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Research article

Reducing livestock quantities to avoid manure nitrogen surplus: would meat self-sufficiency be met in eastern regions of China?

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ABSTRACT

In building a sustainable food system, the management of livestock production should avoid nitrogen (N) surplus and ensure animal-sourced food self-sufficiency. Reducing livestock quantities in regions producing excess of animal-sourced food and livestock manure is an effective approach for mitigating manure N surplus. In this study, we considered the eastern regions of China as a case study to quantitatively analyze whether meat self-sufficiency could be met when reducing the livestock quantity to avoid manure N surplus. In addition to considering the baseline scenario, considering the current livestock quantity (scenario C), we defined three strategies corresponding to livestock reduction scenarios: taking meat self-sufficiency as a priority regardless of the manure balance (scenario TB); taking manure N surplus avoidance as a priority regardless of the meat balance (scenario MNB); and considering the most limiting conditions between satisfying meat self-sufficiency and avoiding manure N surplus (scenario LF). A balance index was used to describe the excess (*i.e.*, positive value) or deficiency (*i.e.*, negative value) of meat and manure N. Concerning the whole of eastern China, in scenario LF, the meat balance index (TBI) and manure N balance index (MNBI) were 0.25 and −0.39, respectively, which could satisfy meat demand while avoid manure N surplus (for scenarios C, TB, and MNB, the TBIs were 1.95, 0, and 1.09, and the MNBIs were 0.56, −0.48, and 0, respectively). At the regional level, the regions with meat self-sufficiency accounted for more than 70% in the LF scenario, and manure N surplus could be avoided in all regions. However, southwestern China should adopt further measures, such as trading among adjacent regions and increasing manure fertilizer application, to satisfy the meat demand while avoiding surplus manure N.

1. Introduction

The global livestock sector, which has sharply increased especially in developing countries and emerging economies (Bao et al., 2019; Jin et al., 2021; Pandey and Chen, 2021), contributes to food security locally and globally (Herrero and Thornton, 2013; Godber and Wall, 2014) but produces large quantities of manure and greenhouse gas emissions. Livestock manure nitrogen (N) is a critical element for crop cultivation and for reducing synthetic fertilizer application (Zhang et al., 2015; Bai et al., 2018; Zhang et al., 2019a; Pinsard et al., 2021). However, its excess has serious environmental implications, such as air and water pollution (e.g., eutrophication) (Oenema et al., 2003; Ryschawy et al., 2017; Xia et al., 2017; Pandey and Chen, 2021), which can hinder the achievement of the United Nations Sustainable Development Goal (SDG) 3 (good health and well-being), SDG 6 (clean water and sanitation), and SDG 13 (climate action) (Chang et al., 2021).

In building sustainable food systems, the management of livestock production should avoid environmental impacts (*i.e.*, N surplus) (Jin et al., 2020) and at the same time, contribute to local animal-sourced

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food self-sufficiency (FAO, 2018). Many countries have implemented policies to ensure food self-sufficiency in the face of the risk of volatile prices in the international market (Clapp, 2017) and for increasing resilience to adverse events, such as temporary isolation (Anderson et al., 2020), supply chain disruptions, and the trade restrictions (Laborde et al., 2020) caused by the COVID-19 pandemic. However, meeting animal-sourced food self-sufficiency and avoiding manure N surplus might constitute a trade-off at the regional level (Li et al., 2022), as the two objectives might not be compatible: an unrestrained increase in the livestock quantity to achieve animal-sourced food self-sufficiency might cause manure N surplus, while avoiding manure N surplus might not ensure animal-sourced food self-sufficiency (Li et al., 2022).

Some strategies can alleviate the trade-off between animal-sourced food self-sufficiency and manure N surplus avoidance. Substituting chemical N with manure N in higher proportions can effectively reduce the manure N surplus while ensuring the same level of animal-sourced food production (Xia et al., 2017). However, given the current state of technology, it is not possible to indefinitely increase the proportion of chemical N substituted with manure N, as doing so reduces crop yields and food security (Lv et al., 2020). Furthermore, according to Li et al. (2022), there are regions where livestock are so abundant that manure N surplus cannot be avoided, even in the theoretical situation of only using manure fertilizer on crops.

Some researchers have argued for reducing livestock quantities as a strategy to mitigate the trade-off between food security and environmental impacts (Foley et al., 2011; Mehrabi et al., 2020). Concerning food security, reducing animal-sourced food production directly decreases feed consumption, which alleviates feed-food competition (Pinsard et al., 2021) and therefore strengthens cereal self-sufficiency in a region. Regarding environmental impacts, reducing the livestock quantity can decrease manure N surplus and greenhouse gas emissions directly as well as the consumption of other resources, such as water and electricity. However, there have been limited studies employing a quantitative approach to analyze the effect of reducing the livestock quantity while considering the dual objectives of minimizing environmental impacts and ensuring self-sufficiency in animal-sourced food. Addressing this would question on what would be the best strategy for lowering livestock: *aiming at regional self-sufficiency, at regional nitrogen balance, or a combination of the two?*

China, especially in its livestock-intense Eastern regions, faces challenges related to the need of livestock reduction, N surplus avoidance, and food self-sufficiency achievement. First, the demand for animal-sourced food in China, the largest emergent economy in the world, is gradually increasing, and the livestock quantity is also increasing, along with rising incomes and rapid urbanization (Bai et al., 2018; Huang and Tian, 2019; Lei and Shimokawa, 2020). Second, previous studies showed that more than 90% of the eastern regions of China produce more meat than the quantity needed based on healthy diet recommendations (Li et al., 2021a); also, 70.1% of adults in China exceeded the appropriate level of meat consumption (Lei and Shimokawa, 2020). Third, more than 80% of the total eastern regions of China have livestock manure N surplus (Li et al., 2022). Fourth, China does not achieve feed self-sufficiency (Wu et al., 2020) and largely imports soybeans. In summary, the eastern regions of China must reduce the livestock quantity to relieve the manure N surplus pressure, meantime, ensuring meat and feed self-sufficiency.

An analysis of animal-sourced food self-sufficiency and manure N surplus levels in the Eastern regions of China can be performed at different scales, with different implications. Nationally, the analysis of animal food self-sufficiency is related to the food security of the entire country and can inform strategies for international trade (Ghose, 2014; Clapp, 2017). However, self-sufficiency can be unequally distributed among regions, particularly in geographically large countries. Regionally, animal food self-sufficiency and manure N surplus can reveal whether regions can achieve food security or experience adverse environmental risks (Pradhan et al., 2014). Concerning the intermediate level between regions and countries, a cluster analysis can reflect situations related to a group of regions characterized by geographical proximity. Aggregated regions that produce excess meat can export meat to nearby regions. Aggregated regions with manure N surplus can aggravate the water, air, and soil pollution risk at a larger scale (Ryschawy et al., 2017), because the long-distance transfer of livestock manure to other regions can be excessively expensive (Dagnall et al., 2000; Wilkins, 2008; Asai et al., 2014). In contrast, if a region with excess meat and manure N production is surrounded by regions with deficient meat and manure N production, then the balance of production and demand for meat/manure N can be realized through short-distance transportation. Overall, we believe that performing a multilevel analysis involving the levels of country, group of regions, and regions can provide a complete picture of the trade-off between meat self-sufficiency and manure N excess.

Li et al. (2022) defined and showed the trade-off between meat self-sufficiency achievement and manure N surplus avoidance. In this study, we go beyond and we mainly have the objective of comparing scenarios of livestock reduction in China, considering the dual objectives of minimizing environmental impact and ensuring self-sufficiency in animal-sourced food. In particular we compare strategies of livestock reduction according to criteria of food self-sufficiency satisfaction, manure N excess avoidance, or a combination of the two. We explored the effect of these strategies with a multilevel analysis involving the levels of country, groups of regions, and region. We considered the eastern regions of China as a case study to explore scenarios of livestock reduction to investigate whether manure N surplus can be reduced while still achieving meat self-sufficiency at different levels.

