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Yixuan Shao and Qilin Cao contributed equally to this work.

Key Points:
- Pinpointing sources of various environmental impacts of livestock production in each region across various livestock species and activities
- Tracing transfers of health, ecosystem, and resource burdens embedded within interregional livestock products trade among provinces
- Revealing critical disparities between production and consumption regions in terms of their environmental burden profiles

Supporting Information:

Supporting Information may be found in the online version of this article.

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Human Health, Ecosystem Quality, and Resource Scarcity Burdens Inflicted by Livestock Production Across Chinese Regions

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Abstract Surge in global population and shift toward animal-based diets have accelerated expansion of livestock production, posing various environmental challenges. It requires inventorying localized, activity-specific, and indicator-extended multidimensional eco-environmental burdens and revealing their transfers within interregional trade to inform holistic livestock production management from both production and consumption sides. Herein, we construct a life cycle framework covering multiple livestock species, feeding regimes, and activities to evaluate nine environmental impacts ending up as human health, ecosystem quality and resource scarcity burdens in Chinese provincial regions. Multi-regional input-output analysis is then conducted to trace transfers of these burdens embedded within trade associated with livestock production. Results indicate that fine particulate matter formation (mainly by livestock housing) and climate change (mainly by enteric fermentation) contribute greater than 60% and 30% to health burdens. Besides for health burdens, for ecosystem burdens primarily caused by housing, and resource burdens mainly aggravated by high on-farm energy use, poultry results in the highest level. The main production regions Shandong, Henan and Sichuan lead from perspectives of both production and consumption-based burdens. Whereas regions with the largest export (Inner Mongolia, 3.87×10^4 DALY for health burdens) or import (Guangdong, 3.92×10^4 DALY for health burdens) do not necessarily bear greatest burdens. This work provides policy instructions in mitigating various eco-environmental burdens imposed by livestock production and promoting sustainable agricultural practices.

Plain Language Summary As the global population grows and diets shift toward more animal-based foods, livestock production has increased significantly, leading to various environmental challenges. This study evaluates the environmental impacts of livestock production, focusing on its effects on human health, ecosystem quality, and resource scarcity across different regions in China. By examining multiple livestock species and livestock production practices, the study identifies key environmental burdens, such as air pollution and climate change, which are closely linked to livestock activities. Additionally, the study traces how these environmental impacts are transferred between regions through interregional trade. For example, while some regions are major producers or consumers of livestock products, they do not necessarily face the greatest environmental burdens. This finding highlights the complexity of managing livestock production sustainably, as it requires coordinated efforts across regions. The insights provided by this research are crucial for developing strategies to reduce the negative environmental impacts of livestock production and promote more sustainable agricultural practices.

1. Introduction

Livestock production has rapidly expanded in recent decades in response to global population explosion and the change in diet from plant-based to animal-based foods (P. He et al., 2018; Thornton, 2010). However, livestock production is implicated in various environmental burdens (ammonia (NH_3) and greenhouse gas (GHG) emissions, eutrophication of surface waters, biodiversity loss, etc.) (Du et al., 2024; Zheng et al., 2024; Zhu et al., 2022). Around 18% global of anthropogenic GHG emissions, encompassing methane (CH_4) and nitrous oxide (N_2O) are contributed by livestock production (Steinfeld et al., 2006). CH_4 emissions from enteric fermentation in ruminants constitute the single largest source of GHG emissions from livestock production, and are also responsible for approximately 30% of total GHG emissions from the agriculture sector (Zhang, Xu, &

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Lahr, 2022). N_2O emissions are primarily derived from housing and storage of livestock manure, entailing urgent improvements in manure management practices (Y. Wang, Dong, et al., 2017). In addition, livestock production negatively affects water quality, as a significant fraction of the manure nitrogen (N) and phosphorus (P) ends up in watercourses, contributing seriously to eutrophication of rivers and lakes (Bai et al., 2018; Strokal et al., 2016; X. Wang et al., 2016; Wiedemann et al., 2015). Environmental deterioration alongside expansion of livestock production has also contributed to habitat destruction and loss of biodiversity, thereby posing a threat to ecosystem integrity (Eldridge et al., 2016). Sounder management in livestock production is crucial to alleviating the environmental burdens and guiding green and low-carbon development of the entire agriculture sector (Central People's Government of the People's Republic of China, 2020; C. Yang et al., 2020).

Life Cycle Assessment (LCA) studies have underscored that enteric fermentation and manure management are pivotal factors intensifying the environmental burdens (McAuliffe et al., 2016; Uwizeye et al., 2020), such as global warming, fossil energy use and eutrophication (Mishima et al., 2005). Many studies have created high-resolution maps or data sets of China's regional livestock production systems (Cheng et al., 2023; Zhu et al., 2022), showing spatial disparities in the effects of feeding regimes and manure management practices (Bai et al., 2013), and highlighting the importance of understanding livestock manure nutrient flows and losses (Bai et al., 2016, 2022; Huang et al., 2012; Liao et al., 2022; M. Wang et al., 2018). Further, a range of measures on both the production and consumption sides have been proposed to address the environmental impacts of livestock production. On the production side, key coping strategies include improving animal feeding efficiency, adopting more sustainable feed sources and eco-agricultural techniques, and managing waste generation (Herrero et al., 2016; M. Wang et al., 2023). On the consumption side, increasing consumer awareness and accessibility to environmentally friendly meat products, as well as facilitating shifts in dietary habits are alternative mitigation strategies (Bashir et al., 2022; Intergovernmental Panel On Climate Change, 2022). Above all, targeted environmental burden inventories, accounting for regional variations in livestock production practices are imperative to ensure accurate assessment of status and formulation of policies. Actually, the contemporary studies on the environmental impacts of livestock production have predominantly focused on direct environmental indicators such as GHG emissions (Grossi et al., 2019; Liu et al., 2023) and N and P losses (Y. Li et al., 2022), which have been instrumental in quantifying the immediate environmental costs. However, the subsequent resultant burdens on, for example, human health, ecosystem quality and resources scarcity dimensions have been overlooked (Pradhan et al., 2013; X. Wang et al., 2022).

Livestock production and the trade of livestock products within China present significant regional imbalances (Bai et al., 2022; Herrero et al., 2016; M. Wang et al., 2023; X. Zhao et al., 2020). For instance, Shandong's beef production is 58 times higher than that of Zhejiang, reflecting stark contrasts in production intensity across provinces. Some southwestern regions, like Sichuan and Yunnan, are experiencing disproportionately high environmental burdens due to more intensive livestock production (Zhang, Zhuo, et al., 2022). In contrast, the northeastern and northwestern regions, with lower production intensity and greater land availability, have a higher capacity to absorb the environmental impacts (H. Zhao et al., 2021). These regional imbalances not only exacerbate spatial polarization of the environmental burdens but also complicate efforts to manage these impacts effectively. Livestock products traded interregional carry with these environmental burdens originating from production, which are often not accounted for in the consuming region's environmental assessments (Grossi et al., 2019). To comprehensively evaluate these environmental burdens, the application of Multi-Regional Input-Output (MRIO) models is indispensable, which can facilitate tracing the environmental impacts embedded in trade, thereby revealing their distribution across regions and supply chains (Liang et al., 2023; S. Wang et al., 2024; M. Yang et al., 2023). Specific to livestock production-related studies, MRIO models have been instrumental in analyzing interregional transfers of environmental burdens. Examples include land degradation due to livestock over-grazing in Inner Mongolia, driven by demands for meat, leather and cashmere in other parts of China (Chen et al., 2022), the shift of forage-livestock conflict centers from non-pastoral to pastoral regions reflecting structural changes in supply chains (M. Yang et al., 2023), and the extensive pressure on ecosystems from global agricultural demand as illustrated by human appropriation of net primary productivity (Liang et al., 2023). These insights reveal the need for integrated approaches that consider both production and consumption impacts to mitigate environmental degradation effectively (Osei-Owusu et al., 2022; Sun et al., 2020), and provoke further understanding of interregional transfers of the human health, ecosystem quality and resource scarcity burdens associated with livestock production.

