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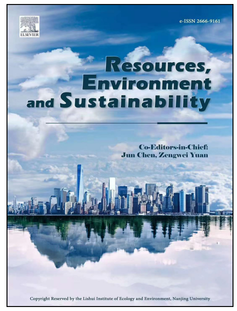

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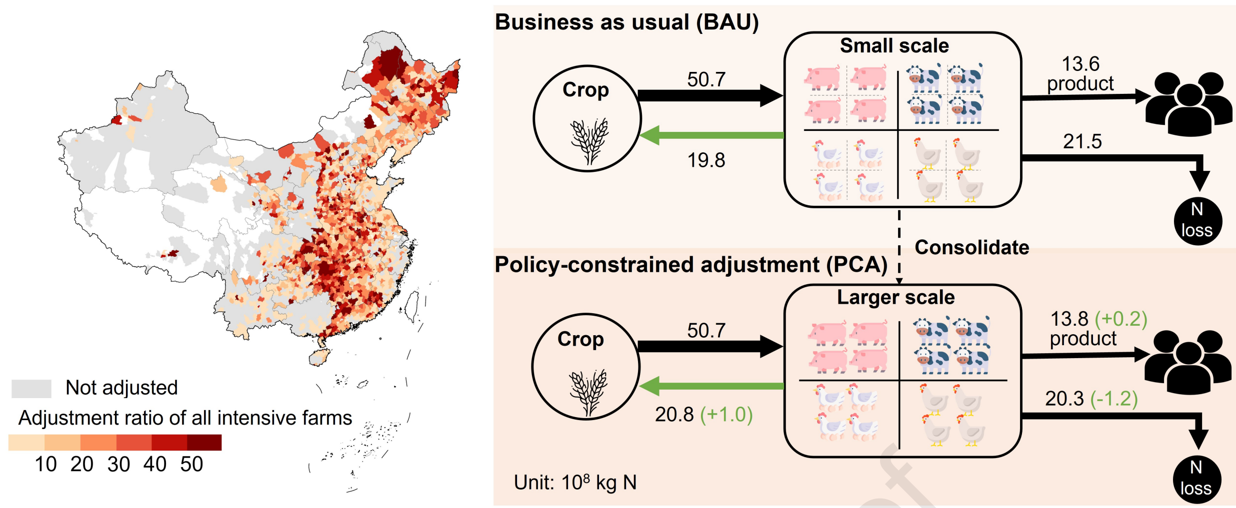
Declaration of competing interest

All authors have no conflicts of interest to report.


Not adjusted
Adjustment ratio of all intensive farms
10 20 30 40 50
Business as usual (BAU)
Crop
50.7
19.8
Small scale
13.6
product
21.5
N
loss
Consolidate
Policy-constrained adjustment (PCA)
Crop
50.7
20.8 (+1.0)
Larger scale
13.8 (+0.2)
product
20.3 (-1.2)
N
loss
Unit: 10^8 kg N

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Abstract

The livestock farm size influences management strategies, affecting nitrogen use efficiency (NUE) and nitrogen losses. Using data from 360,000 farms across China in 2017, covering four major livestock types, the relationship between NUE, nitrogen losses, and farm size is examined. Results show that NUE increases and nitrogen loss intensity decreases as farm size grows for all livestock types, despite manure recycling ratios differ among livestock types, underscoring the need for tailored strategies to manage farm size. Managing farm size for only 16% of intensive farms nationwide could reduce nitrogen losses by 121 Gg (1 Gg=10^9 g), increase production by 21 Gg, and enhance manure recycling by 100 Gg. This strategy would yield a 24% reduction in nitrogen losses, a 9% increase in livestock production, and a 40% rise in manure recycling in smaller-size farming regions, highlighting the critical role of livestock farm size in achieving significant environmental and food security benefits.