We simulated different scenarios for exploring the optimal strategy of livestock reduction, keeping in mind the trade-off between achievement of regional meat self-sufficiency and the regional manure balance. Specifically, we defined (i) a scenario in which livestock quantity was set to the quantity achieving regional meat self-sufficiency (regardless of manure balance), representing a food security policy aimed at local meat self-sufficiency; (ii) a scenario in which livestock quantity was set to the quantity achieving regional manure balance (regardless of meat self-sufficiency), representing an environmental protection policy aimed at manure excess avoidance; (iii) a scenario in which we addressed in each region the most limiting condition between meat self-sufficiency and manure balance, representing an intermediate solution addressing the trade-off between local meat self-sufficiency and manure excess avoidance. The comparison among the three scenarios would help in setting criteria for driving the livestock reduction: should the benchmark be set in relation to food self-sufficiency, nitrogen avoidance, or a combination of the two? To conduct our scenario analysis we followed these two strategic methods: (i) we used the theoretical framework (Li et al., 2022) to quantitatively describe the relationship between the livestock quantity, manure N surplus, and meat self-sufficiency at the regional level; (ii) we considered different scales of analysis, ranging from whole eastern China, to clusters of neighboring regions, and individual regions. At last, the comparison between the outcomes of the tested scenario was conducted.

2. Material and methods

2.1. Study area

The eastern regions of China (261 in total), mainly in the east of the Heihe-Tengchong line (Hu, 1935), were considered in this study, excluding those characterized by a high presence of grasslands [referring to the Vegetation Map of The People's Republic of China (1:1000000) (Zhang, 2007)] (Fig. 1). The climate in these regions is mainly monsoonal, ranging from temperate (in the north) to subtropical (in the south) and tropical (the southernmost areas, e.g., Hainan Province). According to the statistical yearbook, in 2017, these regions had a population density ranging from 6.78 persons • km^{-2} to 6448.60 persons • km^{-2}, a GDP per capita ranging from 2725 dollars • $person^{-1}$ to 26604 dollars • $person^{-1}$ (average value: 7721 dollars • $person^{-1}$), and meat production ranging from 4.12×10^3 ton to 1.81×10^6 ton.

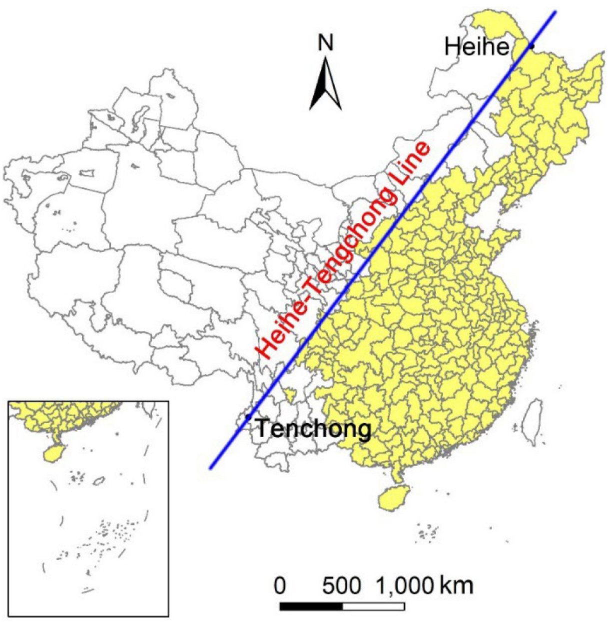

Fig. 1. Chinese regions considered in the study (yellow) and the Heihe-Tengchong line. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.2. Methodological overview

In order to quantitatively analyze the effect of reducing the livestock quantity while considering the dual objectives of minimizing environmental impact and ensuring self-sufficiency in animal-sourced food, we used the theoretical framework introduced by Li et al. (2022), specifically considering the concepts of *meat-optimal* and *manure-optimal* livestock quantity. In addition to this, we involved the concepts of *meat balance index* and *manure balance index* using the definition provided by Li et al. (2021a). Scenarios are then defined and their outputs were measured and compared in terms of balance indices at different spatial scales.

2.3. Calculation of the manure N surplus and meat self-sufficiency

The framework of Li et al. (2022) proposed two theoretical livestock quantities for a region: the *meat-optimal* livestock quantity (L^*), defined as the total livestock quantity that would theoretically produce the amount of meat equal to the human demand, and the *manure-N-optimal* livestock quantity ($\hat{L}$), defined as the total livestock number that would theoretically produce a quantity of manure N equal to crop needs. These two quantities are then compared to the *current* livestock quantity (L), defined as the actual total livestock quantity in the region. When $L \geq L^*$, meat self-sufficiency is met in a region, whereas it is not met when $L < L^*$; the manure N surplus occurs in a region when $L > \hat{L}$, whereas it does not occur when $L \leq \hat{L}$. Therefore, an ideal condition is $L^* \leq L \leq \hat{L}$, with L^* as close as possible to $\hat{L}$

The comparison between L^* and $\hat{L}$ shows the capacity of a region to achieve (or fail) meat self-sufficiency and manure N surplus avoidance *at the same time*. The condition $L^* \leq \hat{L}$ indicates that the livestock quantity required to achieve meat self-sufficiency does not lead to manure N surplus in a region. In contrast, $L^* > \hat{L}$ indicates that satisfying meat demand would cause manure N surplus in a region. In this case, manure N needs to be exported or meat needs to be imported into the region.

The regions could be divided into six types according to the different possible rankings among L, L^*, and $\hat{L}$. Regions labeled with *T–M–*, *T+M–*, and *T+M+* are those in which it is possible to achieve meat self-sufficiency without manure N surplus (*T* stands for "meaT" and *M* stands for "Manure N"; + and – mean that the meat and manure N demand are met or not met, respectively; *T* preceding *M* or *vice versa* indicate that the "meat-optimal" livestock quantity is lower than "manure-N-optimal" livestock quantity or *vice versa*, respectively). Regions labeled *M–T–*, *M+T–*, and *M+T+* are those in which the satisfaction of the meat demand would cause manure N surplus.

The workflow for identifying meat self-sufficiency and manure N surplus in a region referred to Li et al. (2022). The assumptions were as follows: (1) all livestock and crop the species are combined together, and constant parameters within each species, such as meat productivity, excretive coefficient, and nitrogen demand, are averaged using weights corresponding to the quantities of each species; (2) feed composition for all livestock species is assumed the same across all regions; primary crops (*i.e.*, rice, wheat, maize, soybean, vegetables) were taken into consideration; (4) all livestock manure produced is fermented to organic fertilizer, which is then recycled to the crops in the local region; (5) N quantities were used to express the manure balance; (6) an ideal condition of the N cycle is assumed; (7) the healthy dietary guidelines were used to calculate the meat demand. Overall, the calculation of meat production by each livestock category, productivity per hectare of different crop types, manure production by the different livestock categories, manure demand per hectare for the different crops are obtained via livestock- or crop-specific coefficients. The detailed information and formula can be found in Li et al. (2022) and Supplementary Materials. In this study, the manure N demand by crops considered a residual quantity of N left in the soil from the year before, which was not considered by Li et al. (2022).