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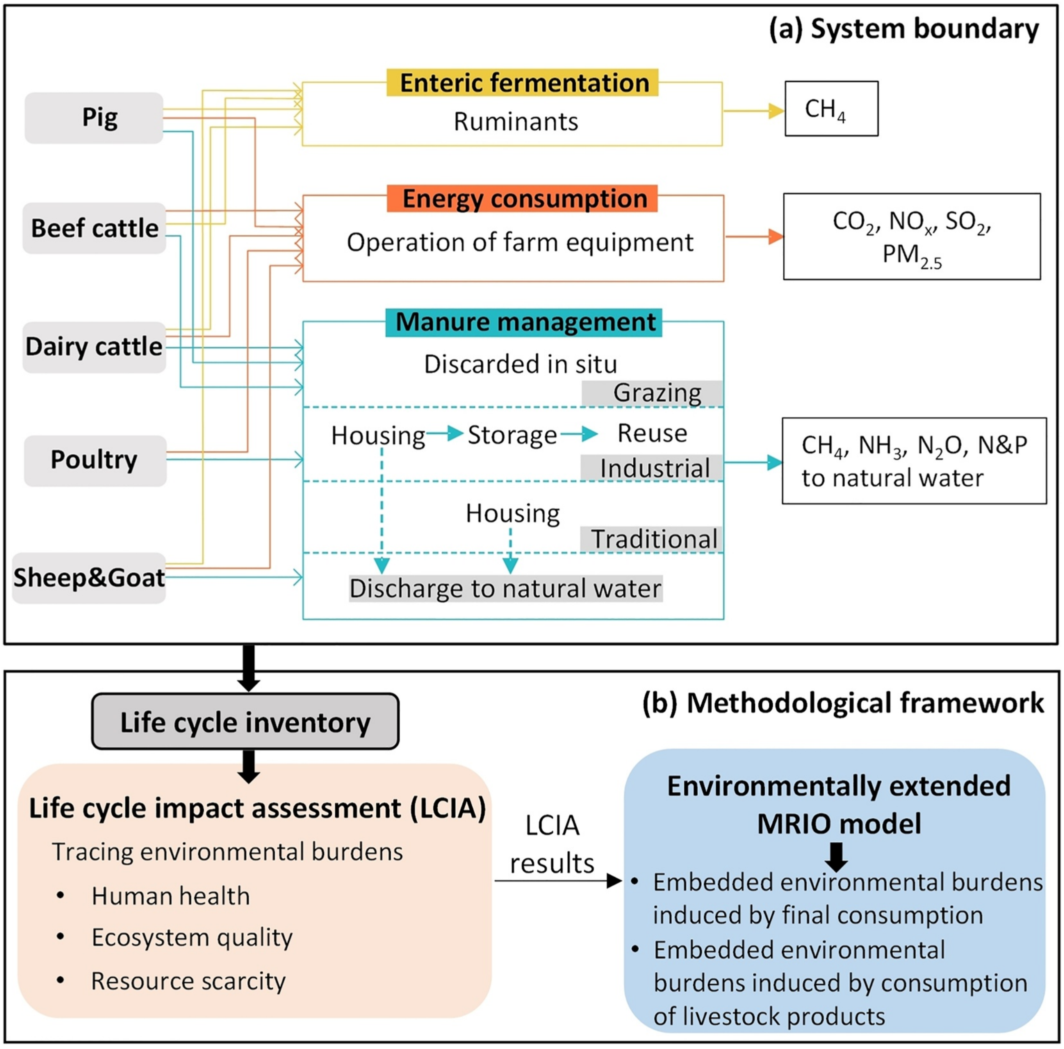

Figure 1. System boundary and methodological framework. *CC*, climate change; *OD*, ozone depletion; *FPMF*, fine particulate matter formation; *OFHH*, photochemical oxidant formation-human health; *OFTE*, photochemical oxidant formation-terrestrial ecosystems; *TA*, terrestrial acidification; *FE*, freshwater eutrophication; *ME*, marine eutrophication; *FRS*, fossil resource scarcity. These abbreviations apply to the following figures.

Existing studies underscore the necessity of establishing a comprehensive environmental burdens inventory to achieve optimized management of livestock production at the regional scale. Targeting Chinese provincial regions, this study emphasizes constructing an inventory characterized by a reduced geographical scale, localized focus, specificity to livestock activities, and the capacity to encompass a multitude of environmental indicators, which finally extend beyond traditional environmental concerns to encompass multidimensional burdens (Figure 1), including human health, ecosystem quality, and resource scarcity for a more holistic understanding of the comprehensive burdens imposed by livestock production. The constructed data sets serve to further explore these burdens embedded in the interregional trade from consumption-based perspective. The findings are expected to facilitates completely understanding the sources, attributions and transfers of multidimensional burdens imposed by livestock production across regions for informing sustainable agricultural practices and consumption patterns.

2. Materials and Methods

2.1. Description of Livestock Production Systems

Five livestock species and three typical production systems for China are distinguished. The five main species include pig, poultry, dairy cattle, beef cattle, and sheep & goat. They altogether generate over 90% of the animal manure in China (Huijbregts et al., 2017). For each species, we distinguish three different production systems according to the feeding regimes, manure management practices, and available statistical data, namely, grazing, traditional, and industrial livestock production systems (Figure 1a). Manure management varies across practices, resulting in different manure flows. Grazing is mainly found in Gansu, Xinjiang, Qinghai, Ningxia, Tibet, Heilongjiang and Inner Mongolia. Most of the manure is directly dropped onto grassland during the grazing period. Traditional livestock production is a semi-confinement practice, in which livestock is raised partially by feeding outdoors and partially by feeding forage in the housing. The manure is discarded in situ without collection when the livestock is outside the housing, while can be collected and utilized for fertilizer and biogas purposes when the livestock is confined in the housing. For industrial livestock production, livestock is confined within the housing, where all manure can be collected. Some of the manure can be used for fertilizer production through composting and for biogas power generation. The remainder is treated to remove most of the chemical oxygen demand, total N and total P through a series of specific technologies (solid-liquid separation, biological N and P removal, and so on) and finally discharged (Osei-Owusu et al., 2022) (See Table S2 in Supporting Information S1 for details).

2.2. Midpoint Environmental Impacts and Endpoint Burdens

According to the system boundary as shown in Figure 1a, the amounts of GHGs and pollutants generated in all processes can be quantified to establish the life cycle inventory. The emission or discharge (E) of GHG or pollutant i from livestock l in process p in region r is calculated by multiplying the activity data (D) by the corresponding emission or discharge factor (F) (Table S4 in Supporting Information S1):

$$E_{i,l,p,r} = D_{i,l,p,r} \times F_{i,l,p,r} \tag{1}$$

For example, when calculating CH_4 emissions from enteric fermentation, $E_{i,l,p,r}$ denotes the amount of CH_4 emissions from a livestock species in the process of enteric fermentation at region r. The life cycle inventory data sets are converted to a set of impact categories using characterization factors. To conduct a comprehensive LCA and cover all environmental impacts at both midpoint and endpoint levels, ReCipe2016 Midpoint and ReCipe2016 Endpoint are used (J. Li et al., 2020).

The ReCipe2016 method provides 18 impact categories at midpoint level, encompassing a broad range of indicators representing environmental interventions of common concern. We evaluate nine aspects of environmental impacts at the midpoint level in 31 provincial regions in China with 2020 as the target year:

$$M^{\mathrm{mid}}_{h,l,p,r} = \sum_{i} E_{i,l,p,r} \times C_{h,i} \tag{2}$$

where $H^{\mathrm{mid}}_{h,l,p,r}$ denotes environmental impact h of livestock l from process p at region r; $C_{h,i}$ represents the characterization factor for converting GHG or pollutant i into environmental impact h (Table S3 in Supporting Information S1).

Our study employs both midpoint and endpoint levels within the ReCipe2016 framework to offer a comprehensive assessment of environmental impacts. Using endpoint characterization factors, ReCipe2016 converts the midpoint results to the endpoint results to cover three “areas of protection,” including damages to human health, ecosystem quality, and resource scarcity. Damages to human health are measured based on disability-adjusted life years (DALY), representing the number of lost life years due to disability, illness, or early death. For ecosystem quality, the damages are described based on lost species in a certain period due to emissions/discharges to freshwater, terrestrial, and marine ecosystems. For resource scarcity, the damages are described by increased costs due to resource extraction and unavailability (J. Li et al., 2020). By incorporating both types of indicators, we are able to assess the entire cause-effect chain, from the specific environmental interventions to their ultimate impact on the environment. This dual approach not only aligns with the recommendations by Huijbregts et al. (2017), but also ensures that our results are policy-relevant by directly reflecting the overall damage in a manner that can inform environmental policy and decision-making. The use of both midpoint and endpoint characterizations thus enhances the robustness and applicability of our Life Cycle Impact Assessment (LCIA) results, allowing for a more nuanced understanding of the environmental burdens associated with livestock production across Chinese regions:

$$M^{\mathrm{end}}_{a,l,p,r} = \sum_h M^{\mathrm{mid}}_{h,l,p,r} \times N_{a,h} \tag{3}$$

where a denotes the area of protection, that is, human health, (terrestrial, freshwater and marine) ecosystems quality or resource scarcity; $N_{a,h}$ is the midpoint-to-endpoint conversion factor for the area of protection (Table S4 in Supporting Information S1). $M^{\mathrm{end}}_{a,l,p,r}$ is summable at livestock level, process level and region level. The damage pathways considered to accumulate from the midpoint to the endpoint level in ReCipe2016, sorted per environmental problem, are summarized in Table S5 in Supporting Information S1. These mid-to-endpoint factors are constant per impact category because environmental mechanisms are considered to be identical for each stressor after the midpoint impact location on the cause-effect pathways (J. Li et al., 2020).