Key words: Livestock farm size; Nitrogen management; Cost-benefit analysis; Mitigation potential

1. Introduction

China plays a prominent role in global livestock production and consumption, contributing 22% of global meat and 7% of global milk production. The country raises nearly half of the world's pigs, 20% of layer chickens, and 30% of broiler chickens (FAO, 2022). With rising living standards, the demand for livestock products in China is projected to double by 2050 (Alexandratos and Bruinsma, 2012). This growing demand presents substantial challenges in terms of environmental pollution, climate change mitigation, and food security (Du et al., 2018; Fang et al., 2023). Furthermore, China's livestock sector contributes 22% of global livestock-related reactive nitrogen (N) emissions (Cheng et al., 2022), accounting for one-third of total anthropogenic N emissions (Uwizeye et al., 2020). These emissions have detrimental effects on the environment, climate, and human health (Erisman et al., 2013; Galloway et al., 2008; Gu et al., 2021). Consequently, identifying effective and practical strategies to reduce livestock N emissions in China while ensuring a sustainable supply of livestock products is of critical importance.

In recent years, intensive farming has become as a key strategy for advancing national livestock production in China (Pan et al., 2019), offering improved economic benefits and reduced resource waste compared to traditional farming methods (Bai et al., 2018; Wei et al., 2018). By 2017, the proportion of intensive farming (measured by the share of intensive farms among all farms) had risen to 45%, up from 31% in 2007 (Zhu et al., 2022). The proportions of intensive farming for pigs, dairy cattle, layer chickens, and broiler chickens were 41%, 49%, 64%, and 72%, respectively. The 14th Five-Year Plan for the Development of the National Animal Husbandry and Veterinary Industry aims to further promote livestock farming intensification (China, M.O.A.A. 2021). Intensification is widely regarded as central to the modernization of the livestock industry, facilitating the adoption of more efficient production techniques (Li et al., 2017), improving production efficiency (McAuliffe et al., 2017; Wang et al., 2016), and enhancing labor productivity. As a result, the shift towards intensive farming has become a national priority in China's livestock sector with the implementation of scientifically grounded intensive management practices viewed as essential for advancing livestock production modernization.

However, without proper management, the transition to intensive farming may lead to manure nutrient losses, and a spatial mismatch between crop and livestock farming, resulting in substantial environmental damages (Jin et al., 2021; Zhu et al., 2022). Beyond environmental impacts, changes in farm structure are also closely associated with animal welfare outcomes. While poorly managed intensification may increase stocking density and stress, well-managed intensive systems can provide more controlled housing conditions and stronger disease prevention, potentially improving animal health compared to poorly resourced small-scale systems (Mench et al., 2011). Small-scale livestock systems are often constrained by limited technical capacity, higher labor inputs, and lower product output. Large farms typically require substantial investments in management, disease prevention, and manure handling (HOU and ZHANG, 2022), but may also deliver higher production efficiency (Wang et al., 2016), and stronger disease control capacity (Li et al., 2017). Small farms are more likely to adopt land- and labor-intensive manure management practices (Pan et al., 2021), while medium- and large-scale farms tend to implement more capital- and knowledge-intensive methods, such as biogas production and composting (Hou and Zhang, 2022), which can reduce N pollution (Wei et al., 2018) and greenhouse gas emissions (McAuliffe et al., 2017). Nevertheless, it is important to recognize that excessively large-scale livestock operations can pose considerable environmental challenges, especially due to the lack of sufficient agricultural land for effective manure application (Liu et al., 2017; Wang et al., 2016), and may also raise animal welfare concerns if scale expansion is not accompanied by appropriate space allocation, management capacity, and regulatory oversight.

