depends on the growth period of the livestock. The manure production, for a region, can be calculated using the stock quantity when the livestock growth period is greater than one year (e.g., in the case of cattle); in contrast, for livestock with a growth period of less than one year (e.g., in the case of pigs), we can use marketable quantities to calculate the manure production in regional level (Zhou et al., 2014). This method can calculate both the meat production and manure production of the livestock whose main function is not to produce meat, such as dairy cattle and layer hens. To achieve uniformity that the three types of total livestock quantity (L, L^*, and $\hat{L}$) can compare, when the total livestock quantity was calculated, the livestock quantity types chosen referred to the livestock quantity types used in manure production estimation. The detailed formulas are presented in the following section.

2.4.1. Current livestock quantity

We defined L_j (head·yr^{-1}) as the current total livestock quantity in region j as follows:

$$L_j = \sum_i a_{ij} \tag{1}$$

where a_{ij} (head·yr^{-1}) is the quantity of livestock of species i in region j. Such quantity might refer to marketable or stock quantity according to the species. Because different livestock species are summed, we set the assumption that, for each region, within the meat-optimal and the manure-optimal livestock quantities, the fractions $f_{ij} = a_{ij}/L_j$ are kept constant as in the data.

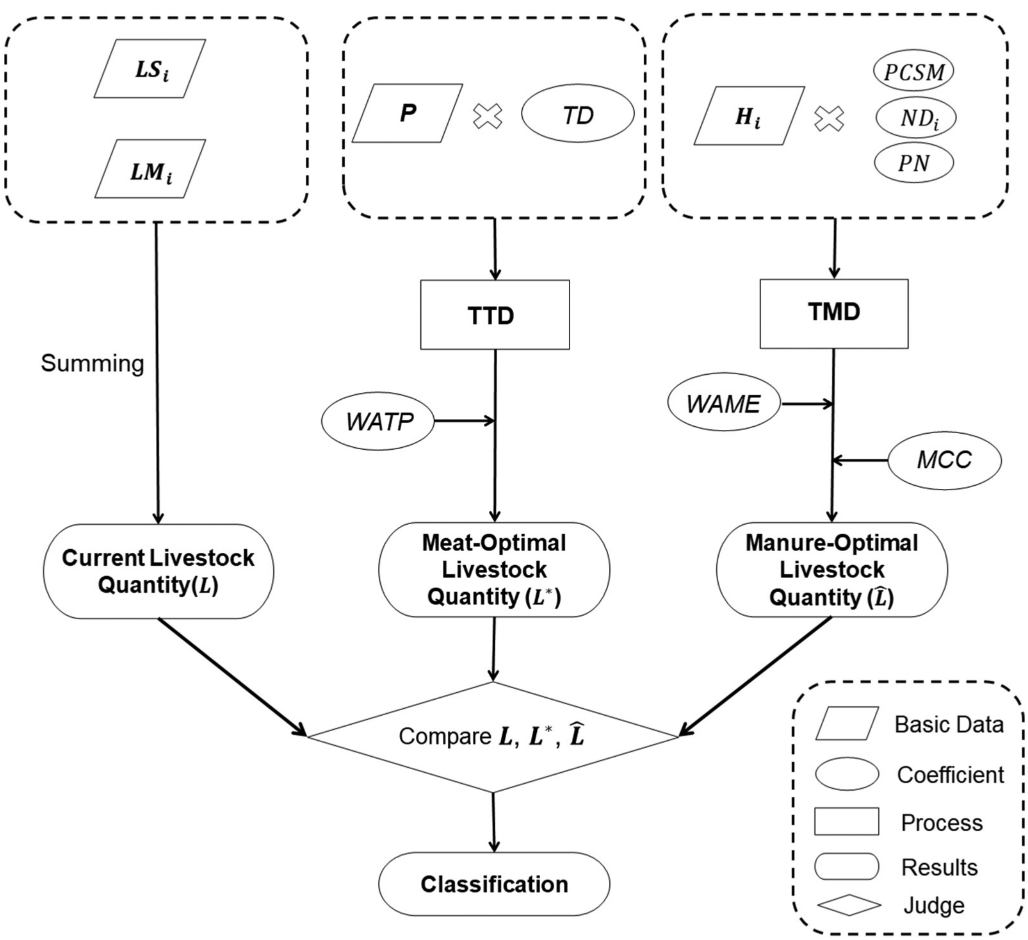

Fig. 2. Procedure to calculate the three notable livestock quantities (L, L^*, and $\hat{L}$) in each region. LS_i: Stock Quantity (i: pig, poultry [broiler and layer hens], etc.), MS_i: Marketable Quantity (i: cattle [dairy and meat], sheep, etc.), *P*: population, *TD*: meat demand per capita, *TTD*: total meat demand, *WATP*: weighted average of meat productivity, H_i: harvest of the crops (i: rice, wheat, maize, soybean, vegetables, etc.), *PCSM*: proportion of chemical N substituted with manure N, *ND*: nitrogen demand per unit production of crop (i: rice, wheat, maize, soybean, vegetables, etc.), *PN*: N content of fermented manure, *TMD*: total fermented manure demand, *WAME*: weighted average of manure excretive coefficient, *MCC*: manure conversion coefficient from fresh manure to fermented manure. The detailed classification based on the comparison among L, L^*, and $\hat{L}$ refers to Fig. 3.

2.4.2. Optimal livestock quantity of satisfying meat demand

The meat-optimal livestock quantity L_j^* (head·yr^{-1}) is defined as

$$L_j^* = \frac{TTD_j}{\sum_i MP_{ij} \times f_{ij}} \tag{2}$$

where TTD_j (ton·yr^{-1}) is the total meat demand in region j, and MP_{ij} (ton·head^{-1}) is the meat productivity of livestock species i in region j.

The total meat demand of people depends on the human population size and dietary requirements. We further defined TTD_j using the following equation.

$$TTD_j = TD_j \times P_j \times DY \tag{3}$$

where TD_j (ton·day^{-1}·person^{-1}) is the meat demand per day per capita in region j, P_j (person) is the population in region j, and DY (days) is the number of days per year.

The meat productivity of the livestock can be calculated by the total meat production divided by the total marketable livestock quantity in a region. We defined MP_{ij} as the following equation.

$$MP_{ij} = \frac{TP_{ij}}{LM_{ij}} \tag{4}$$

In Eq. (4), TP_{ij} (ton·yr^{-1}) is the meat production of livestock i in region j, and LM_{ij} (head·yr^{-1}) is the marketable livestock quantity of livestock i in region j.

2.4.3. Optimal livestock quantity of avoiding manure excess

The manure-optimal livestock quantity $\widehat{L}_j$ (head·yr^{-1}) is defined as follows:

$$\widehat{L}_j = \frac{TMD_j}{\left(\sum_i EC_i \times GP_i \times f_{ij}\right) \times MCC} \tag{5}$$

where TMD_j (ton·yr^{-1}) is the total fermented manure fertilizer demand for all crops in region j and is calculated as the sum of fermented manure fertilizer demand of each crop; EC_i (ton·head^{-1}·day^{-1}) is the excretive coefficient of livestock species i, GP_i (days) is the growth period of livestock species i, and MCC (ton·ton^{-1}) is the manure conversion coefficient from fresh livestock manure to manure fertilizer by usual fermentation processing. To avoid double counting, we used the stock quantity of livestock i when the growth period of livestock i was greater than one year (365 days), and we used the marketable quantity of livestock i when the growth period of livestock i was greater than one year.