2.3. MRIO Analysis of the Endpoint Burdens

Assuming an economy with m regions and n sectors, the MRIO framework entails fundamental linear equations as follow:

$$\begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_m \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & \cdots & A_{1m} \\ A_{21} & A_{22} & \cdots & A_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ A_{m1} & A_{m2} & \cdots & A_{mm} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_m \end{bmatrix} + \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1m} \\ Y_{21} & Y_{22} & \cdots & Y_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ Y_{m1} & Y_{m2} & \cdots & Y_{mm} \end{bmatrix} \tag{4}$$

where X_s is total output ($n \times 1$) of region s; A_{rs} is direct consumption coefficient matrix ($n \times n$) from various sectors of region r to region s; Y_{rs} is final demand ($n \times 1$) from various sectors of region r to region s. Equation 4 can be transform to the Leontief form as follows:

$$\begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_m \end{bmatrix} = \begin{bmatrix} L_{11} & L_{12} & \cdots & L_{1m} \\ L_{21} & L_{22} & \cdots & L_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ L_{m1} & L_{m2} & \cdots & L_{mm} \end{bmatrix} \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1m} \\ Y_{21} & Y_{22} & \cdots & Y_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ Y_{m1} & Y_{m2} & \cdots & Y_{mm} \end{bmatrix} \tag{5}$$

$$L_{rs} = (I - A_{rs})^{-1} \tag{6}$$

where, L ($n \times n$) is the Leontief inverse matrix and I ($n \times n$) is an identity matrix. Dividing the direct health (ecosystem or resource) burdens F ($1 \times n$) by total sectoral output gives the direct burden intensities f ($1 \times n$). The embodied burden intensities E ($n \times n$) are calculated according to Equation 7.

$$f_s = F_s./X_s \tag{7}$$

$$\begin{bmatrix} E_{11} & E_{12} & \cdots & E_{1m} \\ E_{21} & E_{22} & \cdots & E_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ E_{m1} & E_{m2} & \cdots & E_{mm} \end{bmatrix} = \begin{bmatrix} f_1 & 0 & \cdots & 0 \\ 0 & f_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & f_m \end{bmatrix} \begin{bmatrix} L_{11} & L_{12} & \cdots & L_{1m} \\ L_{21} & L_{22} & \cdots & L_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ L_{m1} & L_{m2} & \cdots & L_{mm} \end{bmatrix} \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1m} \\ Y_{21} & Y_{22} & \cdots & Y_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ Y_{m1} & Y_{m2} & \cdots & Y_{mm} \end{bmatrix} \tag{8}$$

where the diagonal f matrix presents direct burden intensities by sector and by region. E_{rs} is the burden export from region r to region s. The burdens are either retained locally, move between regions, or are exported abroad. The diagonal elements of E reflect intra-regional production and consumption linkages, while the remainder represents domestic interregional flows, and the sum of the column vectors of E is the total burden (Liang et al., 2023).

In this study, $n = 43$, $m = 31$. To construct a model specifically addressing the burdens imposed by livestock production, we disaggregate the livestock sector from the agricultural, forestry, animal husbandry, and fishery sector, which leads to the expansion of the original 42-sector IO table to cover 43 sectors. Following the method and proportions outlined by J. Li et al. (2020), which utilized household consumption data from the Statistical Yearbook of the Chinese Household Survey, we disaggregate the MRIO table's household consumption for livestock products into six distinct categories: pork, beef, mutton, poultry, eggs, and dairy products. This disaggregation provides a more nuanced understanding of the consumption patterns, allowing us to assess the environmental burdens associated with each specific livestock product. By incorporating the methodology proposed by Cao et al. (2023), we are able to quantify the embodied burdens associated with interregional trade induced by household consumption of various livestock products, as depicted in Equation 10.

$$H_{\text{livestock}} = H_{\text{pork}} + H_{\text{beef}} + H_{\text{mutton}} + H_{\text{poultry}} + H_{\text{eggs}} + H_{\text{dairy}} \tag{9}$$

$$\begin{bmatrix} EH_{11} & EH_{12} & \cdots & EH_{1m} \\ EH_{21} & EH_{22} & \cdots & EH_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ EH_{m1} & EH_{m2} & \cdots & EH_{mm} \end{bmatrix} = \begin{bmatrix} f_1 & 0 & \cdots & 0 \\ 0 & f_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & f_m \end{bmatrix} \begin{bmatrix} L_{11} & L_{12} & \cdots & L_{1m} \\ L_{21} & L_{22} & \cdots & L_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ L_{m1} & L_{m2} & \cdots & L_{mm} \end{bmatrix} \begin{bmatrix} H_{11} & H_{12} & \cdots & H_{1m} \\ H_{21} & H_{22} & \cdots & H_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ H_{m1} & H_{m2} & \cdots & H_{mm} \end{bmatrix} \tag{10}$$

where EH_{rs} is the burden induced by household consumption of various livestock products from region r to region s. $H_{\text{livestock}}$ is household consumption for total livestock production $(n \times 1)$; H_{pork}, H_{beef}, H_{mutton}, H_{poultry}, H_{eggs}, and H_{dairy} $(n \times 1)$ are household consumption for pork, beef, mutton, poultry, egg and dairy products, respectively. H_{rs} represents household consumption of livestock products from region r to region s $(n \times 6)$.

2.4. Data

The activity data correspond to the year 2020. The data we used can be divided into two main groups: The first group relates to socioeconomic data, which mainly includes the number of livestock, the coefficient of livestock production scale, the breeding cycles of livestock, and the energy costs associated with livestock production. The second group includes emission coefficients for GHGs and pollutants resulting from three main livestock production activities: enteric fermentation, manure management, and energy consumption. We have explicitly delineated the data sets utilized in our study and their respective sources within the SI (Text S2 and Table S6 in Supporting Information S1).

To analyze the uncertainty in the MRIO model due to the absence of a 2020 MRIO table, we base our analysis on the 2017 MRIO table, treating it as the reference. Specifically, we introduce uncertainty by applying a relative uncertainty of sigma = 0.05 to the inter-sectoral transaction matrix, Z, reflecting potential variations between 2017 and 2020. The Monte Carlo simulation is conducted with 1,000 iterations, each time randomly perturbing matrix Z to capture the variability in the model's outputs. Other relevant economic matrix are updated with 2020 values, adjusted to 2017 comparable prices. The results are analyzed for the human, ecosystem, and resource burdens, with the robustness of these estimates evaluated using R^2 values from the simulations.

3. Results

3.1. Midpoint Environmental Impacts and Endpoint Health, Ecosystem, and Resource Burdens at National Scale

We evaluate nine aspects of environmental impacts at the midpoint level (see Figure 1 for detailed categories) combining the LCA procedures and the ReCipe2016 method. Details for quantifying the characterized and

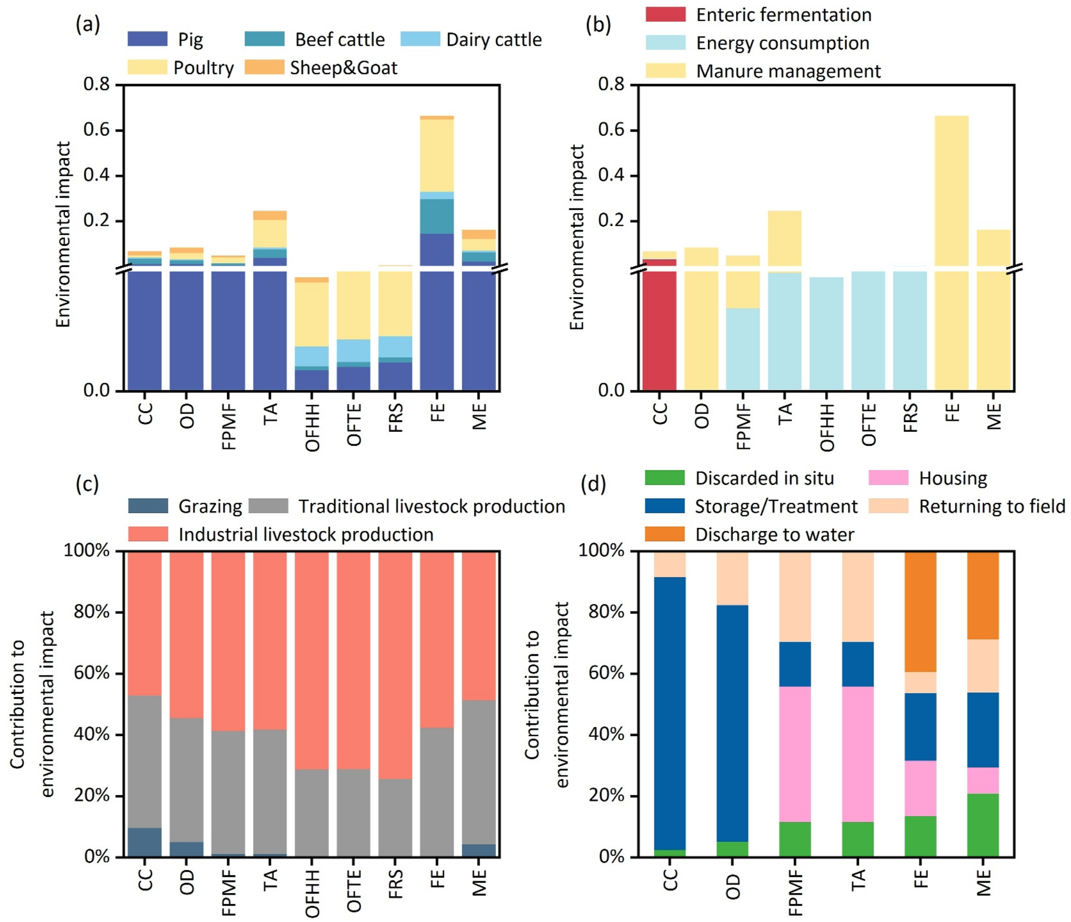

Figure 2. Midpoint environmental impact potentials of livestock production at national scale (based on ReCipe2016 method). (a) Impact potentials of various livestock species. (b) Impact potentials of major livestock activities. (c) Contributions of livestock production practices. (d) Contributions of different manure management stages to total impact potentials caused by manure management. *CC*, climate change; *OD*, ozone depletion; *FPMF*, fine particulate matter formation; *OFHH*, photochemical oxidant formation-human health; *OFTE*, photochemical oxidant formation-terrestrial ecosystems; *TA*, terrestrial acidification; *FE*, freshwater eutrophication; *ME*, marine eutrophication; *FRS*, fossil resource scarcity.