While large-scale, standardized livestock farming has become a dominant trend driven by market and policy incentives, larger farm sizes do not necessarily guarantee better outcomes from a marginal benefit perspective (Soliman and Djanibekov, 2021; Ziętek-Kwaśniewska et al., 2022). Instead, there is an optimal scale at which both production efficiency and environmental benefits are maximized (Liu et al., 2017; Wei et al., 2018; Xiaoxia, 2020). Therefore, it is essential to identify the optimal farm size for livestock production, aiming to improve feed utilization, strengthen the spatial match between livestock and cropland, and minimize pollution. However, quantitative evidence on the interaction between livestock nitrogen management and farm size remains limited. This study addresses this gap by analyzing data from nearly 360,000 intensive farms sampled in the Second National Pollution Census of 2017. Our goal is to explore these interactions and determine an evidence-based and policy-feasible approach to managing farm size through policy-constrained adjustments, with the aim of enhancing livestock production and reduce environmental damage.

2. Data and methods

This study first compiled and harmonized data from approximately 360,000 intensive livestock farms across China, obtained from the 2017 Second National Pollution Census. It then examined the relationships between farm size and three key N-related indicators, N use efficiency (NUE), N emission intensity and manure N recycling ratio, for pig, dairy cattle, broiler, and layer chicken production systems. Building on these relationships, the study developed scenario-based analyses to identify policy-feasible farm-size targets for each system under these adjustment conditions. Lastly, a cost-benefit analysis was conducted to evaluate the economic feasibility of implementing farm size management. The methodological procedures are described in detail in the following subsections.

2.1 Data Sources

The 2017 Second National Pollution Census. Data on geographical coordinates, livestock numbers, and manure removal management methods were derived from the Second National Pollution Census data (Zhu et al., 2022), which included approximately 360,000 intensive farm surveys conducted in 2017. The survey provides detailed information on manure cleaning methods, including manure dry manure removal, mechanical dry manure removal, bedding materials, raised bed farming, water-flushed manure, and blistered manure. It also reports manure treatment process and utilization, including composting, organic fertilizer production, biogas production, bedding material production, cultivation substrate production, and others, as well as data on N loss to water and air. Overall, the Census data provide the foundational farm-level data required for the analysis. When combined with information on livestock species and manure cleaning methods, it enables a detailed characterization of farm-scale management practices, which in turn underpins the calculation of N losses across different pathways. Information on manure treatment and utilization explicitly provides manure N returned to cropland (such as composting and organic fertilizer production), forming the basis for subsequent N balance calculations. The animal production data were primarily extracted from the literature rather than directly obtained from the farm survey data, which was necessary due to the lack of detailed production data (e.g., milk yield per cow, egg production per hen, or live weight gain per pig) in the survey dataset. The literature provided national and regional averages for production outputs (e.g., nitrogen in milk, meat, and eggs), which were applied across farm size categories to estimate nitrogen yields. A summary of the production data has been compiled and added to Table S40.

The National Compilation of Information on Costs and Benefits of Agricultural Products yearbook (Cost and Benefit Yearbook, https://navi.cnki.net/knavi/yearbooks/YNCSY/detail?uniplatform=NZKPT) was used to gather data on livestock yields and concentrate feed intake in 2017. The definition of intensive farms is taken from the Cost and Benefit Yearbook, referring to farms larger than backyard scale, specifically those with more than 30 pigs (slaughtered), more than 10 dairy cattle (stock), more than 300 layer chickens (stock), and more than 300 broiler chickens (slaughtered). The main product of dairy cattle is milk, the main product of pigs (including only finishing pigs) broiler chickens are meat, and the main product of layer chickens is eggs. The crude protein content of the feed intake and the percentage of concentrate feed were described in Table S2. The N content of all livestock products was obtained from Bai et al. (Bai et al., 2016). Climate data containing temperature and precipitation data were from the China Meteorological Data Web (http://data.cma.cn/) and the literature (Fick and Hijmans, 2017), respectively. Per capita GDP and per capita disposable income data at the county scale were derived from province statistical yearbooks of 2017 (https://data.cnki.net/Yearbook/). Data on crop farm size was from the literature (Wang et al., 2022).