Many studies have used a constant value of N demand to calculate the excess of manure N (Oenema, 2004; Zhang et al., 2019). For example, since the 1990s, the Nitrate Directive (Council Directive 91/676/EEC) in the EU-15 regulates the use of N in agriculture, which ensures that in each farm, the amount of N applied via livestock manure shall not exceed 170 kg·ha^{-1}·yr^{-1} (Oenema, 2004). However, here we decided to consider the need of the crops, which depends on the type and production. In this way, our calculations are referred to the physiological crop needs and not on the laws or on the actual usage, which is difficult to estimate.

In this study, we defined TMD_j (ton·yr^{-1}) as follows:

$$TMD_j = PCSM \cdot \sum_i \frac{H_{i,j} \times ND_i}{PN} \tag{6}$$

where $H_{i,j}$ (ton·yr^{-1}) is the harvest of crop i in region j, ND_i (ton·ton^{-1}) is a constant coefficient representing the quantity of nitrogen demand per unit production of crop i, $PCSM$ is the percentage of chemical N substituted with manure N, PN is the N content in the fermented manure fertilizer.

2.5. Data

The data on livestock quantities (stock and marketable quantity), meat production, crops production, socioeconomic variables (i.e., GDP, population, etc.), and agricultural resources (arable land area) were obtained from the provincial or 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 the regions. We used data from 2017, which was the most recent year for which information in all regions was available. The missing data were filled in using information from neighboring years (2016 or 2018).

2.5.1. Meat

The data on meat production in each of the considered regions were directly obtained from the Statistical Yearbook of China. The coefficient for the meat demand calculation [TTD_j in Eq. (3)], we referred to dietary guidelines for Chinese residents, which were developed by experts based on nutrition science, food resources, dietary characteristics, traditions, and nutrient needs. This does not correspond to the effective food consumption of people; however, obtaining this demand data might be quite challenging and may require arranging surveys. A healthy diet is related to human health, environmental sustainability, and benefits sustainable food systems (Willett et al., 2019). Therefore, in this study, we considered the ideal consumption that would occur according to healthy diet recommendations. Referring to the 2016 version (CNS, 2016), we calculated the average daily intake of meat ($TD_j = 57.50 \times 10^{-6}$ ton·day^{-1}·person^{-1}).

2.5.2. Manure nitrogen

The growth period of cattle and sheep is greater than 365 days, while the growth period of pigs and poultry is less than 365 days (refer to Supplementary Table S1). Therefore, the stock quantity of cattle and sheep and the marketable quantity of pig and poultry were used to estimate the manure N production and total livestock quantity in the study area.

The livestock coefficients EC_i and GP_i in Eq. (5) referred to Zhou et al. (2014). The manure conversion coefficient (MCC) in Eq. (5) was surveyed by the manager of an experimental farm that researched on the integrated crop-livestock paradigm in the North China Plain (37°00′ N, 116°34′ E) (Li et al., 2021a) and the MCC value ranged from 0.33 to 0.40 (ton·ton^{-1}). In this study, we used 0.37 (ton·ton^{-1}) of MCC, which is an average value.

For estimating the demand for manure N, we considered the main crops, such as rice, wheat, maize, soybean, and vegetables. The coefficient of the quantity of nitrogen demand per unit production of crop i [ND_i; Eq. (6)] referred to the ideal application from MARAPRC (2018) (see Supplementary Table S2). According to some studies (Geng et al., 2019; Lv et al., 2020; Xie et al., 2016; Yang et al., 2020), the beneficial proportion of chemical N substituted with manure N [$PCSM$ in Eq. (6)] for crops ranged between 20% and 40%. In this study, we used an average value of 30% for $PCSM$. The N content of fermented manure fertilizer [PN in Eq. (6)] used in this study was 1.75%, which is also the surveyed average value from an experimental farm.

2.6. Analysis

2.6.1. Classification of the regions

We calculated the three notable livestock quantities (L, L^*, and $\widehat{L}$) for 261 regions in eastern China. The regions were divided into six types (marked with acronyms) according to the different possible rankings of the three notable livestock quantities (see the schematic representation in Fig. 3). In the regions characterized by $L^* \leq \widehat{L}$ it is possible to satisfy the meat demand without producing excess manure. These regions were marked T−M−, T+M−, and T+M+ (where T stands for "meat" and M stands for "Manure"; + and − means that the meat and manure demand are met or not met, respectively; T preceding M indicates that

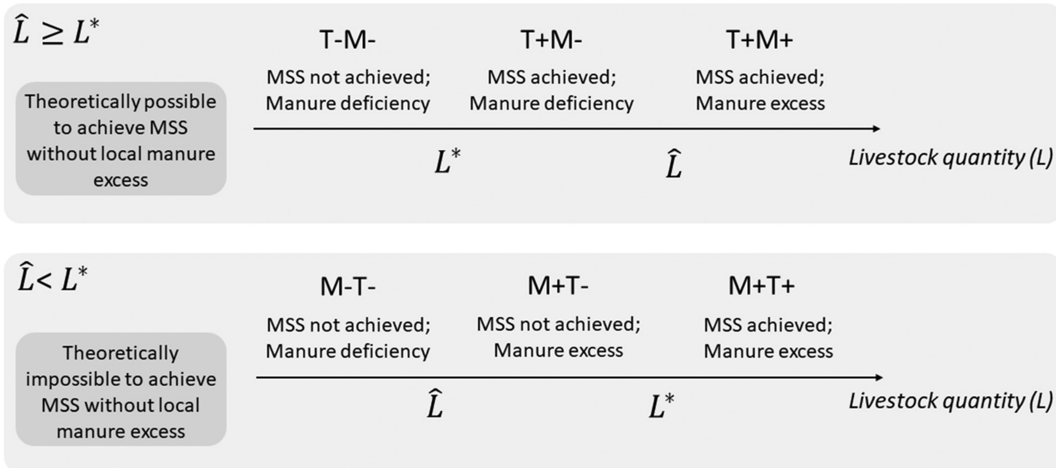

Fig. 3. Relationships among L, L^* and $\hat{L}$. L is the current livestock quantity; L^* is the meat-optimal livestock quantity; $\hat{L}$ is the manure-optimal livestock quantity. T−M− and M−T−: meat self-sufficiency (MSS) not achieved and manure deficiency, T+M+: MSS achieved and manure excess, T+M+ and M+T+: MSS achieved and manure excess, M+T−: MSS not achieved and manure excess.