normalized impact potentials are delineated in Method section. Within the boundary of the livestock production system (Figure 1), the normalized impact potentials vary from 0.003 to 0.665 at the national scale, with poultry being a major contributor (Figure 2a). Freshwater eutrophication is the most prominent environmental impact among all categories, whose potential is nearly 3 times that of the following terrestrial acidification and marine eutrophication. Climate change is mainly intensified by manure management and enteric fermentation of livestock, which account for 62% and 35% (27% by monogastric and 73% by ruminant), respectively (Figure 2b). Observed from three production systems, the environmental impacts of grazing are much less than traditional and industrial livestock production owing to its smaller scale (Figure 2c). Energy consumption of livestock farm operation, mainly industrial livestock farms, is the sole source of photochemical oxidant formation-human health, photochemical oxidant formation-terrestrial ecosystems and fossil resource scarcity. The rest environmental impacts are all aggravated by loss of N and P in different forms into the atmosphere and water by manure management. Furthermore, the environmental impacts of manure management are refined to its constituent stages (Figure 2d). Storage/treatment is the primary source of N_2O emissions, accounting for up to 70% of total N_2O emissions from manure management, and substantially intensifying climate change and ozone depletion. Fine particulate matter formation and terrestrial acidification are intensified by NH_3 emissions from housing and manure reuse for fertilizer in situ. All manure management stages intensify freshwater eutrophication and marine eutrophication.

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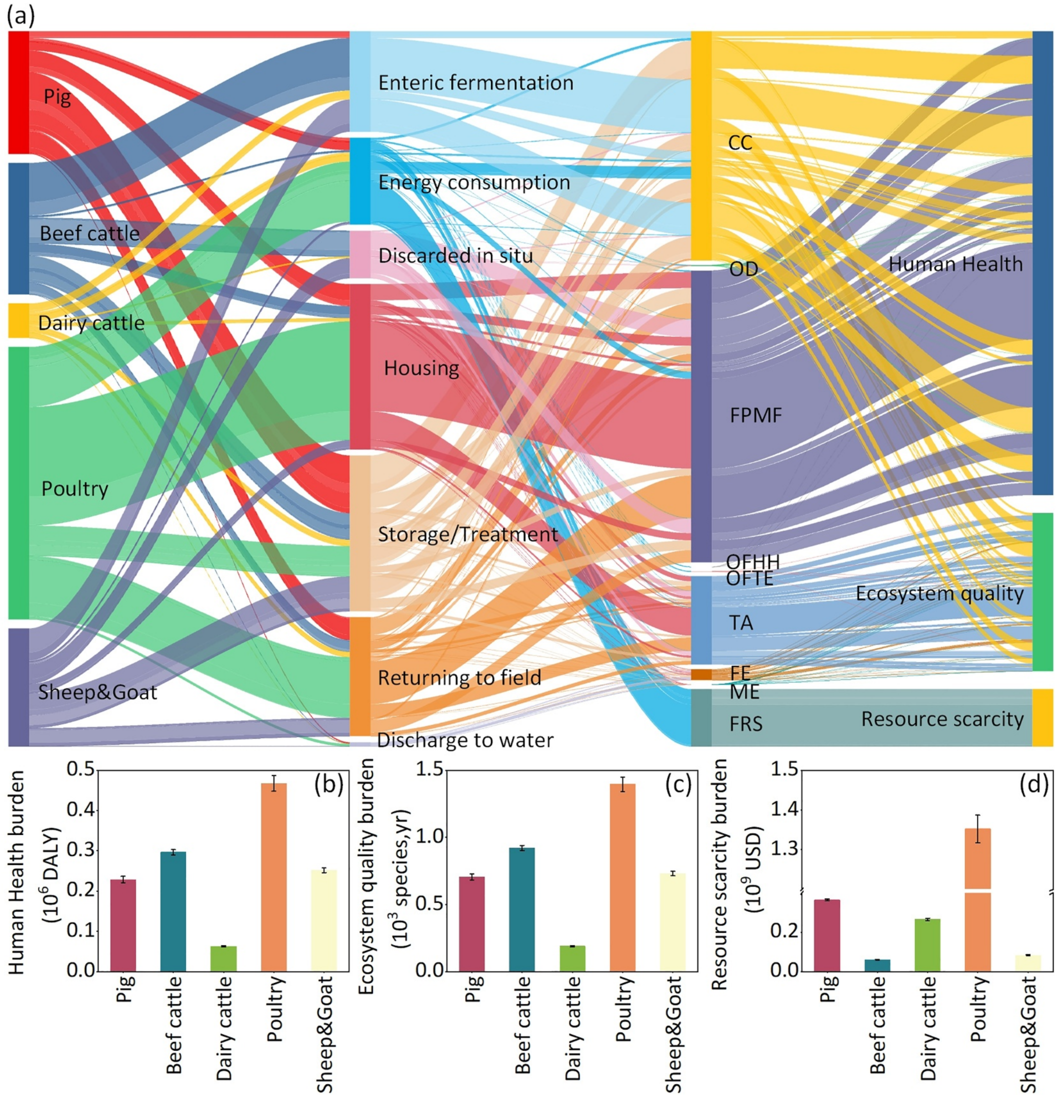

Figure 3. Health, ecosystem, and resource burdens from livestock production in China. (a) Links between livestock species, livestock activities, midpoint impact categories, and health, ecosystem and resource burdens. A larger width of the flow indicates a larger contribution proportion. (b) Human health burdens (Unit: DALY = disability-adjusted life years); (c) Ecosystem quality burdens (Unit: species. yr); (d) Resource scarcity burdens (Unit: United States Dollar (USD) 2013). *CC*, climate change; *OD*, ozone depletion; *FPMF*, fine particulate matter formation; *OFHH*, photochemical oxidant formation-human health; *OFTE*, photochemical oxidant formation-terrestrial ecosystems; *TA*, terrestrial acidification; *FE*, freshwater eutrophication; *ME*, marine eutrophication; *FRS*, fossil resource scarcity.

How the health, ecosystem and resource burdens arise from all activities related to livestock production for different livestock species is illustrated in Figure 3. The health, ecosystem and resource burdens are summarized from the midpoint impact potentials. Among livestock activities, manure management contributes larger than 50% toward human health burdens, which is linked to four midpoint categories (Figure 3a), with the contributions of fine particulate matter formation and climate change greater than 60% and 30%, respectively. Enteric fermentation, housing and energy consumption are the main causes. Housing contributes up to 45% of the formation of fine particulate matter ($PM_{2.5}$) from manure management, which is estimated to cause 1.29×10^4 DALY of human health burdens in China. Regarding ecosystem quality, terrestrial acidification contributes over 50%, and climate change over 30%, with all activities contributing at similar levels. As for livestock species, human health burden is mainly caused by poultry (4.7×10^5 DALY, 35.8%), followed by beef cattle (3.0×10^5 DALY, 22.7%) and sheep & goat (19.3%) (Figure 3b). For ecosystem quality burdens primarily caused by housing, the most significant burden is caused by poultry (1.4×10^3 DALY, 35.4%) (Figure 3c). Regarding resource scarcity burdens mainly aggravated by high on-farm energy use, poultry also results in the highest level of burden (1.4×10^9 USD, 70.0%) (Figure 3d).

3.2. Health, Ecosystem, and Resource Burdens at Regional Scale

Observed region-specifically, human health burden triggered by livestock production is relatively high in the main production areas like Shandong, Henan and Sichuan, which contribute 17.8% of China's livestock production and 22.4% of the human health burdens (Figure 4). Shandong suffers from the highest environmental burdens on human health and ecosystem quality. This is because it has the highest poultry production in China (2.1 billion head), accounting for about 15.0% of the national total. Henan and Shandong have similar farming scales, with 10.4% of the national poultry production and 12.5% of the national sheep production. Sichuan is dominated by industrial production of pigs and sheep, accounting for 10.7% and 10.1% of the national total, respectively. Comparatively, human health burden in Shanghai, Beijing and Tianjin is much more insignificant. As both burdens primarily result from enteric fermentation and manure management processes, like human health burden, ecosystem quality burden is also mainly concentrated in Shandong, Henan and Sichuan, accounting for 17.8% of the national total. For resource scarcity, Shandong, Henan and Guangdong are facing larger burdens, accounting for 13.8% of the national total (Figure 4).