2.2 Nitrogen balance in livestock system

In this study, we describe the comprehensive impact of farm size on the N budget. NUE is used to represent production efficiency and can be used to evaluate the performance of N input in terms of resource use and environmental impact. The analysis of N loss and manure N recycling is used to explore the environment and resource utilization performance of livestock systems. Feed N intake was the N input (N_{feed}) to the livestock system. The N output included livestock products ($N_{product}$), N loss (N_{loss}, including NH_3-N, N_2O-N, N loss to water, other N loss), manure N recycled to the field ($N_{recycle}$). $N_{recycle}$ is excluded from N loss, as it is recovered and reused as fertilizer for agricultural land. Manure excreted by dairy cattle and beef cattle during grazing period was directly deposited on grasslands and was included in the calculation of manure recycling N. The definition of NUE was derived from Gu et al. (Gu et al., 2015), as shown in Eq. (1).

$$NUE = \frac{N_{product}}{N_{feed}} \quad (1)$$

The quantity of manure N recycled to the field for each farm was determined using data from the Second National Pollution Census. This Census provided detailed statistics information on manure treatment methods, including manure cleaning methods, urine and wastewater disposal, and manure treatment disposal such as composting, biogas production, standard emissions, unused manure (discarded), and other utilization (including bedding material production, substrate production, use as fuel, and aquaculture). Biogas production primarily generates methane, and the remaining digestate can be recycled as organic fertilizer for cropland. Both composting and biogas production are considered for recycling manure. Further details are provided in the "Basic Information of Intensive Livestock and Poultry Farms" questionnaire (Table S3). The manure recycling ratio was defined as the proportion of manure N that is actually applied to the agricultural land out of total N excretion. Subsequently, according to the principle of mass conservation, N loss was calculated by subtracting the sum of product N output and manure recycled N from the feed N intake, as illustrated in Eq. (2). N loss and manure N recycling are from both solid and liquid manure.

$$N_{loss} = N_{feed} - N_{product} - N_{recycle} \quad (2)$$

Then, the quantities of different forms of N loss were estimated, including NH_3-N, N_2O-N, N loss to water, and Other N loss (including N_2, discarding N and manure utilized as fuel). Here, N_2 is also categorized as N loss. Although N_2 does not directly harm the environment, reducing N_2 can enhance NUE. Therefore, comprehensive reductions in total N loss reflect improvements in resource use efficiency while supporting environmental protection and food security. Emission estimates explicitly account for spatial and managerial heterogeneity across livestock systems, emission factors (NH_3-N and N_2O-N emissions) are differentiated by livestock species and manure management pathways, with pathway-specific coefficients across various provinces adopted from literature (Tables S20-27). Farm-level information from the Second National Pollution Survey on manure management practices allows emissions to be calculated at the farm scale and aggregated while preserving underlying spatial variation. Grazing-based dairy systems are explicitly considered, with manure excreted during grazing assumed to be returned to grassland systems, based on (Wei et al., 2018a; Wei et al.,2018b). N loss to water was derived from data from the Second National Pollution Survey, and the quantity of other N loss forms was calculated based on the law of mass conservation (i.e., N loss minus the sum of NH_3-N, N_2O-N, and N loss to water). While emission coefficients are derived from the literature due to data and technical constraints that preclude direct measurement of farm-specific emission factors, uncertainty analysis (2.5 Uncertainty analysis and Table S29) was applied to key emission parameters to assess the robustness of emission estimates, thereby mitigating potential bias arising from the use of representative emission factors.

Because the data for all farms are extensive and dispersed, farm size was grouped to examine the relationship of NUE, unit N input, unit yield, manure recycling ratio, and N loss intensity in relation to farm size, respectively. The detailed process of grouping and statistical analysis are provided in the Supplementary Methods (S1.1 Statistical analysis) and Tables S4-7.

2.3 Scenario setting

2.3.1 Regression analysis

Regression analysis was employed to examine the relationships between farm size and both production and environmental performance across pig, dairy cattle, broiler, and layer systems. The regression specifications are grounded in agricultural production theory and bioeconomic considerations, including economies of scale and diminishing marginal returns. The theoretical rationale underlying scale effects and the associated regression hypotheses is described in Supplementary Methods (S1.1.1 Hypothesis on farm size and livestock production and environmental impacts).