"meat-optimal" livestock quantity is lower than "manure-optimal" livestock quantity). T−M− corresponds to $L<L^*<\hat{L}$, indicating that the current livestock quantity cannot satisfy the meat demand of the people, and manure N is not produced in excess. T+M− corresponds to $L^*<L<\hat{L}$, indicating that the current livestock quantity can satisfy the meat demand, and manure N is not produced in excess (favorable configuration). T+M+ corresponds to $L^*<\hat{L}<L$, indicating that the current livestock quantity can satisfy the meat demand for people, and the manure N is produced in excess. In the regions characterized by $L^*>\hat{L}$ the satisfaction of meat demand would cause excess manure. These regions were marked M−T−, M+T−, and M+T+ (where M preceding T indicates that manure-optimal livestock quantity is lower than meat-optimal livestock quantity); M−T− corresponds to $L<\hat{L}<L^*$, indicating that the current livestock quantity cannot satisfy the meat demand for people, and the manure N is not produced in excess. M+T− corresponds to $\hat{L}<L<L^*$, indicating that the current livestock quantity causes excess production of manure N, while not satisfying the demand for meat. M+T+ corresponds to $\hat{L}<L^*<L$, indicating that the current livestock quantity can satisfy the meat demand for people, and the manure N is not produced in excess. Among all the typologies presented, T+M− is the optimal situation that not only produces enough meat but also avoids excess manure.

For the first objective of this study, we mapped the regions in which meat demand was satisfied and whether manure N was present in excess (according to the six types defined). We also tested (using ANOVA and Tukey HSD test) if the distribution of socio-economic indicators (GDP per capita) and agricultural resources (arable land area per capita) was significantly affected by the typologies.

2.6.2. Scenarios to increase the proportion of manure N substituted with chemical N

For the second objective of our study, we investigated the role of increasing *PCSM* [defined in Eq. (6)]. We varied the coefficient *PCSM* (which affects the total manure demand for crops) in Eq. (6) in the range of 0–100%. Other livestock, crop, and population data were kept constant. Along with this range, we tracked the change in the number of regions for each of the six types. Increasing the *PCSM* value can increase the manure fertilizer demand for crops and benefit to avoid excess manure if the livestock quantity is not changed.

3. Results

3.1. Classification of regions according to satisfaction of meat and manure balance

We mapped the regions of eastern China according to six types defined in relation to meat and manure N balance (Fig. 4). A total of 178 regions were characterized by $L^*<\hat{L}$ [T−M− ($n = 1$), T+M− ($n = 39$), T+M+ ($n = 138$)], indicating that approximately 68% of the regions of eastern China can satisfy ideal meat demand and avoid manure excess by adjusting livestock quantity; 83 regions were characterized by $L^*>\hat{L}$ [M−T− ($n = 5$), M+T− ($n = 17$), M+T+ ($n = 61$)], indicating that approximately 32% of the regions can satisfy ideal meat demand and avoid manure excess only by importing meat products or increasing manure demand for crops. The regions in which manure N is not currently in excess (T−M−, T+M−, and M−T−) are mainly distributed in northern and central China, accounting for approximately 17% of the total eastern regions of China. The proportion of regions with surplus meat self-production was 91% (T+M−, T+M +, M+T+).

3.2. Characteristics of different classification

The distributions of GDP per capita and arable resources per capita are significantly affected by the types of meat and manure balance (Fig. 5). Type T−M− consisted of only one region, so it was not considered for the ANOVA analysis. The GDP of regions of types M−T− and M+T− were higher than that of regions of type T+M−, T+M+, and M+T+ ($p < 0.001$), indicating that the higher the GDP per capita of the regions, the lower the ability to satisfy the ideal meat demand. The arable land per capita was higher in regions of type T+ M− than that of other regions ($p < 0.001$), indicating that the more the arable land per capita of the region, the higher the possibility of achieving the optimal conditions that satisfy ideal meat demand and avoids excess manure.

3.3. Scenarios that increase the proportion of manure N substituted with chemical N

The number of regions belonging to each typology changed as a function of *PCSM* (Fig. 6). If the *PCSM* was low (<5%), there were four types of regions, including T+M+ (22 regions), M+T− (22 regions), and M+T+ (216 regions), meaning that almost all the regions had

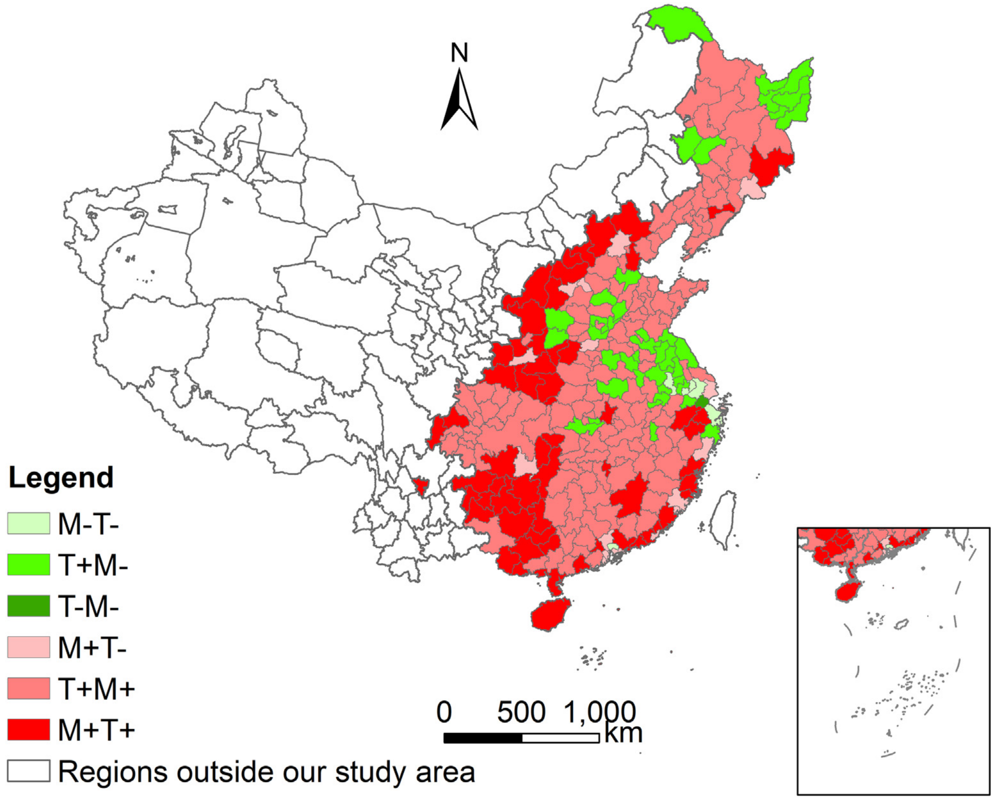

Fig. 4. Eastern regions of China classified according to manure deficiency/excess and meat demand satisfaction/unsatisfaction. Green regions are characterized by manure N deficiency, red regions are characterized by manure N excess. Different nuances of red and green are indicated in the legend and refer to the typology defined in the study. The meaning of T−M− ($n = 1$), T+M− ($n = 39$), T+M+ ($n = 138$), M−T− ($n = 5$), M+T− ($n = 17$), and M+T+ ($n = 61$) refer to Fig. 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

manure excess if the manure was not utilized. The number of regions of both the T−M− and T+M− types increased gradually, whereas the number of regions of types M+T− and M+ T+ decreased gradually; for T+M+, the number of regions first increased and then decreased with the inflection point approximately 30%; for M−T−, the number of regions first increased and then stabilized when the *PCSM* was greater than approximately 50%. If the *PCSM* achieved 100% (theoretical situation in which all the crop agriculture is organic), the T−M−, T+M−, T+M+, M−T−, M+T−, and M+T+ types included 10, 167, 64, 5, 8, and 7 regions, respectively, meaning that there were in total 241 regions that could satisfy ideal meat demand and avoid manure excess by adjusting livestock quantity (T−M−, T+M−, and T+M+), while 20 regions could satisfy ideal meat demand and avoid manure excess only by importing meat products (M−T−, M+T−, and M+T+).