2.4. Balance index of meat and manure N

To quantitatively analyze the degree of meat self-sufficiency and manure N surplus in different scenarios, we used the *balance index* (BI) (Li et al., 2021a):

$$BI_j = \frac{P_j - D_j}{D_j} \tag{1}$$

where P_j (tons • yr^{-1}) and D_j (tons • yr^{-1}) are the annual production and demand of meat or manure N in region j, respectively. For the meat balance index (TBI), a positive value indicates surplus meat availability, with higher positive values indicating higher robustness of self-sufficiency, including the possibility of storing or exporting meat; conversely, a negative value indicates the impossibility of satisfying the meat demand, with more negative values indicating higher severity of the deficit and the region needing to import meat or increase the meat quantity. For the manure N balance index (MNBI), a positive value indicates manure N surplus, with higher positive values indicating higher risks related to manure N surplus, including manure N pollution to soil, air, or water; in contrast, a negative value indicates a low risk of manure N surplus, with more negative values indicating lower manure N surplus and also the impossibility of having enough manure N supply to satisfy crop growth, so the region will need to import manure N or use chemical N for crop fertilization.

The TBI and MNBI could also be applied to the whole study area (expressed as TBI_w and $MNBI_w$), from which we can learn the meat self-sufficiency and manure N surplus in the whole area, independent of how production and demand are distributed among individual regions. Higher positive values of TBI_w and $MNBI_w$ indicate higher robustness of meat self-sufficiency and a higher risk of manure N surplus, respectively, at the level of eastern China.

2.5. Scenarios of livestock quantity adjustments

After distinguishing the region types according to meat and manure N surplus/deficit, we set rules for defining four scenarios of livestock quantity adjustment according to the region types. We remind that

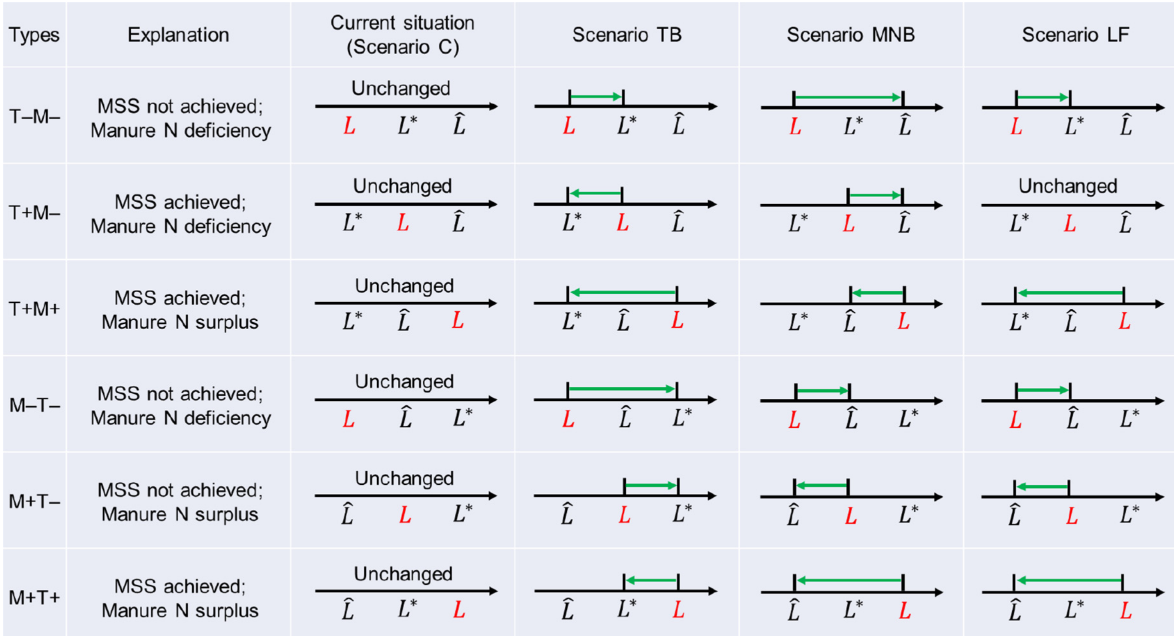

Fig. 2. Explanation of the classification of regions and scenarios. The region types refer to the different possible rankings of *current* livestock quantity (L), the theoretical *meat-optimal* livestock quantity (L^*), and the theoretical *manure-N-optimal* livestock quantity ($\hat{L}$). T–M– and M–T–: meat self-sufficiency (MSS) is not achieved and manure N surplus is avoided, T+M–: MSS is achieved and manure N surplus is avoided, M+T–: MSS is not achieved and there is manure N surplus, T+M+ and M+T+: MSS is achieved and there is manure N surplus. The scenarios, depending on the region type and the strategy represented, adjust the current livestock quantity L to different theoretical quantities L^*or $\hat{L}$. Scenario C: the current situation (corresponding to L in each region); scenario TB: in all the regions the livestock quantity was adjusted to L^*; scenario MNB: in all the regions the livestock quantity was adjusted to $\hat{L}$; scenario LF: the most limiting conditions between satisfying meat self-sufficiency and avoiding manure N surplus in all types of regions except T+M– where L is left unchanged. The green arrows indicate that the livestock quantity adjustment of different region types from *current* livestock quantity (L) to the theoretical quantity, *i.e. meat-optimal* livestock quantity (L^*) or *manure-N-optimal* livestock quantity ($\hat{L}$), in different scenarios. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

meat self-sufficiency is met in a region when $L \geq L^*$, whereas it is not met when $L < L^*$; the manure N surplus occurs in a region when $L > \hat{L}$, whereas it does not occur when $L \leq \hat{L}$. The scenarios, in the different region types differ in the way the current livestock quantity L remains unchanged or is adjusted to the theoretical quantities L^*, when regional meat balance is targeted, or $\hat{L}$, when regional manure balance is targeted. All the ways in which current livestock quantity is changed in the different scenarios and region types is provided in Fig. 2.

Scenario C (*current*), used as the baseline, corresponds to the current livestock quantity (L) left unchanged in each region. Scenario TB (*meaT balance*) corresponds to prioritizing meat self-sufficiency regardless of the manure balance; therefore, in each region *j*, the livestock quantity was adjusted to the meat-optimal livestock quantity (L^*), resulting in $TBI_j = 0$ in all regions. Scenario MNB (*Manure N Balance*) corresponds to prioritizing manure N surplus avoidance regardless of the meat balance; therefore, in each region *j*, the livestock quantity was adjusted to manure-N-optimal livestock quantity ($\hat{L}$), resulting in $MNBI_j = 0$ in all regions. Scenario LF (as a *Limiting Factor*) corresponds to the most limiting conditions between satisfying meat self-sufficiency and avoiding manure N surplus in all types of regions except when *T+M–* (otherwise meat would be deficient in the whole study area). The following rules were applied for this scenario: (i) if $L^* > \hat{L}$ (regions labeled *M–T–*, *M+T–*, and *M+T+*), the livestock quantity is set to $\hat{L}$ (manure N surplus is avoided even though this causes local meat deficiency); (ii) if $L^* < \hat{L}$ (regions labeled *T–M–*, *T+M–*, and *T+M+*), the livestock quantity is not changed (regions labeled *T+M–*) or is set to L^* (meat demand is satisfied, with some unsatisfied manure demand). In this scenario, manure N surplus is always avoided, but it might create some manure N deficit, although the local meat demand is satisfied.

We changed the livestock quantities in the different regions for the different scenarios, which affected meat and manure N production, while other coefficients (e.g., population, meat demand per capita per day, and crop production) were kept constant, as we only wanted to focus on the influence of strategies involving livestock reduction. In this study, we used the marketing rate $MR_i = LM_i/LS_i$ to conduct a transformation between the stock quantity (LM_i) and marketable quantity (LS_i) of livestock with a growth period of more than 365 days, *i.e.,* cattle and sheep. We assume the MR_i of the same type of livestock *i* is constant in all regions and used the surveyed data of marketable rate (MR_i) of cattle ($MR_{cattle} = 0.67$) and sheep ($MR_{sheep} = 1.02$) in China.