At the regional scale, the burden intensities (burden per number of livestock) of livestock production show spatial disparities (Figure 5). Regions with larger grazing areas for ruminant production (Inner Mongolia, most northwestern regions) have greater burden intensities for human health and ecosystem quality (Figures 5a and 5b). The burden intensities for resource scarcity in the eastern and southern regions greatly exceed the national level, owing to the high proportion of intensive industrial livestock production (Figure 5c). At national scale, the burden intensities vary greatly across livestock species and production systems. Industrial production system has the highest burden intensities (about 4.6×10^{-4} DALY/head, 1.4×10^{-6} species, yr/head and 0.5 USD/head), followed by those for traditional system (4.0×10^{-4} DALY/head, 1.2×10^{-6} species, yr/head and 0.5 USD/head) (Figures 5d–5f). The burden intensities of beef cattle and dairy cattle are higher, as ruminants produce larger amounts of emissions from enteric fermentation and the manure management emissions are also larger than from other animal species.

3.3. Health, Ecosystem, and Resource Burdens Embedded Within Interregional Trade

As our results reveal consistency within three types of burdens, we only display the results for human health in the main text and provide the rest results in Text S3 in Supporting Information S1. Shandong (1.00×10^5 DALY, Table S19 in Supporting Information S1), Sichuan (8.58×10^4 DALY), and Henan (7.13×10^4 DALY) rank top three in terms of consumption-based human health burdens (Figure 6a). Shandong and Sichuan are importers (trade balance coefficient (TBC) < 1, TBC = export/import) with high local consumption ratio (LCR), both above 80% (Table S19 in Supporting Information S1). By introducing TBC, we can better understand the role of regional trade in shifting environmental burdens, highlighting areas that offload or absorb these burdens. This metric is crucial for identifying disparities in regional responsibilities and informing targeted policy interventions. In contrast, Henan is an exporter (TBC > 1) with a much lower LCR (67%, Table S19 in Supporting Information S1), which implies that Henan may bear greater human health burden from trade. These regions, well-known for their large populations, are identified as the top regions in terms of both production-based and consumption-based human health burdens consistently. Similar patterns can be found for the production-based and consumption-based ecosystem quality burdens (Figure S1 in Supporting Information S1). However, for resource scarcity burdens (Figure S2 in Supporting Information S1), Guangdong, as an importer with a TBC of 0.55 (Table S19 in Supporting Information S1), advances to the second position, diverging from the dominance of Shandong, Sichuan and Henan in other burdens.

The patterns of export and import across regions do not align with the production-based and consumption-based burdens. For human health burdens (Figure 6c and Table S19 in Supporting Information S1), the top three exporters are Inner Mongolia (3.87×10^4 DALY, TBC = 4.06), Henan (3.54×10^4 DALY, TBC = 1.52) and Yunnan (3.09×10^4 DALY, TBC = 2.96), while the top three importers are Guangdong (3.92×10^4 DALY, TBC = 0.33), Zhejiang (3.66×10^4 DALY, TBC = 0.11) and Jiangsu (2.67×10^4 DALY, TBC = 0.35), with ecosystem quality burdens showing identical patterns (Figure S1c in Supporting Information S1). For resource scarcity burdens (Figure S2c in Supporting Information S1), the top three importers remain consistent with other

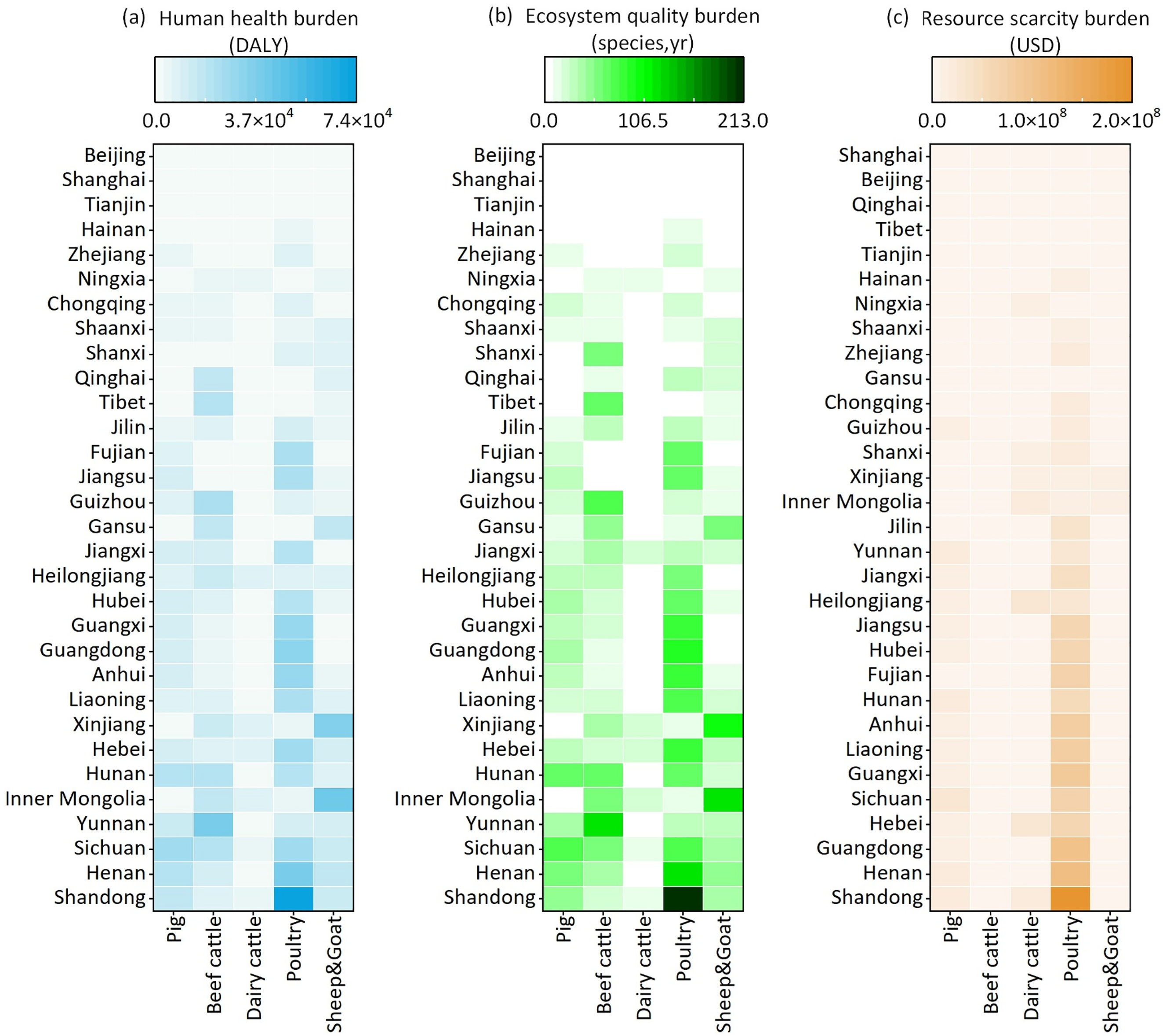

Figure 4. Contributions of different livestock species to health, ecosystem and resource burdens at regional scale, from the provincial regions with the highest burden at below (e.g., Shandong) to those with the lowest burden at the above (e.g., human health and ecosystem quality for Beijing and resource scarcity for Shanghai). (a) Human health burden. (b) Ecosystem quality burden. (c) Resource scarcity burden.

burdens, but the leading exporters diverge significantly, as Henan, Hebei and Heilongjiang. We assess the local use-related burdens (self-production and self-consumption) for each region and find that those with larger values are Shandong, Sichuan, Henan, and other densely populated regions, which aligns well with the patterns revealed by production-based and consumption-based burdens. For human health burdens, Shandong and Sichuan, the top two regions in local use, have a LCR of over 80%, whereas Hunan, the third-ranked one, has a much lower LCR of 67% (see Table S19 in Supporting Information S1). As shown in Figures 6c, Figures S3c and S4c in Supporting Information S1, we use the TBC to measure the export-import imbalance of three burdens, which indicates trade surplus when TBC > 1 and trade deficit when TBC < 1. We find that regions with higher trade surplus intensity are Qinghai (5.89, health and ecosystem burdens), Inner Mongolia (4.06, health and ecosystem burdens) and Xinjiang (3.41, health and ecosystem burdens), while those with higher trade deficit intensity are Beijing (0.02, all burdens), Shanghai (0.04, all burdens), and Shanxi (0.06, all burdens). The notable difference for resource scarcity burdens is that regions with higher trade surplus intensity are Guangxi, Jilin and Hebei.