4. Discussion

We analyzed the trade-off between meat supply and manure excess in eastern China. The Chinese government has implemented several policies to promote the optimization of spatial agricultural production distribution according to the resource and environment carrying capabilities, such as the Guiding Opinions of the Ministry of Agriculture on Further Adjusting and Optimizing the Agricultural Structure, National Agricultural Sustainable Development Plan (2015–2030) (MARAPRC, 2015a,b). However, based on the metrics of N balance, our results showed that manure N production was greater than the ideal manure N demand for crops in most regions in eastern China (Fig. 4), in which the number of regions with excess manure accounted for approximately 83% of the total regions. Jia et al. (2018) found that 11 provinces in China, which are mainly distributed in the eastern region, exceeded the national average value of manure N load. The goal of meat production and meat demand satisfaction might be a priority in China (such as the "Shopping Basket Program"), without the consideration of environmental consequences. Lack of awareness of nutrient management and inappropriate policy guidelines could explain the excessive fertilization in China's major croplands (Jiao et al., 2018). In most rural areas of China, untrained workers conducted farming, and they did not recognize the importance of nutrient management due to a lack of efficient channels to transfer technologies to Chinese farmers (Zhang et al., 2016). Notably, based on the philosophy of high input and output and the low price of chemical fertilizer due to massive subsidies, excessive fertilization in China's major croplands is common (Vitousek et al., 2009).

4.1. Spatial distribution of meat and manure N balance

To investigate the situations of meat demand satisfaction and manure balance, we divided all the regions into six types. The most favorable type of region was the one in which ideal meat demand was satisfied, and manure N excess was avoided (T+M−). This type of region accounted for approximately 15% of the total regions in eastern China, mainly distributed in the Middle East and North (Fig. 4), which is consistent with the results of Zheng et al. (2019); in fact, the Lower Reaches of the Yangtze River and North China have enough space for the expansion of livestock and poultry farming from the nitrogen land-bearing capacity. The regions of type T+M− have a higher arable land per capita than other types of regions. The larger arable land per capita of the regions not only mitigates feed-food competition to raise more livestock (Muscat et al., 2019), but also consumes more manure N to avoid excess (Zhang et al., 2019). For types T−M− and M−T−, meat production was deficient, and manure N was not excessive. These two types of regions were mainly distributed in the Yangtze River Delta and the Pearl River Delta (Fig. 4), where the main target to improve the environment was the Air Pollution Prevention and Control

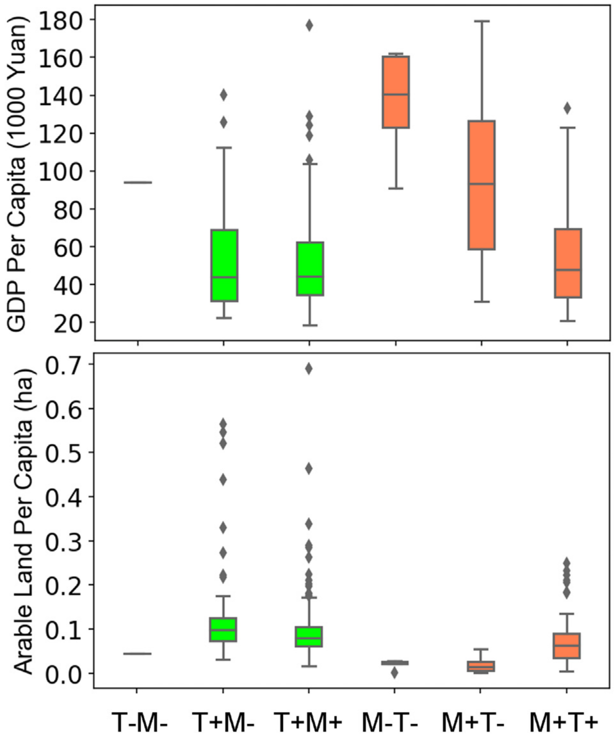

Fig. 5. Box plots of GDP (gross domestic product) per capita distribution (panel above) and arable land per capita distribution (panel below) in six classification types. Green boxes represent regions that can satisfy ideal meat demand and avoid manure excess by adjusting livestock quantity; red bars represent regions that can satisfy ideal meat demand and avoid manure excess only by importing meat products or increasing manure demand for crops. The meaning of T−M− ($n = 1$), T+M− ($n = 39$), T+M+ ($n = 138$), M−T− ($n = 5$), M+T− ($n = 17$), and M+T+ ($n = 61$) refer to Fig. 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Action Plan published in 2013 (SCPRC, 2013). In addition, both areas were developed regions, where the GDP per capita was higher than other types of regions (Fig. 5), and these areas tended to achieve meat

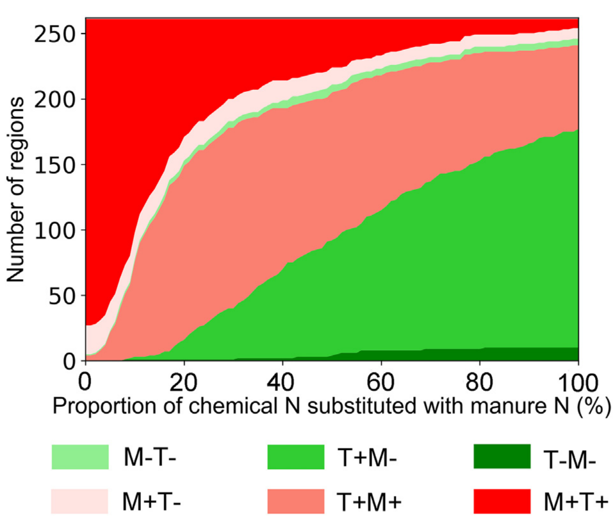

Fig. 6. Changes in the regions' number of six types with the scenarios that increase *PCSM*. Regions represented with green nuances are characterized by manure N deficiency, regions represented by red nuances are characterized by manure N excess. The meaning of T−M−, T+M−, T+M+, M−T−, M+T−, and M+T+, please refer to Fig. 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

demand satisfaction through trade. However, imports and exports of meat would consume more fuel and cause adverse effects on the environment (Kriewald et al., 2019; Pradhan et al., 2020). Nevertheless, there are differences between the regions of T−M− and M−T−. The regions of T−M− can achieve the optimal condition (i.e., becoming T+M−) for meeting meat demand without excess manure production by increasing the livestock quantity. This is because the arable land per capita in the region of T−M− was higher than that in M−T− (refer to Fig. 5); however, a statistical test cannot be conducted due to only one region of T−M−. For M+T −, the manure N was in excess, and the meat was deficient. Regions of this type were mainly developed cities, which have higher GDP per capita and lower arable land per capita (Fig. 5). Previous studies have shown that Chinese industrial livestock systems are located near large cities having high population density (Li et al., 2008), and it is difficult to satisfy the meat demand by increasing the local production. Zheng et al. (2019) found that big cities (e.g., Beijing and Tianjin) have a higher risk producing excess manure. The regions of T+M+ and M+T+, accounting for approximately 76% of the total regions, could satisfy meat demand but cause excess manure N production. These regions produce more meat than they demand, causing environmental problems.