2.6. Data

Basic data on livestock (stock and marketable) quantities, meat production, and crop production were obtained from the provincial or municipal Statistical Yearbook of China, which can be obtained from the China Economic and Social Big Data Research platform (https://data.cnki.net/) and the regional Statistics Bureau website. The crops considered in this study were wheat, rice, maize, soybean, and vegetables, and the livestock species considered were beef cattle, dairy cattle, sheep, pig, broiler poultry, and layer hens. The data we used in this study were from 2017, which was the most recent year for which information in all regions was available. The data on meat demand corresponded to healthy diet recommendations that could nurture human health and support environmental sustainability (CNS, 2016; Willett et al., 2019). Missing data were filled in using information from neighboring years (2016 or 2018). Detailed information is provided in Supplementary Materials.

2.7. Spatial analysis

To perform a multilevel analysis involving the levels of country, groups of regions, and region, we analyzed the spatial distribution of the balance indexes TBI_j and $MNBI_j$ in each scenario to understand the performance of the different scenarios at different scales. To understand the meat self-sufficiency and manure N for whole eastern

China, we calculated TBI_w and $MNBI_w$. To understand the spatial distribution of meat self-sufficiency and manure N at the regional level, we mapped the TBI_j and $MNBI_j$ under these different scenarios.

To understand the characteristics of the spatial distribution of meat self-sufficiency and manure N surplus in clusters of neighboring regions, we used the local Moran's index I (*i.e.*, the local indicator of spatial association [LISA]), which can detect spatial disparity (Li et al., 2015; Ma et al., 2019). The basic idea of this spatial analysis is to investigate whether regions with a surplus in meat or manure N are surrounded by regions in surplus or deficit. If regions in surplus are surrounded by regions in deficit, it is possible to create exchanges among adjacent regions.

The Moran index I_i can be calculated by the following equation:

$$I_i = \frac{n(x_i - \overline{x}) \sum_{j=1}^{n} w_{ij}(x_j - \overline{x})}{\sum_{i=1}^{n}(x_i - \overline{x})^2} \quad (2)$$

Where I_i is the local Moran's I index of region i. x_i and x_j are the meat balance index or manure N balance index of region i and j, respectively; n is the number of study regions; $\overline{x}$ is the average value of the meat balance index or manure N balance index of all regions; and w_{ij} is a metric describing spatial relationship between region i and j ($w_{ij} = 1$ if the two regions are adjacent, $w_{ij} = 0$ otherwise). A positive value of I_i indicates clustering of regions with similar values of the attributes (either high or low), while a negative value of I_i indicates spatial proximity of regions with different values (e.g., a location with high values surrounded by neighbors with low values). The larger the absolute value, the higher the degree of proximity (Anselin, 1995; Mitchel, 2005).

The contiguity weight was used in the spatial autocorrelation analysis. Two regions, Hainan and Panzhihua, are not adjacent to any region in the considered geographical distribution; therefore, they were assumed to be adjacent to closer regions. In this study, a univariate analysis TBI_j and $MNBI_j$, which can show the aggregated regions of the indices themselves, and a bivariate analysis of TBI_j and $MNBI_j$, which can show the spatial relationship between TBI_j and $MNBI_j$, were conducted in different scenarios on the GeoDa platform (Anselin et al., 2010).

Based on the LISA methodology, four types of clustering regions could be identified: high-high (H-H), high-low (H-L), low-high (L-H), and low-low (L-L), where the first and second letter indicate values of the first and second index considered in the analysis. We performed a univariate and a bi-variate analysis. In the univariate analysis, we used the same index as first and second variable. So, the types indicate regions with a relatively high or low TBI_j ($MNBI_j$), surrounded by regions with a relatively high or low TBI_j ($MNBI_j$). In the bivariate analysis we considered different indices as first and second variable. Taking the example where TBI_j is the first variable and $MNBI_j$ is the second variable (TBI_j-$MNBI_j$), the H-L regions indicated that regions with a high value of TBI_j are surrounded by regions with a low value of $MNBI_j$. If the $MNBI_j$ is set as the first variable and TBI_j is set as the second variable ($MNBI_j$-TBI_j), the H-L regions indicated that regions with a high value of $MNBI_j$ are surrounded by regions with a low value of TBI_j.

Some analyses were meaningless because of scenario constraints: we did not consider TBI_j in scenario TB or $MNBI_j$ in scenario MNB for the univariate analysis, and scenarios TB and MNB in the bivariate analysis.

3. Results

3.1. Meat balance index and manure N balance index in the whole of eastern China under different scenarios

The overall livestock quantity in eastern China can be reduced to mitigate the trade-off between meat self-sufficiency and manure N surplus. As depicted in Fig. 3, the TBI_w and the $MNBI_w$ were positive in scenario C (1.95 and 0.56, respectively), showing a surplus in both meat and manure N production, and suggesting that the total livestock quantity can be reduced to some extent, alleviating manure N surplus still without causing meat deficit. In scenario TB, the TBI_w was 0 (consistent with the definition of the scenario as the livestock quantities in all regions were adjusted to the meat-optimal quantity) and the $MNBI_w$ was −0.48, showing that meat self-sufficiency could be met without manure N surplus, while more synthetic fertilizer may be needed to satisfy N demand for crops. Concerning MNB, the TBI_w was 1.09 and the $MNBI_w$ was 0 (consistent with the definition of the scenario, where livestock quantities were adjusted to the manure-N-optimal quantity in all regions), indicating that with manure N production equal to the demand, it was still possible to satisfy meat demand, but meat production was still in excess compared with meat demand. Concerning scenario LF, the TBI_w was 0.25 and the $MNBI_w$ was −0.39, showing that meat production can satisfy meat demand while avoiding manure N surplus. The LF scenario was the most satisfactory in eastern China, as it brought both the TBI_w and $MNBI_w$ closest to the value of 0.

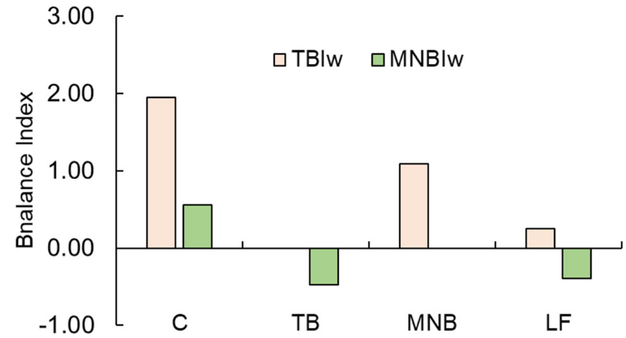

Fig. 3. Meat balance index (TBI_w) and manure nitrogen balance index ($MNBI_w$) in the whole of eastern China in different scenarios. C: current livestock quantity; TB: meat-optimal livestock quantities in each region; MNB: manure-N-optimal livestock quantities in each region; LF: the most limiting conditions between satisfying meat self-sufficiency and avoiding manure N surplus in all regions except *T+M–* (meat self-sufficiency is achieved and manure N surplus is avoided).

3.2. Spatial characteristics of the meat balance index and manure N balance index in regions of eastern China under different scenarios

3.2.1. Spatial distribution of the meat balance index and manure N balance index

Currently, most of the eastern regions of China could achieve meat self-sufficiency and most of the regions had manure N surplus. As shown in Fig. 4, the TBI_j was positive in most regions in scenario C, showing that the livestock quantity was often enough to satisfy local meat demand, and only 9% of regions could not satisfy the meat demand through local livestock production, mainly in the eastern coastal areas. However, approximately 74% of regions had manure N surplus, and only regions in the northeast and mid-east avoided this (Fig. 5). In scenario TB, the TBI_j in all regions was 0, as imposed by the scenario constraints, while regarding the $MNBI_j$, 27% of regions (mainly distributed in eastern coastal areas and western regions) had a manure N surplus. Regarding scenario MNB, 27% of regions could not achieve meat self-sufficiency, which were mainly distributed in coastal areas and western regions. As for the $MNBI_j$, the manure N supply and manure N demand were balanced in all regions, as imposed by the scenario constraints. For scenario LF, 73% of regions were characterized by meat self-sufficiency, except for coastal and western regions (accounting for 27% of the entire study area). In addition, 50% of the regions had $TBI_j = 0$, *i.e.*, the meat production was equal to the meat demand, while no regions had a manure N surplus. Scenario LF, compared with the MNB scenario, had decreased, as expected, livestock quantity in some regions, but the percentage of meat-self-sufficient regions did not decrease.