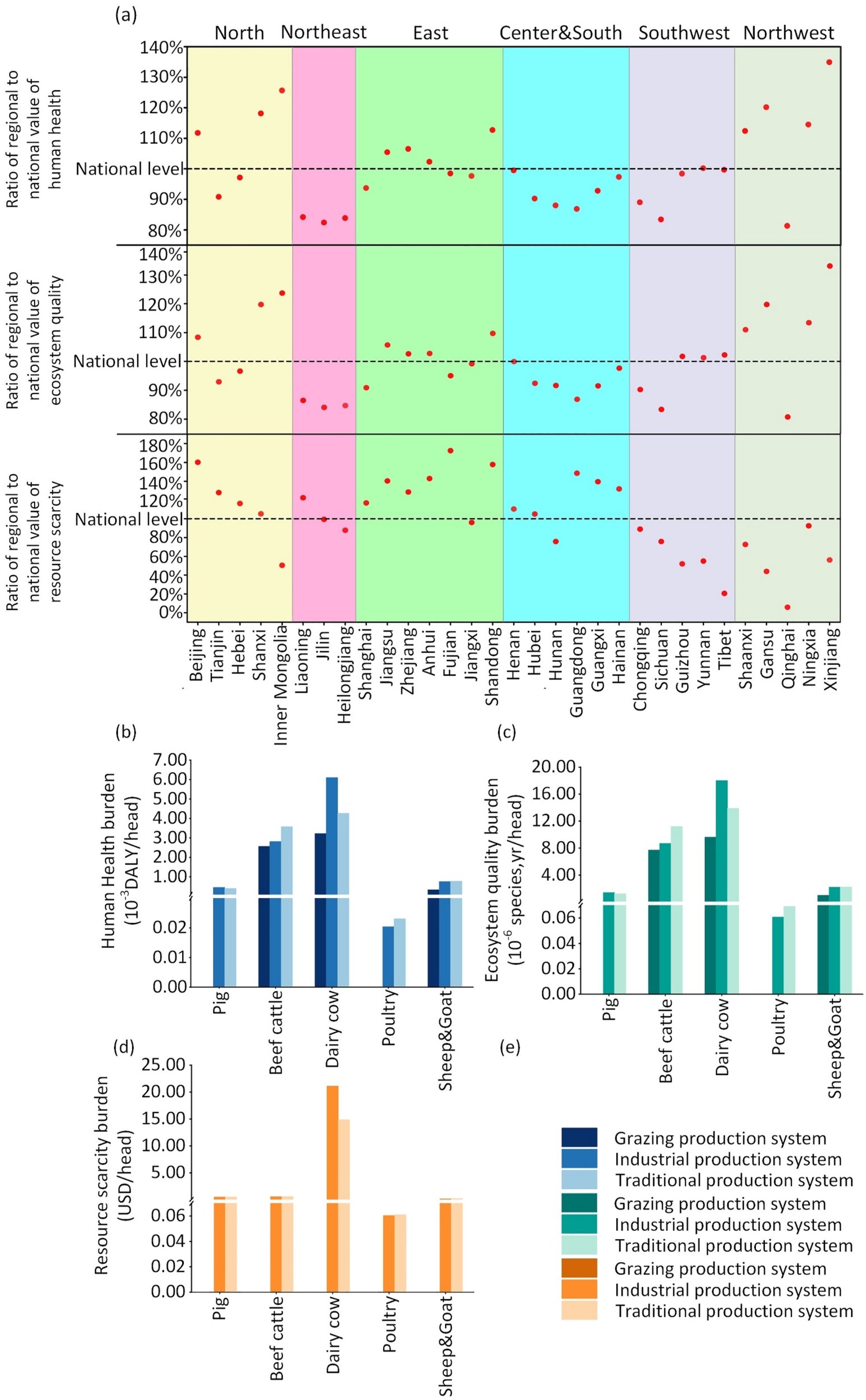
(a)
North
Northeast
East
Center&South
Southwest
Northwest
Ratio of regional to national value of human health
Ratio of regional to national value of ecosystem quality
Ratio of regional to national value of resource scarcity
National level
Beijing
Tianjin
Hebei
Shanxi
Inner Mongolia
Liaoning
Jilin
Heilongjiang
Shanghai
Jiangsu
Zhejiang
Anhui
Fujian
Jiangxi
Shandong
Henan
Hubei
Hunan
Guangdong
Guangxi
Hainan
Chongqing
Sichuan
Guizhou
Yunnan
Tibet
Shaanxi
Gansu
Qinghai
Ningxia
Xinjiang
(b)
Human Health burden (10^{-3}DALY/head)
(c)
Ecosystem quality burden (10^{-6} species,yr/head)
(d)
Resource scarcity burden (USD/head)
(e)
Pig
Beef cattle
Dairy cow
Poultry
Sheep&Goat
Grazing production system
Industrial production system
Traditional production system

Figure 5.

We investigate the top 10 interregional flow paths for three burdens (see Figures 6a, Figures S1a and S2a in Supporting Information S1). The paths for human health and ecosystem quality burdens are consistent, featuring flows Inner Mongolia → Shanxi, → Hebei, and → Tianjin; Heilongjiang → Jilin; Gansu → Shaanxi; Shaanxi → to Henan; Yunnan → Guizhou; Guizhou → Guangdong; and Guangxi → Guangdong. These paths reveal clear patterns: (a) the burdens generally flow from north to south and from west to east across China; (b) Specifically, in the Northeast, the flow is primarily from Heilongjiang to Jilin; in the North, from Inner Mongolia to Shanxi and the Beijing-Tianjin-Hebei area; in the Northwest, from the Shaanxi-Gansu area to Henan; and in the Southwest, ultimately to Guangdong. For resource scarcity burdens, the paths slightly differ from the other two. However, four common paths exist across all burdens: Inner Mongolia → Shanxi, Heilongjiang → Jilin, Shaanxi → Henan, and Guangxi → Guangdong.

By disaggregating the household consumption for livestock production sector into six product categories: pork, beef, mutton, poultry, egg, and dairy, as shown in Figure 7 and Figure S4 in Supporting Information S1, the results show stronger coherence than the final consumption-induced burdens, especially for importers and TBC. For all burdens and six product categories, Yunnan, Hebei, Qinghai, and Xinjiang are among the top exporters. Interestingly, although Hebei and Yunnan are the top two exporters in most cases, Hebei's trade surplus intensity is always lower than Yunnan's when we focus on the TBC (taking pork for human health burdens as an example: Hebei 20.10, Yunnan 58.42, Table S20 in Supporting Information S1). Beijing, Tianjin, and Guangdong are the top importers. However, when focusing on the trade deficit intensity, Beijing and Tianjin maintain the top level, whereas Guangdong does not. Notably, Shanxi, despite its moderate import, consistently records extremely top trade deficit intensity (frequently at top 1, trade deficit intensity ≤ 0.01 for all burdens and products, Table S20 in Supporting Information S1). These results indicate that the largest exporters and importers are not necessarily the most severe in terms of trade surplus intensity or trade deficit intensity. For local shares, like the patterns for final consumption-induced burdens, populous regions such as Sichuan and Shandong usually have larger local shares. However, there are some exceptions, such as Qinghai, Tibet and Xinjiang with the largest local shares for beef and sheep products induced burdens.

3.4. Uncertainty and Sensitivity Analysis

The uncertainties in the results of three burdens originate from the estimation process, which involves numerous parameters. The Monte Carlo method is a numerical computing method that involves statistical simulation and random sampling to address uncertainty problems and is widely used in uncertainty analysis of emission inventories. Monte Carlo analysis usually entails repeating the calculation a statistically significant number of times ranging from 100 to 10,000. Owing to a scarcity of information about the statistical distribution of the parameters, triangular distribution is assumed in the Monte Carlo simulation for the selection of individual values (we set an uncertainty range of 10%–30% based on different data quality). We perform the analysis 1,000 times, randomly selecting any feasible value within the assumed uncertainty limits for various variables. The uncertainty results are presented in Figures 3b–3d, in terms of livestock species, with the results for poultry having the highest uncertainty, within −14%–12% in human health burden, and beef cattle having the lowest uncertainty, within −7%–8% in human health burden, and all species in three burdens varying within −14%–12%, we provide the detailed results in Text S4 in Supporting Information S1. Besides, we make sensitivity analyses as a complement to the sensitivity to key parameters, using the "one-variable-at-a-time" method. The sensitivity of midpoint environmental impacts to changes in the key parameters is presented in Table S22 in Supporting Information S1. A 1% change in most parameters induces a less than 0.8% change in the midpoint environmental impacts. For several impact categories, changes in the mitigation or intensification effects could exceed 1% when certain parameters change by 1%. Furthermore, to deal with the deviations of the current situation of livestock production and its environmental burdens with the temporary economic structure due to relying on the China MRIO Table 2017, the Monte Carlo simulation for the MRIO analysis is conducted. It reveals that the R^2 values across all simulations consistently remain above 0.993 (as depicted in Figure S5 in Supporting Information S1), and

Figure 5. Intensities of health, ecosystem and resource burdens from livestock production. The intensities are measured by per number of livestock. All livestock numbers are converted to pig unit: 1 beef cattle = 5 pigs; 1 dairy cow = 10 pigs; 30 layers = 1 pig; 60 broilers = 1 pig; 3 sheep or goat = 1 pig. The dots indicate the ratio of regional value to national value. The black dashed line indicates a ratio of 100%. (a) Intensities of health, ecosystem and resource burdens. (b) Human health burden intensities by livestock species at national scale. (c) Ecosystem quality burden intensities by livestock species at national scale. (d) Resource scarcity burden intensities by livestock species at national scale. (e) Legend for figures (b–d).