4.2. Expanding manure fertilizer demand for crops

Fig. 4 shows that most regions in eastern China (approximately 83%) faced the challenge of livestock manure excess when utilizing a reasonable manure quantity (*PCSM* = 30%). Keeping the livestock number constant and increasing the *PCSM* is the direct method to increase manure N application for crops, which can improve the environmental carrying capacity for livestock manure and reduce manure N excess (Zheng et al., 2019). Fig. 6 shows that when *PCSM* = 50%, the proportion of the regions with excess manure would decrease to 62%; when *PCSM* = 100%, the proportion would decrease to 30%. This also means that there were still some regions with excess manure, even in the theoretical situation of using the highest possible quantity of manure fertilizer for crops. These regions should decrease their livestock quantities and satisfy their meat demand by importing meat.

Indeed, China faces serious problems of synthetic N overuse, resulting in environmental pollution (Jiao et al., 2018); increasing the *PCSM* not only can avoid excess manure production without lowering livestock quantity but would also decrease the use of mineral fertilizers. Encouraging farmers to use organic manure instead of mineral N could be an effective object of policy. According to the study of Wang et al. (2018) and Chadwick et al. (2015), policies should promote farmers to join cooperatives, and subsidies on organic fertilizers should be given to farmers to help them make manure or compost themselves.

The crop yield, nutrient use efficiency, and soil environment are affected by a different proportion of chemical N substituted with manure fertilizer, although increasing the *PCSM* can reduce excess manure. For crop yield, approximately 20–40% substitution of chemical N with manure fertilizer is beneficial for improving productivity (Xie et al., 2016). For nutrient utilization, Guo et al. (2020) found that 50% substitution of chemical N with manure fertilizer was a potential option in maize production systems to decrease N losses by approximately 45%. For the soil environment, if there was an increase in *PCSM*, the soil pH, available potassium, organic carbon, total N, and microbial biomass C and N increased as well (Ji et al., 2018). For the greenhouse gas (GHG) emissions, the more manure fertilizer application, the more CH_4 emissions from the cropland, which exacerbates climate change. For the agricultural systems, with *PCSM* the increasing, there is one trade-off between decreasing productivity and decreasing environmental pressure (Li et al., 2021a). Apparently, increasing the *PCSM* is beneficial for the soil environment, while crop yield may be adversely affected. Therefore, *PCSM* cannot increase unlimitedly.

4.3. Limitations and perspectives of the study

This study analyzed the trade-off between producing enough meat for people while avoiding excess manure in eastern China. There are several limitations and perspectives in our study. First, the study assumed that all the fresh livestock manure was converted to organic fertilizer by fermentation and returned to the cropland in the local region. However, it would be possible to utilize livestock manure in other ways (e.g., biogas) (Roubík et al., 2018). The manure demand calculation can be improved by considering multiply manure utilization approaches. Besides, the transportation of livestock manure can be another approach to avoid excess manure when the transportation price could be accepted by the farmers. Second, calculations were done under ideal conditions, namely, ideal nitrogen demand from main crops (i.e., rice, wheat, maize, soybean, vegetables), and ideal meat demand data were obtained from the Chinese Dietary Guidelines recommended by the Chinese Nutrition Society. However, other crops (e.g., cotton, oil plants, fruit) also need manure fertilizer N, which the results can be improved through considering all the crops. Meat waste,which affects food self-sufficiency and increases GHG emissions (Hiç et al., 2016), was not considered. The data on meat consumption can be improved through conducting a in-depth survey. Third, feed production was not considered. The global feed demand is predicted to almost double by 2050 compared to 2000 (Pradhan et al., 2013). This is particularly important in China, given that there is a high dependency on soybean imports (Gale et al., 2019; Wang, 2019; Li et al., 2021b). Forth, CH_4 emissions from ruminants' enteric fermentation were not considered, which is one of the important GHG to exacerbate global warming. Fifth, nitrogen was used to be the metric for manure balance in this study, and other nutrients (e.g., phosphorus) and other pollutants like heavy metal elements are also important to be accounted for, and the method proposed in our study can be used to study other nutrients balance. Although N loss was not considered to check the potential carrying capacity of manure N in this study, the loss ratios of leaching and runoff are 9.2% and 2.6% for organic fertilizer, respectively, based on a global meta-analysis (Wei et al., 2021). The results of the current manure N balance can be improved by considering N loss when the data is available. Sixth, although the laying hens and dairy cattle were considered when calculating the manure and meat production, in this study, the eggs and milk self-sufficiency were not studied. Li et al. (2021b) reported that most regions are self-sufficient or close to self-sufficiency in meat, however, concerning eggs southern regions were deficient, and concerning milk almost all of the eastern regions are in extreme shortage. Therefore, it is significant to target meat as it regards almost all the eastern regions, but it is relevant for future studies to adjust the livestock quantity among different types of livestock to improve self-sufficiency for all animal-sourced food items and adjust the total livestock quantity to avoid excess manure. The method framework in our study can be used to achieve meat self-sufficiency while avoiding excess manure through adjusting livestock quantity for each region.

5. Conclusion

In this study, we proposed one quantitative methodology to assess the meat self-sufficiency and manure nutrient surplus at the regional level, which is related to food security and environmental protection. This methodology is useful in different ways. First, it can help evaluate whether the livestock manure nutrient N was excessive and, meanwhile, whether the meat was sufficient for a region. Also, with the methodology framework it would be possible to analyze the relationship between meat self-sufficiency and other manure nutrient surplus (e.g., phosphorus) for a region according to agricultural nutrient cycling. Second, this methodology framework can be applied in the optimization of the livestock quantity for a region to avoid excess manure nutrients and, at the same time, satisfy local meat demand, and help the government to determine the optimal livestock quantity in regional level. The methodology can be applied in other countries or regions with negligible grassland surface and with intensive livestock systems, as long as the data are available.

Based on this method, we analyzed the trade-off between the achievement of meat self-sufficiency and the avoidance of manure excess in eastern regions of China, and, at the best of our knowledge, this is the first study addressing this. We found that the most favorable type of regions, that satisfies meat demand and also avoids excess manure, accounted for only 15% of the total regions, mainly distributed in the Middle East and North of China. Approximately 83% of the total regions had excess manure, and 91% of the total regions produced more meat than they ideally needed. This means that many regions with excess manure in China are provoked by an excess of unnecessary livestock density to produce meat in many regions. There were still 30% of regions that cannot conciliate meat self-sufficiency with manure excess avoidance, even in the theoretical situation of using the highest possible quantity of manure fertilizer for crops, where should decrease their livestock quantities and satisfy their meat demand by importing meat.