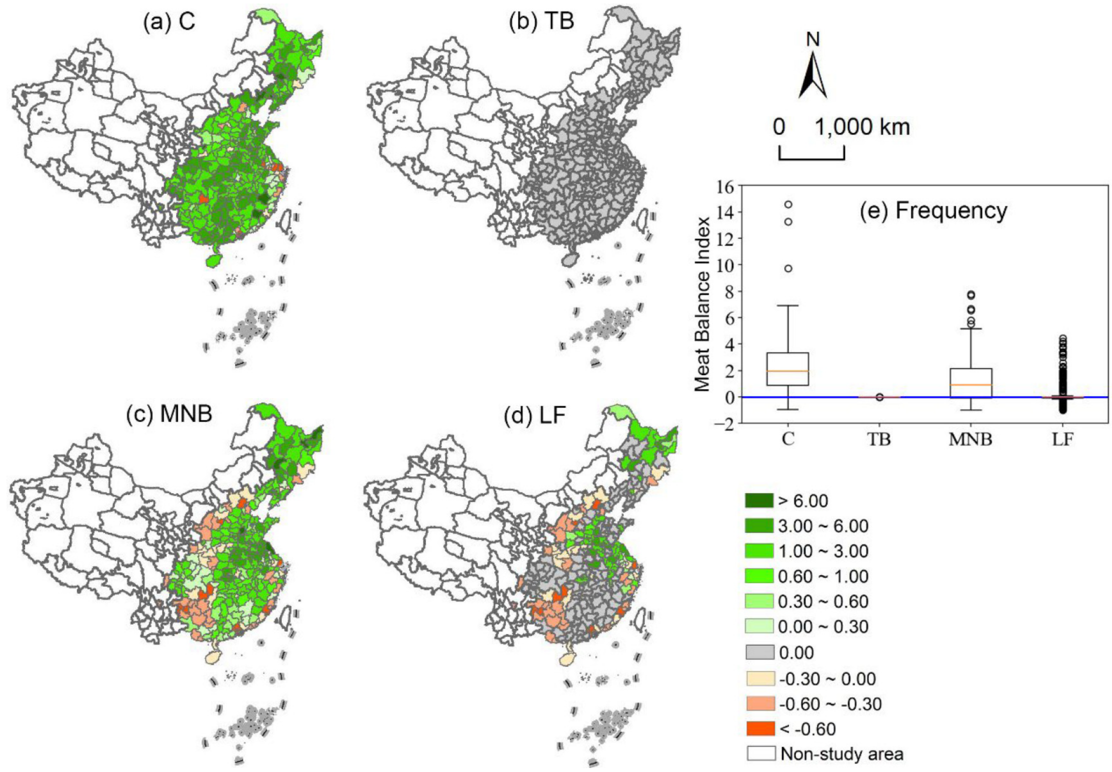

Fig. 4. Spatial distribution of meat balance index (TBI_j) in each region of eastern China in scenarios (a) C, (b) TB, (c) MNB, and (d) LF. For definitions of the scenarios, refer to Fig. 3. (e) Box plots of TBI_j in eastern regions of China. The blue line is the value of 0. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

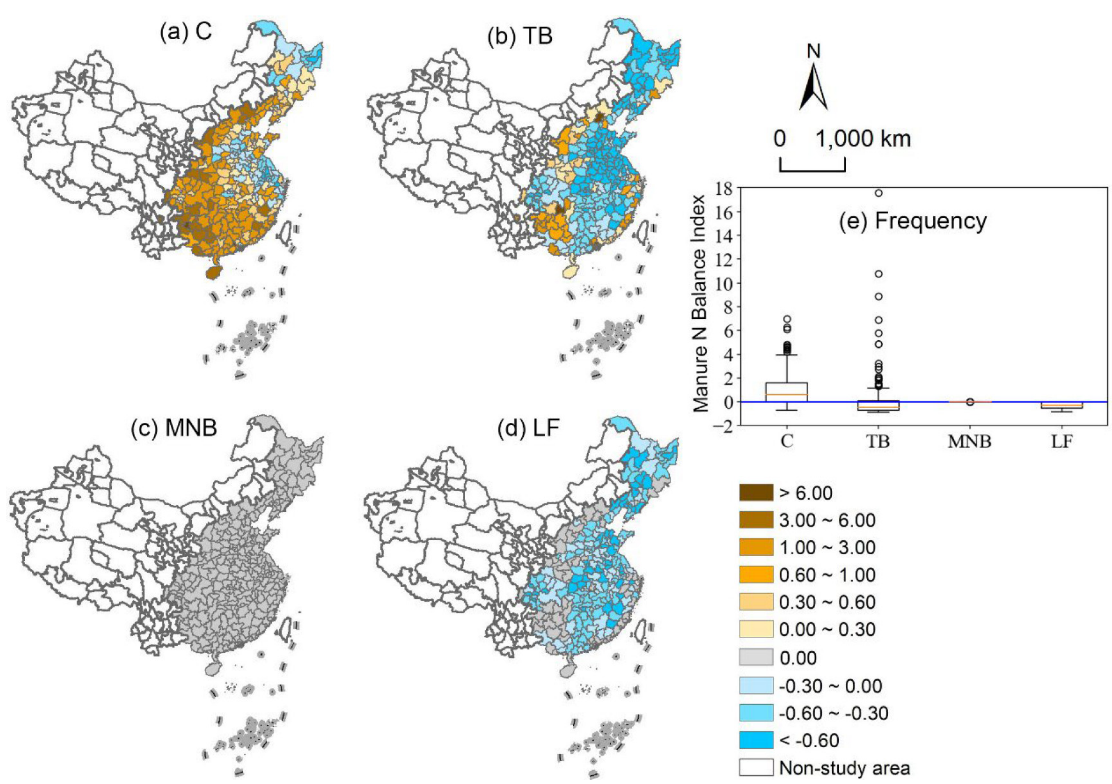

Fig. 5. Spatial distribution of the manure nitrogen (N) balance index ($MNBI_j$) in each region of eastern China in scenarios (a) C, (b) TB, (c) MNB, and (d) LF. For definitions of the scenarios, refer to Fig. 3. (e) Box plots of $MNBI_j$ in eastern regions of China. The blue line is the value of 0. There was one region (Shenzhen) where the $MNBI_j$ was greater than 20, so this outlier region was removed to improve the analysis of the $MNBI_j$.. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Statistics of the LISA of regions using the univariate analysis for the meat balance index in region j (TBI_j) and the manure nitrogen (N) balance index in region j ($MNBI_j$). For each LISA type, the number of regions is indicated, along with the percentage of the total study regions (in parentheses).

Index	Scenario	H-H	L-L	L-H	H-L
TBI_j	C	13 (5%)	29 (11%)	4 (2%)	2 (1%)
	TB	/	/	/	/
	MNB	42 (16%)	52 (20%)	6 (2%)	2 (1%)
	LF	30 (11%)	30 (11%)	13 (5%)	0 (0%)
$MNBI_j$	C	34 (13%)	68 (26%)	4 (2%)	0 (0%)
	TB	7 (3%)	59 (23%)	3 (1%)	0 (0%)
	MNB	/	/	/	/
	LF	30 (11%)	19 (7%)	4 (2%)	9 (3%)

3.2.2. Local spatial correlation effect using a univariate analysis

The LISA spatial agglomeration univariate analyses for the TBI_j and $MNBI_j$ are shown in Fig. 6. Among the types of regions identified, most belonged to the H-H and L-L clustering types, while L-H and H-L regions were fewer in all scenarios.