These theoretical considerations motivate the comparison of linear and quadratic functional forms. A linear specification captures the average scale effect, while a quadratic specification allows for nonlinear responses consistent with diminishing returns. Accordingly, for each livestock type, both linear models including farm size and quadratic models including farm size and its squared term were estimated. The quadratic specification was retained only when the squared term was statistically significant (two-sided t-test, $p < 0.05$) and improved goodness of fit as measured by adjusted R^2. Otherwise, the linear specification was adopted to maintain model parsimony. Details of the regression implementation are provided in Supplementary Methods (S1.1.3 Regression analysis).

Given the large sample size and potential intra-group similarities within livestock categories, a preliminary grouping of each livestock type was performed prior to regression modelling. Detailed grouping criteria are provided in Supplementary Methods (S1.1.2 Data grouping criteria) and Tables S4-7. Rather than dichotomizing farms into simplistic “small” and “large” categories, farms were classified into multiple livestock-specific size classes. This grouping approach enables a detailed examination of production and environmental performance from small-scale to very large-scale operations, allowing heterogeneity and potential nonlinear responses across the full farm size spectrum to be assessed. Model robustness was further assessed using alternative grouping strategies, yielding consistent results. Details of these alternative classifications are provided in Tables S12-15. Based on the regression outcomes, optimal farm size scenarios were identified for each livestock system. Comprehensive statistical procedures are detailed in Supplementary Methods (S1.1 Statistical analysis).

2.3.2 Policy-constrained adjustment scenario

In Business as Usual (BAU) scenario, there are issues as follows: In some regions, the low availability of cropland for manure application, which limits the potential for organic fertilization. The high levels of manure discharge into water bodies and the associated environmental impacts, particularly in regions where small-scale farms are concentrated. Based on this observation, the Policy-constrained adjustment scenario (PCA) was developed.

The concept of moderate-scale farming has gained broad recognition in previous studies and is increasingly supported by policy frameworks. In this study, regression relationships between N loss intensity and farm size were established to characterize how N loss varies across farm sizes for different livestock types (Table S8-S11). These relationships were used as an analytical basis for defining PCA scenario, and to inform the identification of farm-size thresholds associated with lower N loss intensity. Therefore, the PCA was defined by managing farm size to reduce N loss. Managing farm size refers to consolidating excessively small farm sizes. Meanwhile, farming NUE showed a significant correlation with farm size, implying that optimizing farm size would have an impact on the quantity of feed N intake and product outputs. To investigate the impacts of the PCA on N loss, production, and manure recycling, total feed N input was held constant.

In PCA scenario, the adjusted strategy is consolidating small farm sizes to align with the farm size corresponding to the national average N loss intensity level. Setting the optimal scenario at the largest possible farm size may lead to diminishing returns to scale and was therefore not adopted. Large farms may face difficulties in sourcing sufficient agricultural land to absorb manure, posing significant risks to the surrounding land and environment. Previous research findings (Liu et al., 2017; Wei et al., 2018; Xiaoxia, 2020) and national policies (China M.O.A.A., 2021) suggest that moderate-scale farming is more beneficial. This approach prioritizes the aggregation of smaller farms, ensuring they achieve improved NUE and reduced N loss intensity, as observed in farms operating near the national average size. For farms exceeding this optimal size, no changes will be made. To ensure the feasibility of this approach and to avoid risks associated with decoupling cropland cultivation and livestock farming, all farm consolidations are implemented at the county level. Specifically, corresponding consolidation strategies were applied for each livestock species within individual counties. The specific adjustment approach is outlined below.