The natural resources and the social economy vary for different types of regions and are correlated to meat self-sufficiency and manure nutrient balance in a region. GDP per capita is negatively correlated to the ability to satisfy meat demand in a region; arable land per capita is positively correlated with the capability of a region to satisfy local meat demand while avoiding excess manure.

Expanding manure fertilizer demand for crops by increasing the proportion of manure N as a substitute for chemical N can improve the environmental carrying capacity of livestock manure and solve the problem of excess manure N. However, in order to maintain optimal crop yield and nutrient use efficiency, the proportion of chemical N substituted with manure N cannot increase unlimitedly. Additionally, eastern China needs to advocate a healthy diet and strengthen the management and supervision of food waste and livestock manure.

Credit authorship contribution statement

Yang Li: Methodology, Formal analysis, Investigation, Data Curation, Writing – Original Draft, Visualization, Results interpretation. **Zhigang Sun**: Conceptualization, Supervision, Results interpretation. **Francesco Accatino**: Conceptualization, Methodology, Results interpretation, Validation, Writing – Review & Editing, Visualization, Supervision.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.151568.

References

Asai, M., Langer, V., Frederiksen, P., Jacobsen, B.H., 2014. Livestock farmer perceptions of successful collaborative arrangements for manure exchange: a study in Denmark. Agric. Syst. 128, 55–65. https://doi.org/10.1016/j.agsy.2014.03.007.

Bai, Z., Ma, W., Ma, L., Velthof, G.L., Wei, Z., Havlík, P., Oenema, O., Lee, M.R., Zhang, F., 2018. China's livestock transition: Driving forces, impacts, and consequences. Sci. Adv. 4 (7), eaar8534. https://doi.org/10.1126/sciadv.aar8534.

Barker, J., Zublena, J., 1995. Livestock manure nutrient assessment in North Carolina. Final Report. North Carolina Agricultural Extension Service, North Carolina State University, Raleigh, NC.

Bateman, A., van der Horst, D., Boardman, D., Kansal, A., Carliell-Marquet, C., 2011. Closing the phosphorus loop in England: the spatio-temporal balance of phosphorus capture from manure versus crop demand for fertiliser. Resour. Conserv. Recycl. 55, 1146–1153. https://doi.org/10.1016/j.resconrec.2011.07.004.

Cai, Z., Wang, B., Xu, M., Zhang, H., He, X., Zhang, L., Gao, S., 2015. Intensified soil acidification from chemical N fertilization and prevention by manure in an 18-year field experiment in the red soil of southern China. J. Soils Sediments 15 (2), 260–270. https://doi.org/10.1007/s11368-014-0989-y.

Chadwick, D., Wei, J., Yan'an, T., Guanghui, Y., Qirong, S., Qing, C., 2015. Improving manure nutrient management towards sustainable agricultural intensification in China. Agric. Ecosyst. Environ. 209, 34–46. https://doi.org/10.1016/j.agee.2015.03.025.

CRSY, China Rural Statistical Yearbook, 2018. National Bureau of Statistics, Rural Social and Economic Survey Division. China Statistics Press.

Clapp, J., 2017. Food self-sufficiency: making sense of it, and when it makes sense. Food Policy 66, 88–96. https://doi.org/10.1016/j.foodpol.2016.12.001.

CNS, Chinese Nutrition Society, 2016. Dietary Guidelines for Chinese Residents. People's Medical Publishing House.

Dagnall, S., Hill, J., Pegg, D., 2000. Resource mapping and analysis of farm livestock manures—assessing the opportunities for biomass-to-energy schemes. Bioresour. Technol. 71, 225–234. https://doi.org/10.1016/S0960-8524(99)00076-0.

Deng, X., Bai, X., 2014. Sustainable urbanization in western China. Environ. Sci. Policy Sustain. Dev. 56, 12–24. https://doi.org/10.1080/00139157.2014.901836.

Deng, Y., Liu, S., Cai, J., Lu, X., Nielsen, C.P., 2015. Spatial pattern and its evolution of Chinese provincial population: methods and empirical study. J. Geogr. Sci. 25, 1507–1520. https://doi.org/10.1007/s11442-015-1248-x.

Dimkpa, C.O., Fugice, J., Singh, U., Lewis, T.D., 2020. Development of fertilizers for enhanced nitrogen use efficiency–Trends and perspectives. Sci. Total Environ. 731, 139113. https://doi.org/10.1016/j.scitotenv.2020.139113.

FAO, 2006. Livestock's Long Shadow. FAO Collection: Environmental Issues and Options. Food and Agriculture Organization of the United Nations, Rome, p. 390.

Gale, F., Valdes, C., Ash, M., 2019. Interdependence of China, United States, and Brazil in Soybean Trade. US Department of Agriculture's Economic Research Service (ERS) Report, New York, pp. 1–48.

Galloway, J.N., Dentener, F.J., Capone, D.G., Boyer, E.W., Howarth, R.W., Seitzinger, S.P., Asner, G.P., Cleveland, C.C., Green, P., Holland, E.A., 2004. Nitrogen cycles: past, present, and future. Biogeochemistry 70, 153–226. https://doi.org/10.1007/s10533-004-0370-0.

Gandhi, V.P., Zhou, Z., 2014. Food demand and the food security challenge with rapid economic growth in the emerging economies of India and China. Food Res. Int. 63, 108–124. https://doi.org/10.1016/j.foodres.2014.03.015.

Geng, Y., Cao, G., Wang, L., Wang, S., 2019. Effects of equal chemical fertilizer substitutions with organic manure on yield, dry matter, and nitrogen uptake of spring maize and soil nitrogen distribution. PLoS One 14, e0219512. https://doi.org/10.1371/journal.pone.0219512.

Gerber, P., Chilonda, P., Franceschini, G., Menzi, H., 2005. Geographical determinants and environmental implications of livestock production intensification in Asia. Bioresour. Technol. 96, 263–276. https://doi.org/10.1016/j.biortech.2004.05.016.

Guo, S., Pan, J., Zhai, L., Khoshnevisan, B., Wu, S., Wang, H., Yang, B., Liu, H., Lei, B., 2020. The reactive nitrogen loss and GHG emissions from a maize system after a long-term livestock manure incorporation in the North China Plain. Sci. Total Environ. 137558. https://doi.org/10.1016/j.scitotenv.2020.137558.

Hansen, J., Gale, F., 2014. China in the next decade: Rising meat demand and growing imports of feed. Amber Waves. https://www.ers.usda.gov/amber-waves/2014/april/china-in-the-next-decade-rising-meat-demand-and-growing-imports-of-feed/.

Hiç, C., Pradhan, P., Rybski, D., Kropp, J.P., 2016. Food surplus and its climate burdens. Environ. Sci. Technol. 50 (8), 4269–4277. https://doi.org/10.1021/acs.est.5b05088.

Ji, L., Wu, Z., You, Z., Yi, X., Ni, K., Guo, S., Ruan, J., 2018. Effects of organic substitution for synthetic N fertilizer on soil bacterial diversity and community composition: a 10-year field trial in a tea plantation. Agric. Ecosyst. Environ. 268, 124–132. https://doi.org/10.1016/j.agee.2018.09.008.