Concerning the TBI_j, for scenario C, the H-H regions were scattered and accounted for 5% of the total study area (Table 1), while the L-L regions, mainly distributed in the northwest and eastern coastal areas, accounted for 11%. For scenario MNB, the H-H regions were mainly distributed in northeastern and mid-eastern China and accounted for 16%, while the L-L regions were mainly distributed in the western and southeastern coastal areas and accounted for 20%. For scenario LF, the H-H regions were distributed in northeast and mid-eastern China, and the L-L regions were distributed in the western and southeastern coastal areas; the H-H regions and L-L regions both accounted for 11% of the study area. There were fewer types of L-H and H-L regions in all scenarios, which comprised no more than 5% of the regions in each scenario.

Concerning the $MNBI_j$, for scenario C, the H-H regions were mainly distributed in the southwestern area and accounted for 13% of the total study area, while the L-L regions were mainly distributed in northeastern and mid-eastern China and accounted for 26% of the study area. For scenario TB, the H-H regions were less and accounted for only 7% of the study regions, while the L-L regions were mainly distributed in northeastern and mid-eastern China and accounted for 23%. For scenario LF, the H-H regions were mainly distributed in the western and southwestern areas and accounted for 11% of the study regions, while the L-L regions were more dispersed and accounted for 7%. There were fewer types of L-H and H-L regions, which accounted for no more than 3% of the regions in each scenario. The regions that did not pass the significance test showed that TBI_j and $MNBI_j$ had little influence in these regions, and there was no significant spatial correlation.

3.2.3. Local spatial correlation effect with a bivariate analysis

To explore the spatial correlation between meat self-sufficiency and manure N surplus, we mapped the outcomes of the bivariate analysis of LISA between TBI_j and $MNBI_j$ (Fig. 7).

Concerning the TBI_j-$MNBI_j$ analysis, for scenario C, the H-H and L-H regions were mainly distributed in the southwest and accounted for 6% and 9% of regions (Table 2), respectively, while the L-L and H-L regions were mainly distributed in northeastern and mid-eastern China, accounting for 15% and 9% of regions, respectively. For scenario LF, the spatial distribution of each type of aggregated region was similar to scenario C. The L-H regions were mainly distributed in the western and southeastern coastal areas, while other types of aggregated regions were less and were scattered.

Concerning the $MNBI_j$-TBI_j, for scenario C, the aggregated regions that were significant were mainly distributed in the northeastern and southeastern coastal areas, of which the L-L regions accounted for the highest proportion of regions (10%). For scenario LF, the H-H and L-H regions were mainly distributed in northeastern and mid-eastern China, accounting for 5% and 11%, respectively, while the L-L and H-L regions were mainly distributed in the southwestern and southeastern coastal areas, accounting for 1% and 10% of regions, respectively.

4. Discussion

While a number of studies advocate for lowering livestock quantities in countries like China, few studies focused on *setting criteria* about how to lower livestock. The main novelties of our studies lie in the following: we considered the need of lowering livestock in Eastern China; we considered the trade-off between regional meat self-sufficiency and regional manure balance; we considered a range of scale of analysis for evaluating the outputs of the tested strategies, the whole eastern China, individual regions and clusters of regions.

Considering whole of eastern China, we found that in the current situation (scenario C), livestock are in excess and more meat is produced than is required based on healthy diet recommendations, leading to an overall manure N surplus (Fig. 3), which were similar to Li et al. (2021a, 2022). This means that there are excessive numbers of livestock in China from the perspectives of meat consumption and manure N surplus. An excess of livestock to supply meat can exacerbate unessential feed-food competition (Muscat et al., 2019) and, because China is far from achieving feed self-sufficiency, especially for soybean (Li et al., 2021a), this can lead to environmental problems in feed-exporting countries (Boerema et al., 2016; Sun et al., 2018). Adjusting livestock quantities to the meat-optimal livestock quantity in all eastern regions (scenario TB) allowed the avoidance of excess manure N in eastern China but lowered the MNBI (−0.48). As a result, this strategy requires more synthetic N, which would cause more unrenewable resource consumption (Li et al., 2021b) and environmental pollution (Jiao et al., 2018). Adjusting to the manure-N-optimal livestock quantity in all eastern regions (scenario MNB) avoided manure N surplus but caused a very high TBI (1.09), meaning that unnecessary meat production would occur. Concerning the strategy of adjusting the livestock quantity to the most limiting condition (scenario LF), meat self-sufficiency was achieved while the TBI and MNBI were close to 0, which seemed the best strategy for the whole of eastern China among the scenarios explored. However, for more conclusive insights, the spatial characteristics of the TBI and MNBI in different scenarios need to be analyzed.

4.1. Meat self-sufficiency and manure n surplus at the regional level

Meat self-sufficiency and manure N surplus at the local level are worthy of attention, particularly in large countries such as China. The regions showed disparities due to different factors, e.g., their different agricultural land availability, population density, economic development level, climatic characteristics.

In the current situation (scenario C), more than 90% of the eastern regions of China produce excess meat according to healthy diets (Fig. 4e), while more than 70% of regions experience manure N surplus (Fig. 5e). Lei and Shimokawa (2020) found that 70.1% of adults exceeded the proper level of meat consumption by sampling observation and Jia et al. (2018) found that 11 provinces that are mainly distributed in eastern China surpassed the national average value of manure N. These findings indicate that some regions, such as the central regions of China, can alleviate the effect of manure N surplus by reducing the quantity of meat-livestock. However, in the coastal and western regions, it is not possible to satisfy the meat demand when the manure N production is exactly equal to the manure N demand (scenario MNB) (Fig. 4c), and manure N surplus cannot be avoided when meat production is equal to the meat demand (scenario TB) (Fig. 5b). Coastal regions are usually more developed and populated, and the arable land per capita is low in China (Li et al., 2022). In western regions, the agricultural and pastoral transition area, the arable land area has been