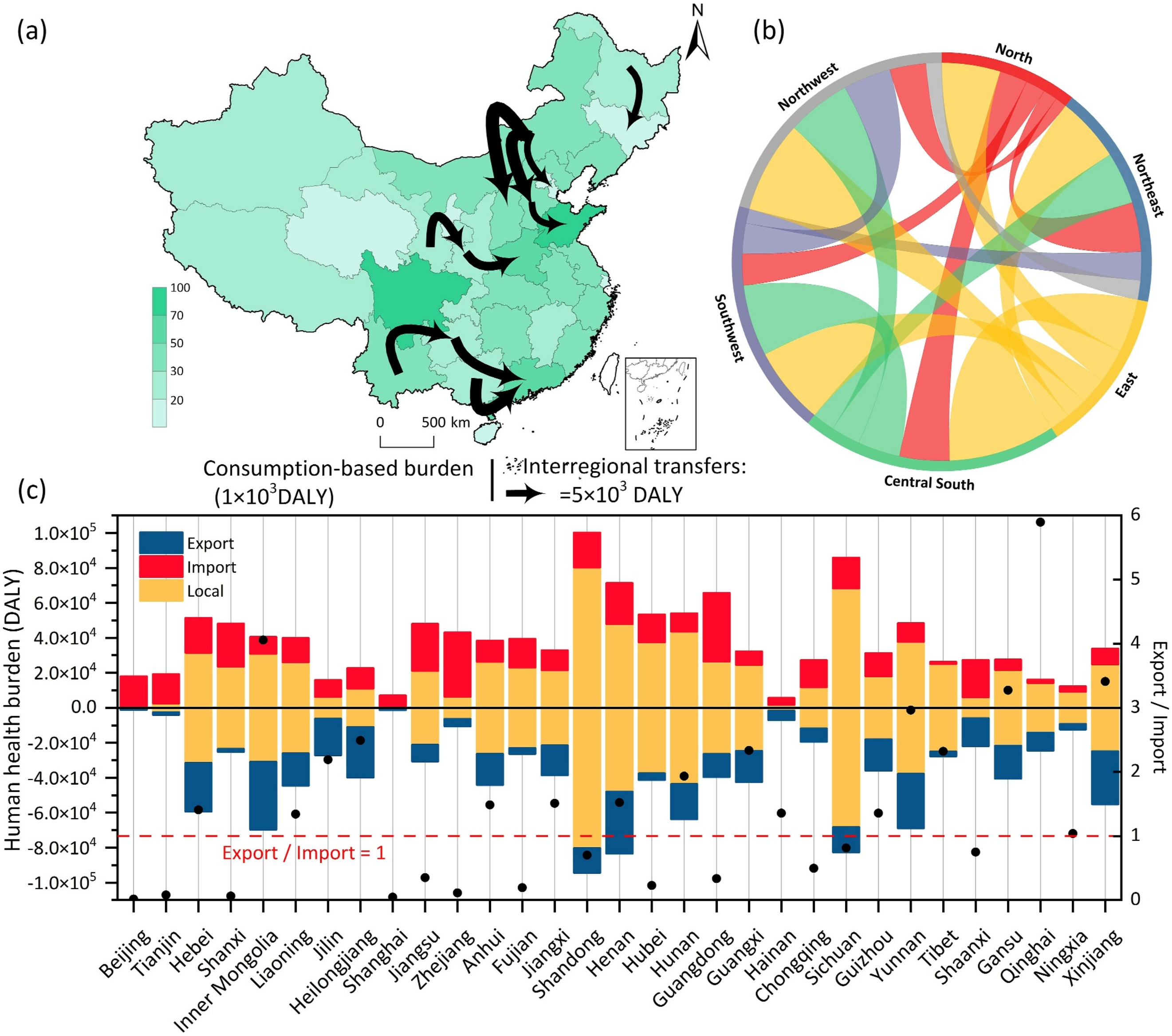

Figure 6. Human health burdens from livestock production induced by final consumption. (a) Top 10 transfer paths for embedded human health burdens. The direction of the arrow is from exporters to importers. (b) Transfers of embedded human health burdens among areas, with the path color determined by the area whose import is greater than export. (c), Exports/imports of embedded human health burdens in all provincial regions.

resource scarcity burdens exhibit the greatest variability. Nevertheless, applying recent-year trade structures in livestock MRIO analysis can still provide reliable results. Admittedly, updating trade data in a timelier manner would allow our model to produce even more precise estimates.

4. Discussion and Conclusion

The burdens triggered by livestock production to human health, ecosystem quality and resource scarcity has led to increasing concern and advocacy for sustainable and green livestock production (Y. Wang, Dong, et al., 2017). Here, we quantify the health, ecosystem and resource burdens imposed by livestock production in China at a finer geographic scale by inventorying GHGs or pollutants emitted/discharged by various livestock activities and incorporating endpoint indicators into the assessment at a higher level of aggregation. The results reveal consistency in a certain stage in the livestock production system and a certain impact category with previous studies (Bai et al., 2018; D. He et al., 2023; Osei-Owusu et al., 2022; Sun et al., 2020; Zhu et al., 2022), which facilitate to

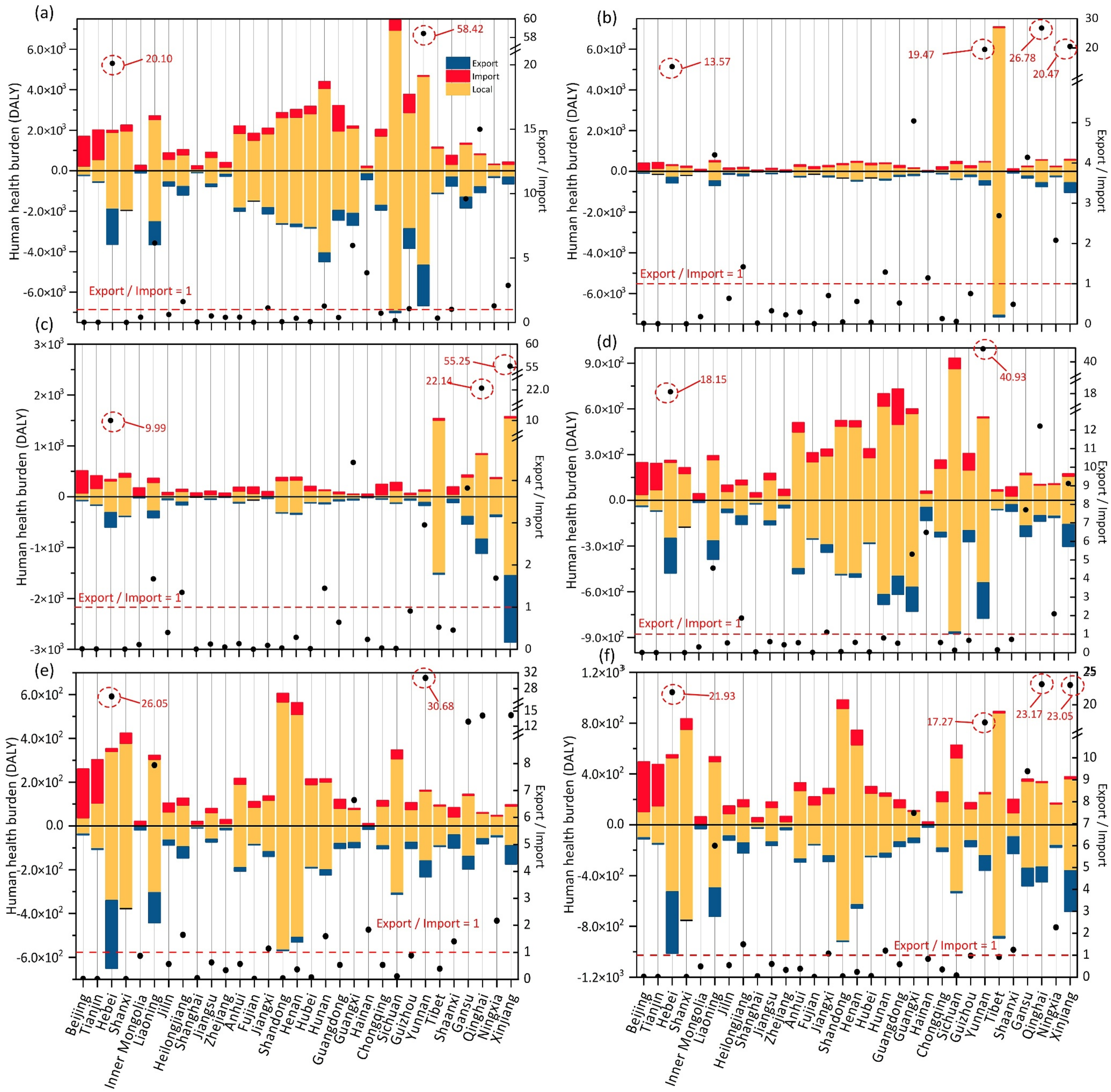

Figure 7. Human health burdens induced by livestock products consumption in each provincial region. (a, pork; b, beef; c, mutton; d, poultry; e, egg; f, dairy).

pinpoint key environmental impact categories, key livestock activities and key livestock species. Many studies have focused on single pollutants or individual management stages, overlooking pollution swapping as well as tradeoffs between mitigation objectives. Our work enables a comprehensive perspective that encompasses the entire manure management chain and complete livestock species, ensuring the strategic application of suitable mitigation technologies at each stage to maximize environmental benefits.