Jia, W., Qin, W., Zhang, Q., Wang, X., Ma, Y., Chen, Q., 2018. Evaluation of crop residues and manure production and their geographical distribution in China. J. Clean. Prod. 188, 954–965. https://doi.org/10.1016/j.jclepro.2018.03.300.

Jiao, X., He, G., Cui, Z., Shen, J., Zhang, F., 2018. Agri-environment policy for grain production in China: toward sustainable intensification. China Agric. Econ. Rev. https://doi.org/10.1108/CAER-10-2017-0201.

Kriewald, S., Pradhan, P., Costa, L., Ros, A.G.C., Kropp, J.P., 2019. Hungry cities: how local food self-sufficiency relates to climate change, diets, and urbanisation. Environ. Res. Lett. 14 (9), 094007. https://doi.org/10.1088/1748-9326/ab2d56.

Laborde, D., Martin, W., Swinnen, J., Vos, R., 2020. COVID-19 risks to global food security. Science 369 (6503), 500–502. https://doi.org/10.1126/science.abc4765.

Lassaletta, L., Billen, G., Garnier, J., Bouwman, L., Velazquez, E., Mueller, N.D., Gerber, J.S., 2016. Nitrogen use in the global food system: past trends and future trajectories of agronomic performance, pollution, trade, and dietary demand. Environ. Res. Lett. 11 (9), 095007. https://doi.org/10.1088/1748-9326/11/9/095007.

Leinonen, I., 2019. Achieving environmentally sustainable livestock production. Sustainability 11 (1), 246. https://doi.org/10.3390/su11010246.

Li, X., Yuan, Q., Wan, L., He, F., 2008. Perspectives on livestock production systems in China. Rangel. J. 30 (2), 211–220. https://doi.org/10.1071/RJ08011.

Li, Y., Sun, Z., Accatino, F., Hang, S., Lv, Y., Ouyang, Z., 2021a. Comparing specialised crop and integrated crop-livestock systems in China with a multi-criteria approach using the emergy method. J. Clean. Prod. 127974. https://doi.org/10.1016/j.jclepro.2021.127974.

Li, Y., Sun, Z., Accatino, F., 2021b. Spatial distribution and driving factors determining local food and feed self-sufficiency in the eastern regions of China. Food Energy Secur. https://doi.org/10.1002/fes3.296.

Liu, Y., Wang, J., Long, H., 2010. Analysis of arable land loss and its impact on rural sustainability in southern Jiangsu Province of China. J. Environ. Manag. 91, 646–653. https://doi.org/10.1016/j.jenvman.2009.09.028.

Lv, F., Song, J., Giltrap, D., Feng, Y., Yang, X., Zhang, S., 2020. Crop yield and N2O emission affected by long-term organic manure substitution fertilizer under winter wheat-summer maize cropping system. Sci. Total Environ. 139321. https://doi.org/10.1016/j.scitotenv.2020.139321.

MARAPRC, 1988. Ministry of Agriculture and Rural Affairs of the People's Republic of China. Shopping Basket Program.

MARAPRC, Ministry of Agriculture and Rural Affairs of the Peoples Republic of China, 2015a. The Guiding Opinions of the Ministry of Agriculture on Further Adjusting and Optimizing the Agricultural Structure.

MARAPRC, Ministry of Agriculture and Rural Affairs of the Peoples Republic of China, 2015. National Agricultural Sustainable Development Plan (2015-2030).

MARAPRC, Ministry of Agriculture and Rural Affairs of the Peoples.Republic of China, 2018. Technical guide for measuring land carrying capacity of livestock manure.

MARAPRC (Ministry of Agriculture and Rural Affairs of the People's Republic of China), MEEPRC (Ministry of Ecology and Environment of the People's Republic of China), 2020. Notice on further clarifying the requirements for returning livestock manure to the field and strengthening the supervision of manure pollution.

Mehrabi, Z., Gill, M., van Wijk, M., Herrero, M., Ramankutty, N., 2020. Livestock policy for sustainable development. Nat. Food 1 (3), 160–165. https://doi.org/10.1038/s43016-020-0042-9.

Metelkova, E., Demishkevich, G., Gusev, A., 2019. State support for the production of cattle meat: the experience of countries with high levels of self-sufficiency. IOP Conference Series: Earth and Environmental Science. IOP Publishing, p. 012036.

Moraine, M., Duru, M., Therond, O., 2017. A social-ecological framework for analyzing and designing integrated crop–livestock systems from farm to territory levels. Renew. Agric. Food Syst. 32, 43–56. https://doi.org/10.1017/S1742170515000526.

Mullen, A.M., Álvarez, C., Zeugolis, D.I., Henchion, M., O'Neill, E., Drummond, L., 2017. Alternative uses for co-products: harnessing the potential of valuable compounds from meat processing chains. Meat Sci. 132, 90–98. https://doi.org/10.1016/j.meatsci.2017.04.243.

Muscat, A., de Olde, E., de Boer, I.J., Ripoll-Bosch, R., 2019. The battle for biomass: a systematic review of food-feed-fuel competition. Glob. Food Sec. 100330. https://doi.org/10.1016/j.gfs.2019.100330.

NBS, National Bureau of Statistics, n.d. NBS, National Bureau of Statistics. China Rural Statistical Yearbook. 1989, 2019. China Statistics Press.

NCAPCB, National Compilation of Agricultural Product Cost and Benefitcollab, 2018. National Development and Reform Commission, Price Division. China Statistics Press.

Nugroho, E., Azizah, S., Susilawati, T., Novianti, I., 2013. Socio-economic potential of Indonesian native cattle in supporting meat self-sufficiency in Indonesia. Livest. Res. Rural. Dev. 25 (11), 12.

Oenema, O., 2004. Governmental policies and measures regulating nitrogen and phosphorus from animal manure in European agriculture. J. Anim. Sci. 82, E196–E206. https://doi.org/10.2527/2004.8213_supplE196x.

Peng, L., Bai, Y., 2013. Numerical study of regional environmental carrying capacity for livestock and poultry farming based on planting-breeding balance. J. Environ. Sci. 25, 1882–1889. https://doi.org/10.1016/S1001-0742(12)60244-7.

Peyraud, J.L., Taboada, M., Delaby, L., 2014. Integrated crop and livestock systems in Western Europe and South America: a review. Eur. J. Agron. 57, 31–42. https://doi.org/10.1016/j.eja.2014.02.005.

Pinsard, C., Martin, S., Léger, F., Accatino, F., 2021. Robustness to import declines of three types of European farming systems assessed with a dynamic nitrogen flow model. Agric. Syst. 193, 103215. https://doi.org/10.1016/j.agsy.2021.103215.

Pradhan, P., Kriewald, S., Costa, L., Rybski, D., Benton, T.G., Fischer, G., Kropp, J.P., 2020. Urban food systems: how regionalization can contribute to climate change mitigation. Environ. Sci. Technol. 54 (17), 10551–10560. https://doi.org/10.1021/acs.est.0c02739.