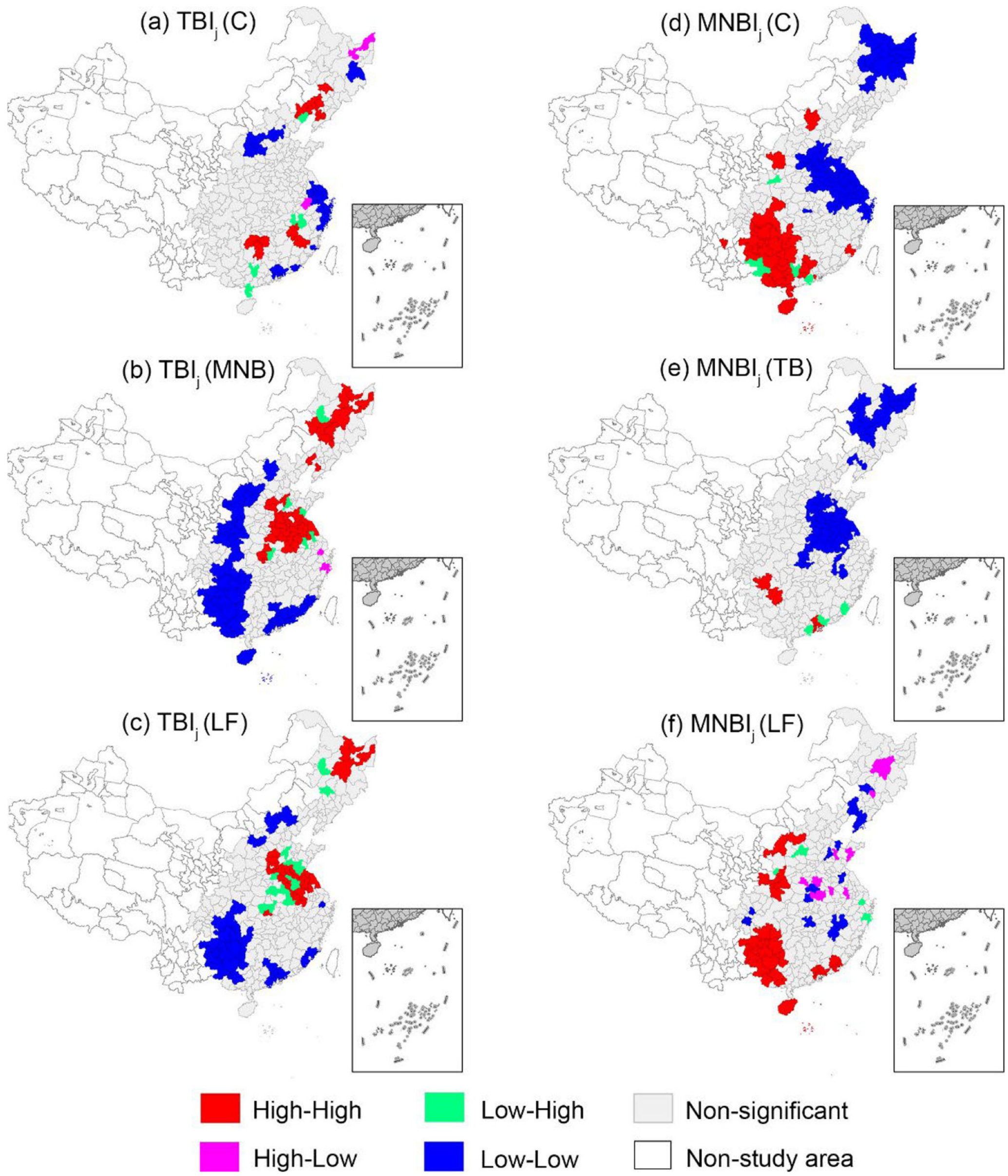

Fig. 6. The univariate analysis of the local indicator of spatial association (LISA) of the meat balance index in region j (TBI_j) and the manure nitrogen (N) balance index in region j ($MNBI_j$) in different scenarios. The symbol inside the parentheses are the scenarios. Refer to Fig. 3 for definitions of the scenarios.

Table 2
Statistics of the LISA of regions using the bivariate analysis between for the meat balance index in region j (TBI_j) and the manure nitrogen (N) balance index in region j ($MNBI_j$) (%). For each LISA type, the number of regions is indicated, along with the percentage of regions (in parentheses).

Index		Scenario	H-H	L-L	L-H	H-L
x-coordinate	y-coordinate					
TBI_j	$MNBI_j$	C	15 (6%)	40 (15%)	23 (9%)	28 (11%)
		TB	/	/	/	/
		MNB	/	/	/	/
		LF	1 (1%)	20 (6%)	29 (9%)	7 (3%)
$MNBI_j$	TBI_j	C	7 (3%)	26 (10%)	10 (4%)	5 (2%)
		TB	/	/	/	/
		MNB	/	/	/	/
		LF	14 (5%)	3 (1%)	29 (11%)	27 (10)

decreasing, such as in Zhangjiakou City (Liu et al., 2017), and the productivity of crops is extremely limited because of land desertification, soil erosion, and water scarcity, such as in Dingbian County (Wang and Li, 2019), which weakens the ability to achieve meat self-sufficiency while avoiding manure N surplus. Although scenario LF was good for eastern China, with meat self-sufficiency achieved and manure N surplus avoided, the western regions could not satisfy meat demand under this scenario. Therefore, coastal and western regions of China can reduce livestock quantity to avoid manure N surplus and satisfy meat demand by import.

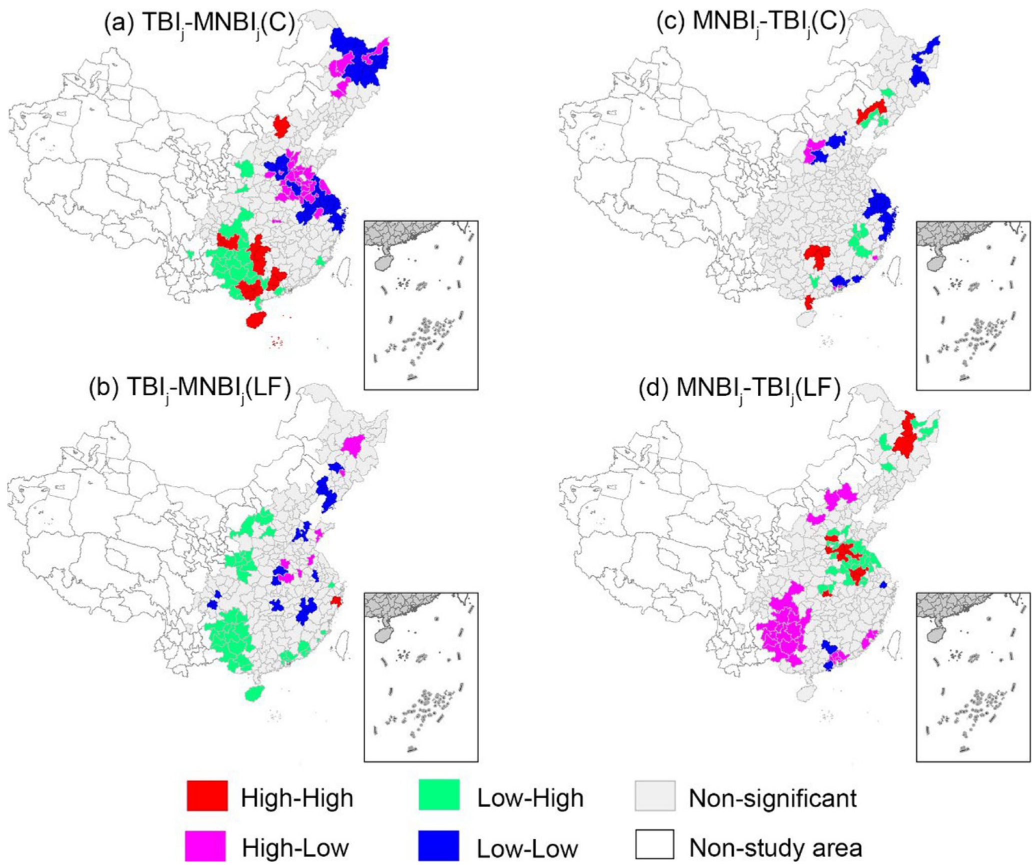

Fig. 7. The bivariate analysis of the local indicator of spatial association (LISA) between the meat balance index in region j (TBI_j) and the manure nitrogen (N) balance index in region j ($MNBI_j$) in different scenarios. TBI_j-$MNBI_j$: TBI_j was set as the first variable and $MNBI_j$ was set as the second variable; $MNBI_j$-TBI_j: $MNBI_j$ was set as the first variable and TBI_j was set as the second variable. The symbol inside the parentheses are the scenarios, the definitions of which can be found in Fig. 3.

4.2. Analysis at the level of region clusters

There are different implications for the clustering characteristics of the TBI_j and $MNBI_j$. Concerning the TBI_j, the H-H regions were the aggregated areas characterized by the overproduction of meat, the L-L regions were the aggregated areas more dependent on imported meat, and the H-L and L-H regions had the potential advantage of satisfying the meat demand of regions that produced inadequate meat by trading with surrounding regions. Concerning the $MNBI_j$, the H-H regions were the aggregated areas that may have a high environmental risk by manure N surplus and need to advocate more enterprises that convert fresh manure to dried commercial organic manure to alleviate this problem. The L-L regions were the aggregated areas that may need to import organic manure fertilizer; otherwise, these regions depend more chemical fertilizer, which is an unrenewable resource. The H-L and L-H regions have advantages in avoiding the manure N surplus of the regions that produce excess livestock manure and can transport surplus manure to the surrounding regions.