Climate change and fine particulate matter formation are the dominant contributors to human health burden, which is also highlighted by Long et al. (2021). In particular, climate change is mainly associated with enteric fermentation for ruminants and manure storage/treatment, with similar opinions from Grossi et al. (2019). At the enteric fermentation stage, the main livestock species is beef cattle, with significant contribution to manure emissions that represent a substantial portion of agriculture's total GHG emissions (Xing et al., 2022). In addition,

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manure storage/treatment witnesses pig as the leading livestock species (D. He et al., 2023). Fine particulate matter formation is predominantly linked to manure housing and its return to agricultural fields. In both stages, poultry stands out as a significant contributor, which is attributed to the fact that poultry produces ammonia emissions at a considerably higher rate than other livestock species. Regarding ecosystem quality burden, climate change and terrestrial acidification are the main drivers (Rosa et al., 2022). While the main sources of climate change are consistent with human health burden, terrestrial acidification is mainly related to the housing stage of manure management, with poultry being the main source of emissions (Yan et al., 2024). Poultry is also the main source of emissions related to resource scarcity, resulting from on-farm fossil energy consumption. The shift in the primary sources of three burdens highlights that different livestock species have distinctively different impact patterns. Manure management that encompasses a range of stages with each contributing differently to the overall environmental burden proves to be a pivotal component in mitigating the burdens imposed by livestock production (Zhu et al., 2022). The implementation of targeted mitigation strategies across various stages of manure management chain can lead to a substantial reduction in the burdens (Wei et al., 2024; Zhi et al., 2022).

To ensure a thorough analysis, it is crucial to take into account the regional variations in livestock production practices. In Shandong, Henan, and Sichuan, where industrial livestock production is prevalent, the significant amount of manure generated necessitates sophisticated management systems that can efficiently handle manure waste while minimizing environmental impacts. In these regions, the adoption of composting and biogas production from manure has shown promise in reducing human health and ecosystem quality burdens. However, challenges remain in the form of high capital and operational costs, which may hinder widespread implementation (Zhi et al., 2022). Consequently, there is a necessity to reinforce the adjustment and optimization of the regional distribution of livestock production. In Inner Mongolia and other pastoral regions, extensive grazing practices result in different manure management challenges. The direct deposition of manure onto grasslands can have both positive and negative effects. While it contributes to nutrient cycling and soil fertility, excessive deposition can lead to nutrient imbalances and groundwater pollution (Wei et al., 2024), requiring an optimal balance. Furthermore, we suggest incorporating a socio-economic perspective to understand the barriers and incentives for adopting improved manure management practices. This includes examining the role of government policies, market forces, and farmer behavior in shaping the adoption of sustainable practices.

The health and ecosystem burdens exhibit a strong alignment, with Shandong, Sichuan, and Henan consistently emerging as the top regions for both production-based and consumption-based impacts. These regions not only show high local consumption ratios but also experience significant local burdens due to their large populations and intensive livestock production. However, resource burdens diverge notably from this pattern. While Guangdong ranks second in resource scarcity burdens as an importer with a TBC of 0.55, it does not follow the dominance seen in health and ecosystem burdens. This indicates that regions heavily involved in trade, such as Guangdong, may bear resource burdens differently compared with health and ecosystem burdens. Interregional trade patterns further highlight these differences. For health and ecosystem burdens, the major exporting regions include Inner Mongolia, Henan, and Yunnan, while Guangdong, Zhejiang, and Jiangsu are key importers. Resource burdens, however, show a different set of leading exporters, such as Hebei and Heilongjiang, underscoring the distinct nature of resource scarcity in the trade network. This underscores the need for tailored regional strategies to address the unique challenges posed by each type of burden.

The MRIO analysis results also provide evidence that challenges the common assumption linking trade intensity directly to the burdens. For instance, in terms of human health burden, Shandong emerges as with the most severe burdens, both in production-based and consumption-based assessments. However, despite this, the largest exporter of human health burdens is Inner Mongolia, while Guangdong emerges as the largest importer. This discrepancy underscores the complex nature of the burdens associated with trade, where the largest exporters and importers may not necessarily correspond to those with the greatest burdens. This is reinforced by references (Feng et al., 2014; Yarlagadda et al., 2023), emphasizing the intricate relationship between international trade and regional environmental disparities, further supporting the notion that the largest exporters and importers may not always bear the greatest burdens. Additionally, the use of TBC to measure trade surplus intensity and trade deficit intensity is an innovative approach that provides insights into the imbalance of exporter-importer relationships. This is a novel contribution to the literature, as most studies focus on net exports and imports without considering the intensity of trade surplus or deficit (F. Wang, Liu, & Zhang, 2017; Xu et al., 2009). Regions with a trade surplus in environmental burdens effectively shift their burdens to importing regions, which can create an imbalance in environmental responsibilities. These trade patterns are often linked to socioeconomic factors. For

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example, regions with high production capacities may prioritize economic gains from exports, leading to a trade surplus in environmental burdens. In contrast, economically advanced regions with stringent local environmental regulations might import more, resulting in a trade deficit. Understanding these dynamics is crucial for crafting targeted policies that promote equitable distribution of environmental responsibilities, ensuring that both exporting and importing regions take actions to mitigate their impacts. For regions with both high import and export activities, such as Henan and Shandong, on the production side, the composting and anaerobic digestion technologies could be employed to manage livestock manure to alleviate its direct impacts efficiently. On the consumption side, policies should focus on introducing mechanisms to offset their environmental burdens through interregional cooperation and burden-sharing agreements. Import-intensive regions like Beijing and Shanghai could adopt consumption taxes or environmental tariffs on high-impact livestock products, thereby internalizing the environmental costs and encouraging reduced consumption. This would ensure that regions benefiting from lower direct impacts also contribute to mitigating the environmental burdens, fostering greener livestock production on a national scale. The assessment of three burdens induced by livestock products consumption and their interprovincial transfers is a contribution to the literature. While other studies have looked at embodied energy exchanges (Mehrabi et al., 2020) and environmental impact transfers (Deng et al., 2023), our research provides a more detailed analysis of the livestock production sector, which consists of a significant part of China's agricultural trade.

To situate our findings within the broader scope of cross-scientific research, comparisons have been drawn with emerging fields, such as development geography and the sustainable development goals (SDGs). Development geography, with its focus on the spatial aspects of economic and social progress, offers valuable insights into the regional disparities in livestock production's environmental impacts. For instance, the geographical distribution of livestock production, as discussed in Mehrabi et al. (2020) and Deng et al. (2023), can be linked to the spatial imbalances in the burdens that our study reveals. The concentration of the burdens in major production areas like Shandong, Henan, and Sichuan corresponds to regions with high livestock density, reflecting the geographical dimensions of environmental pressures. This spatial perspective is crucial for formulating targeted regional policies that account for both production and consumption patterns. Furthermore, our findings on the health, ecosystem, and resource burdens can be directly related to several SDGs, including Goal 3 (Good Health and Well-being), Goal 12 (Responsible Consumption and Production), and Goal 15 (Life on Land). By assessing the environmental burdens within the SDGs framework, we can better understand the tradeoffs and interconnections between different aspects of sustainable development. For example, the mitigation strategies proposed in our study, such as improving manure management practices, can contribute to achieving Goal 12 while also supporting Goal 3 by reducing the health burdens associated with poor manure handling.

Through our findings, a more effective response can be mounted to the environmental challenges posed by livestock production while ensuring the sustainability of the food production system. However, this study also has some limitations and avenues for future work. We employ process-based LCA with limitations inherent in the approach. One stems from the necessity of compiling a substantial amount of activity data and parameters to develop an exhaustive life cycle inventory, as detailed in Supporting Information S1. The reliance on a vast array of data makes the analysis susceptible to uncertainties (Toniolo et al., 2021), particularly when faced with the challenge of data scarcity. The sensitivity analysis outcomes further reveal potential pathways for mitigating environmental impacts. Notably, the analysis indicates that the impact of fine particulate matter formation exhibits heightened sensitivity to fluctuations in data. This suggests that meticulous attention to the accuracy and precision of data pertaining to particulate matter emissions could be instrumental in developing targeted strategies to reduce the environmental footprint of livestock production systems. By prioritizing the refinement of these critical data sets, researchers and policymakers can more effectively tailor interventions. Furthermore, our sensitivity analysis reveals that resource scarcity burdens are more sensitive to changes in data timeliness. To address the limitations of outdated MRIO tables, using recent-year trade structures or employing statistical methods to estimate current data can be effective solutions. Future work in this area could focus on refining data collection methods and expanding the scope of available data sets to further enhance the precision and applicability of process-based LCA. In addition, the future work could be extended to parallel the MRIO data with updated results of the environmental burdens of regional livestock production and be expanded to the global scale to explore the transfers of detailed environmental impacts intensified by livestock production among global countries.

Data Availability Statement

The socioeconomic data (the number of livestock, the coefficient of livestock production scale, the breeding cycles of livestock, and the energy costs associated with livestock production), and the emission coefficients for GHGs and pollutants resulting from livestock production activities employed in this study are mainly sourced from: National Bureau of Statistics of China (2021); Ministry of Agriculture and Rural Development of China; Bao et al. (2018), Dong (2022), Ministry of Ecology and Environment of the People's Republic of China (2014), Bai et al. (2016), National Development and Reform Commission of the People’s Republic of China (2021), Chinese Academy of Environmental Planning (2023), Ministry of Ecology and Environment of the People's Republic of China (2016) [Dataset].

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