Increasing farm size can reduce N emissions as the N loss intensity would decrease as farm size expand. To achieve moderate-scale farming and avoid the issue of insufficient agricultural land for manure absorption associated with overly large farms, we adjust the farm size of each livestock species to the farm size corresponding to the national N loss intensity level. For farms exceeding the optimal farm size, no changes will be made. Therefore, the adjusted strategy is to combine farms with N loss intensity higher than the national average intensity ($NL_{country}$)

and farm size smaller than the corresponding farm size ($Size_{country}$) to $Size_{country}$. County boundaries were used for this analysis. First, the $NL_{country}$ was calculated based on BAU (Business as Usual) data, and $Size_{country}$ was then estimated using the regression relationship between N loss intensity and farm size. Secondly, screen out the farms whose N emission intensity above $NL_{country}$ and farm size below $Size_{country}$. Thirdly, farms within the same county were merged, and the adjusted farm size ($Size_{optimized}$) was calculated as the total livestock numbers divided by the adjusted numbers of farms. The corresponding adjusted N loss intensity ($NL_{optimized}$) was then estimated based on the regression curves. Fourthly, the adjusted livestock production ($TN_{op-production}$) was calculated using the NUE function (the regression curve between NUE and farm size), as shown in Eq. (3). The total N loss ($TN_{op-loss}$) under the PCA are estimated by multiplying $TN_{op-production}$ and $NL_{optimized}$, as indicated in Eq. (4). Finally, the manure recycled N ($TN_{op-recycle}$) was calculated using total feed N intake TN_{feed} minus $TN_{op-loss}$ and $TN_{op-production}$). The detailed calculation procedure diagram is shown in Fig. S15.

$$TN_{op-production,i} = e^{f_{NUE}(lnSize_{optimized,i})} \times TN_{feed,i} \tag{3}$$

$$TN_{op-loss,i} = e^{f_{NL}(lnSize_{optimized,i})} \times TN_{op-production,i} \tag{4}$$

where *i* represent the livestock types, the $f_{NUE}(lnSize_{optimized})$ is the function of NUE and farm size for pig and layer chickens, and the $f_{NL}(lnSize_{optimized})$ is the function of N loss intensity and farm size for pig and layer chickens. $TN_{feed,i}$ is the total feed N input, which remains unchanged in the PCA scenario.

2.4 Cost-benefit assessment framework

2.4.1 Implementation cost. To implement the adjustment scenario, the first step involves dismantling farms with unreasonable farm size that have high N loss. The second step is to build new farms to support appropriate-sized livestock operations. Therefore, the first step is to calculate the dismantling cost of the farms ($Cost_{dismantle,i}$), and the second step is to calculate the cost of rebuilding the farms (main routine costs), which include feed costs, depreciation costs of fixed machinery, labor costs, newborn animal costs, and other costs. The base scenario also includes main routine costs.

The implementation cost was calculated by accounting for the expense associated with farm demolition and the difference in the main routine costs between BAU and PCA, including the feed costs, depreciation costs of fixed machinery, labor costs, newborn animal costs, and other costs. Firstly, the cost of farm demolition was calculated using data on the cost of demolition per unit of floor area ($Unit_{dismantle}$), obtained from the bidding information of farm demolition on the websites of all provincial government procurement networks and public trading centers. For provinces lacking bidding notices of livestock farm demolition, information from the dismantling of other buildings was adapted to be used. Detailed data on $Unit_{dismantle}$ by province can be found in the Supplementary Data 13 and 14. The unit floor area data ($Unit_{floor}$) for all livestock are obtained from the national farming construction standards (NY/T 1568-2007; NY/T 2969-2016; NY/T 1567-2007). ($Unit_{floor}$) multiplied by $Unit_{dismantle}$ to get the cost of demolishing farms ($Cost_{dismantle}$), calculating as Eq. (5).

$$Cost_{dismantle,i} = \frac{Unit_{floor,i} \times Unit_{dismantle,i} \times N_i}{20} \quad (5)$$

where $N_{i,}$ is the total numbers for livestock i, and 20 is referred to the dismantling cost discounted to annual data based on 20 years.