In the current situation (scenario C), the southeastern coastal regions that mainly contain the most developed cities are the aggregated areas where meat production is lower than the local demand (Fig. 4a and Fig. 6a), which is consistent with Li et al. (2021a). The southwestern regions are aggregated areas with manure N surplus (Fig. 5a and Fig. 6d), and thus have a high risk of environmental pollution due to manure N surplus. Combining Fig. 4a, Fig. 5a, and Fig. 7a, we infer that the mid-east regions are the aggregated non-meat-self-sufficient regions surrounded by regions which are deficient in manure N production for crop demand, indicating that these aggregated areas still have the potential to strengthen meat self-sufficiency and avoid manure N surplus by increasing the livestock quantity. In contrast, several southwestern regions are aggregated areas in which meat-deficient regions are surrounded by regions with manure N surplus, indicating a serious trade-off between meat self-sufficiency and manure N surplus avoidance.

Livestock manure is more expensive to transport across distant regions (Dagnall et al., 2000; Wilkins, 2008; Asai et al., 2014) when the manure N is in surplus, however, regions with manure N surplus adjacent to regions with deficient manure N could build connections. For example, in scenario TB, several regions in the southeastern coastal area that were characterized by a lower MNBI were surrounded by regions characterized by a higher MNBI (Fig. 5b and Fig. 6e), so manure N resources could be reallocated by short-distance transportation among these adjacent regions.

In scenario LF, all regions avoided manure N surplus, and only 27% of the regions distributed in the southwest and coastal areas were deficient in meat production (Figs. 4d and 5d). From the viewpoint of the connection between adjacent regions to alleviate the trade-off between meat self-sufficiency and manure N surplus avoidance, it is still difficult for southwestern aggregated areas (with deficient meat production) to satisfy meat demand by meat trade among adjacent regions, because they are surrounded by regions with a balance between meat production and demand (TBI = 0) (Fig. 4d, Fig. 5d, and Fig. 7b). Therefore, this small fraction of regions can satisfy the meat demand by long-distance transportation. In addition, increasing the proportion of organic manure application can alleviate manure N surplus (Zhang et al., 2019b). As a result, southwestern China could adopt comprehensive solutions that increase organic manure application and reduce livestock quantity to alleviate the trade-off between meat self-sufficiency and manure N surplus avoidance.

4.3. The priority of manure N surplus avoidance

To reduce greenhouse gas emissions and mitigate the prominent problem of environmental pollution and resource restriction, China has proposed a major strategic decision to reach a peak in carbon emissions by 2030 and achieve carbon neutrality by 2060 (Liu et al., 2021). Thus, at the regional level, manure N surplus avoidance is advocated, and a reduction of excess meat production at the regional scale is advocated to reduce greenhouse gas emissions. When all eastern regions of China achieved a balance between manure N supply and demand (scenario MNB), the total meat production was still greater than the meat demand in the whole study area, indicating the potential for some regions to further reduce the meat-livestock quantity. In scenario LF, meat production was further reduced compared with scenario MNB (Fig. 3), and more than 70% of regions could satisfy meat demand, including 50% of the regions that could achieve a balance of the manure N supply and demand, which could reduce meat transport; as a result, not only could the livestock quantity be reduced but meat self-sufficiency could be ensured in most regions. Regions that could not achieve meat self-sufficiency (less than 30% of the regions) in scenario LF could satisfy meat demand by importing meat products from regions that produce excess meat in China.

Overall, although several regions could not satisfy the meat demand, we consider scenario LF to be the most satisfactory because the manure N surplus was avoided in all regions and the livestock quantity was greatly reduced in eastern China, alleviating the risk of manure N surplus, and relieving the pressure of feed shortage in the eastern regions of China.

4.4. Limitations and perspectives of the study

This study analyzed whether meat self-sufficiency could be achieved by reducing the livestock quantity while avoiding a manure N surplus in the eastern regions of China. There are several limitations and perspectives in our study. First, single utilization of livestock manure was assumed in this study, however, manure demand calculation can be improved by considering a variety of ways to utilize manure resources (e.g., biogas) (Roubík et al., 2018) or to address manure resources (e.g. nitrifying-enriched activated sludge approach) (Sepehri and Sarrafzadeh, 2018, 2019). Second, ideal manure N demand for crops and ideal meat demand for humans were assumed. Crop growth and livestock dynamics were not considered in this model, and the results were obtained by data. This study did not consider meat waste, which affects the calculation of meat production. Doing an in-depth questionnaire survey can improve the data on meat consumption. Third, manure N surplus was measured by our model, while the effects of manure N surplus on environment (e.g., water and soil pollution, greenhouse gas emissions, etc.) were not considered.

Moreover, the strategies of scenario LF for adjusting livestock quantity may face several potential challenges. Concerning the crop-livestock integration, the links between crops and livestock were not close, and the livestock manure cannot be recycled to crop systems completely due to economic constraints and low efficiency compared to chemical fertilizer. A subsidy for utilizing livestock manure fertilizer and preaching the benefits of manure fertilizer application in the long term may promote the integration of crops and livestock. Concerning the regions that increasing livestock quantity (*M*–*T*– and *T*–*M*–), feed supply should be considered because the feed in some regions may be insufficient. Concerning the regions that reduce livestock quantity (*T*+*M*+, *M*+*T*–, and *M*+*T*+), the income of farmers may be affected and the policymakers could give a certain subsidy to farmers who reduce livestock quantity (Byrne et al., 2020; Ding et al., 2022). Concerning meat consumption for humans, a healthy diet should be advocated and food waste should be avoided through reasonable measures. In fact, a sustainable crop-livestock system concerns multiple targets, including food security, the income of farmers, and environmental benefits (Garnett, 2014), and it is important for future studies to coordinate the multi-targets for a crop-livestock system by optimizing the crop-livestock structure (Li et al., 2024).

5. Conclusion

We designed scenarios with a quantitative approach to reduce livestock quantities to balance meat self-sufficiency and manure N surplus avoidance in the eastern regions of China. The analysis framework in this study can also be applied to other intensive agricultural regions in other countries to adjust livestock quantities to alleviate the trade-off between manure N surplus avoidance and meat self-sufficiency in local regions.

We found that in eastern China, the current meat-livestock quantity exceeded the meat demand, leading to an unnecessary manure N surplus. Among the scenarios explored, scenario LF revealed the most promising strategy: adjusting the livestock quantity to the most constraining conditions between achieving meat self-sufficiency and avoiding a manure N surplus. We found that with this strategy, the TBI and MNBI were closer to 0 compared with other scenarios, making it a better strategy for eastern China as a whole.

Concerning spatial characteristics in scenario LF, the regions that could satisfy meat demand were more than 70% of the whole regions, including 50% of the regions that achieved a balance of manure N supply and demand, which were more favorable to meat self-sufficiency and manure N surplus avoidance. However, for a small fraction of the southwestern regions, it was impossible to satisfy the meat demand and avoid manure N surplus only by adjusting the livestock quantity, and trading among adjacent regions did not adapt to these regions because of the high values of MNBI in these cluster regions; therefore, further measures should be adopted, such as increasing the application of organic manure. Although this strategy needs to be refined and improved (especially in relation to elements not included in the model), our study paves the way for finding criteria for strategies to reduce livestock in China.

CRediT authorship contribution statement

Yang Li: Methodology design, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Zhigang Sun:** Conceptualization, Writing – review & editing, Supervision. **Xiangzheng Deng:** Validation, Writing – review & editing. **Francesco Accatino:** Methodology design, 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 material related to this article can be found online at https://doi.org/10.1016/j.resenv.2024.100156.

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