Pradhan, P., Lüdeke, M.K., Reusser, D.E., Kropp, J.P., 2013. Embodied crop calories in animal products. Environ. Res. Lett. 8 (4), 044044. https://doi.org/10.1088/1748-9326/8/4/044044.

Qian, Y., Song, K., Hu, T., Ying, T., 2018. Environmental status of livestock and poultry sectors in China under current transformation stage. Sci. Total Environ. 622, 702–709. https://doi.org/10.1016/j.scitotenv.2017.12.045.

Roubík, H., Mazancová, J., Banout, J., 2018. Current approach to manure management for small-scale Southeast Asian farmers-using Vietnamese biogas and non-biogas farms as an example. Renew. Energy 115, 362–370. https://doi.org/10.1016/j.renene.2017.08.068.

Russelle, M.P., Entz, M.H., Franzluebbers, A.J., 2007. Reconsidering integrated crop–livestock systems in North America. Agron. J. 99, 325–334. https://doi.org/10.2134/agronj2006.0139.

Ryschawy, J., Choisis, N., Choisis, J., Joannon, A., Gibon, A., 2012. Mixed crop-livestock systems: an economic and environmental-friendly way of farming? Animal 6 (10), 1722–1730. https://doi.org/10.1017/S1751731112000675.

Ryschawy, J., Martin, G., Moraine, M., Duru, M., Therond, O., 2017. Designing crop–livestock integration at different levels: toward new agroecological models? Nutr. Cycl. Agroecosyst. 108 (1), 5–20. https://doi.org/10.1007/s10705-016-9815-9.

Savci, S., 2012. Investigation of effect of chemical fertilizers on environment. Apcbee Procedia 1, 287–292. https://doi.org/10.1016/j.apcbee.2012.03.047.

SCPRC, State Council of the Peoples.Republic of Chinacollab, 2013. Air Pollution Prevention and Control Action Plan.

Shimokawa, S., 2015. Sustainable meat consumption in China. J. Integr. Agric. 14 (6), 1023–1032. https://doi.org/10.1016/S2095-3119(14)60986-2.

Tamminga, S., 2003. Pollution due to nutrient losses and its control in european animal production. Livest. Prod. Sci. 84 (2), 101–111. https://doi.org/10.1016/j.livprodsci.2003.09.008.

Tang, X., Wu, M., Yang, W., Yin, W., Jin, F., Ye, M., Currie, N., Scholz, M., 2012. Ecological strategy for eutrophication control. Water Air Soil Pollut. 223 (2), 723–737. https://doi.org/10.1007/s11270-011-0897-3.

Vitousek, P.M., Naylor, R., Crews, T., David, M., Drinkwater, L., Holland, E., Johnes, P., Katzenberger, J., Martinelli, L., Matson, P., 2009. Nutrient imbalances in agricultural development. Science 324 (5934), 1519–1520. https://doi.org/10.1126/science.1170261.

Wang, H., 2019. Study on Game Model of Soybean Price: A Case Study of China-US Trade War, 2018 International Symposium on Social Science and Management Innovation (SSMI 2018). Atlantis Press.

Wang, X., Wu, X., Yan, P., Gao, W., Chen, Y., Sui, P., 2016. Integrated analysis on economic and environmental consequences of livestock husbandry on different scale in China. J. Clean. Prod. 119, 1–12. https://doi.org/10.1016/j.jclepro.2016.01.084.

Wang, Y., Zhu, Y., Zhang, S., Wang, Y., 2018. What could promote farmers to replace chemical fertilizers with organic fertilizers? J. Clean. Prod. 199, 882–890. https://doi.org/10.1016/j.jclepro.2018.07.222.

Wei, Z., Hoffland, E., Zhuang, M., Hellegers, P., Cui, Z., 2021. Organic inputs to reduce nitrogen export via leaching and runoff: a global meta-analysis. Environ. Pollut. 118176. https://doi.org/10.1016/j.envpol.2021.118176.

Wilkins, R.J., 2008. Eco-efficient approaches to land management: a case for increased integration of crop and animal production systems. Philos. Trans. R. Soc. B 363 (1491), 517–525. https://doi.org/10.1098/rstb.2007.2167.

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., 2019. Food in the anthropocene: the EAT–Lancet commission on healthy diets from sustainable food systems. Lancet 393 (10170), 447–492. https://doi.org/10.1016/S0140-6736(18)31788-4.

Xia, L., Lam, S.K., Yan, X., Chen, D., 2017. How does recycling of livestock manure in agroecosystems affect crop productivity, reactive nitrogen losses, and soil carbon balance? Environ. Sci. Technol. 51 (13), 7450–7457. https://doi.org/10.1021/acs.est.6b06470.

Xie, Z., Tu, S., Shah, F., Xu, C., Chen, J., Han, D., Liu, G., Li, H., Muhammad, I., Cao, W., 2016. Substitution of fertilizer-N by green manure improves the sustainability of yield in double-rice cropping system in South China. Field Crop Res. 188, 142–149. https://doi.org/10.1016/j.fcr.2016.01.006.

Yang, Y., Lei, T., Du, W., Liang, C., Li, H., Lv, J., 2020. Substituting chemical fertilizer nitrogen with organic manure and comparing their nitrogen use efficiency and winter wheat yield. J. Agric. Sci. 158 (4), 262–268. https://doi.org/10.1017/S0021859620000544.

Zhang, C., Liu, S., Wu, S., Jin, S., Reis, S., Liu, H., Gu, B., 2019. Rebuilding the linkage between livestock and cropland to mitigate agricultural pollution in China. Resour. Conserv. Recycl. 144, 65–73. https://doi.org/10.1016/j.resconrec.2019.01.011.

Zhang, W., Cao, G., Li, X., Zhang, H., Wang, C., Liu, Q., Chen, X., Cui, Z., Shen, J., Jiang, R., 2016. Closing yield gaps in China by empowering smallholder farmers. Nature 537 (7622), 671–674. https://doi.org/10.1038/nature19368.

Zhang, X., Davidson, E., Mauzerall, D., Searchinger, T., Dumas, P., Shen, Y., 2015. Managing nitrogen for sustainable development. Nature 528 (7580), 51–59. https://doi.org/10.1038/nature15743.

Zheng, L., Zhang, Q., Zhang, A., Hussain, H.A., Liu, X., Yang, Z., 2019. Spatiotemporal characteristics of the bearing capacity of cropland based on manure nitrogen and phosphorus load in mainland China. J. Clean. Prod. 233, 601–610. https://doi.org/10.1016/j.jclepro.2019.06.049.

Zhou, T., Fu, Q., Zhu, Y., Hu, Z., Yang, F., 2014. Optimizing pollutant generation coefficients of livestock industry and mapping patterns of the pollutant constitution in China. Geogr. Res. 33 (4), 762–776. https://doi.org/10.11821/dlyj201404015.

Zhou, X., Lu, Y., Liao, Y., Zhu, Q., Cheng, H., Nie, X., Cao, W., Nie, J., 2019. Substitution of chemical fertilizer by chinese milk vetch improves the sustainability of yield and accumulation of soil organic carbon in a double-rice cropping system. J. Integr. Agric. 18 (10), 2381–2392. https://doi.org/10.1016/S2095-3119(18)62096-9.