Data on the unit main routine cost ($CostR_{Optimized}$) for all livestock was derived from Cost and Benefit Yearbook. The Cost and Benefit Yearbook provides provincial data on unit main routine cost, which include feed costs (comprising feed purchasing fees and feed processing expenses), depreciation of fixed machinery, labor costs, costs of newborn animals, and other costs (such as technical service fees, etc.). The depreciation of fixed assets refers to buildings, structures, machines, and transportation equipment with a useful life of more than one year. The reference depreciation rates for different types of fixed assets are as follows: 8% for special production houses and permanent bar sheds, 25% for simple sheds, 12.5% for equipment such as machinery and transportation tools, and 20% for all other fixed assets. The difference in the routine cost between the BAU and Optimized scenarios was calculated using the following Eq. (6).

$$CostR_{Optimized,i} = UnitR_{Optimized,i} \times N_i - UnitR_{BAU,i} \times N_i \quad (6)$$

where $N_{i,}$ is the total numbers for livestock *i*, $UnitR_{Optimized,i}$ and $UnitR_{BAU,i}$ are the unit routine costs for PCA and BAU scenario, respectively, which conclude the feed costs, depreciation costs of fixed machinery, labor costs, newborn animal costs and other costs. Dairy cattle are not counted in the costs of newborn animals.

2.4.2 Economic benefits assessment. The Economic benefit assessment was conducted to evaluate the variations in the output values of livestock products between BAU and PCA. This benefit does not include the use of other technology or other mitigation option, but solely reflects the product output benefits resulting from the changes in technology and equipment due to the adjustment of farm size. The output values are from main products (meat, milk and eggs) as well as by-products. Firstly, the overall economic output of each farm under the BAU scenario was computed by multiplying the unit output value by the total number of livestock *i*. Then, the total economic output under PCA was quantified based on the new farm size of $Scale_{optimized}$. Finally, the net economic benefits were estimated following Eq. (7).

$$NetEconomic_{opimized} = UnitE_{Optimized,i} \times N_i - UnitE_{BAU,i} \times N_i - CostR_{Optimized,i} \quad (7)$$

where $UnitE_{Optimized,i}$ and $UnitE_{BAU,i}$ are unit economic value from main products and by-products under the Optimized and BAU scenarios, respectively.

2.4.3 Societal benefits assessment. The societal benefits of managing farm size are the benefits from avoiding damage costs of decreasing N emissions (NH_3-N, N_2O-N and NO_3^--N), including ecosystem benefits (E_{benfit}), human health benefits ($H_{benefit}$) and climate mitigation benefits ($C_{benefit}$), as calculated using Eq. (8). Ecosystem benefits were estimated using unit N damage costs derived from the European Nitrogen Assessment and adjusted to the Chinese context by accounting for differences in willingness to pay (WTP) and purchasing power parity (PPP). Human health benefits were quantified based on avoided premature mortality resulting from $PM_{2.5}$ reduction, using unit health damage costs for N emissions that link emission abatement to population exposure, income level, and years of life lost. Climate benefits were estimated by combining the cooling effect of N_2O abatement with the warming effect associated with reduced NH_3 emissions, using literature-based unit climate benefit coefficients. Climate mitigation benefits are limited to those arising from changes in N-related emissions under the adjustment scenario, and do not include carbon-dioxide or methane-related emissions. Detailed calculation procedures are provided in Supplementary Methods (S1.3 Societal benefits assessment).

$$SO_{benefit} = E_{benfit} + H_{benefit} + C_{benefit} \quad (8)$$

2.5 Uncertainty analysis

Given that the Second National Pollution Census data (Census data) comprise over 360,000 points, it is challenging to quantify detailed data on feed intake, emission parameters, and yield for every farm due to difficulties in obtaining such information directly from farm owners. Census data provides detailed information on manure treatment methods, including manure cleaning methods, urine and wastewater disposal, and manure treatment disposal such as composting, biogas production, standard emissions, discarded manure, and other utilization (including bedding material production, substrate production, use as fuel, and aquaculture), which can be obtained from the survey questionnaires for every farm (Table S3, Fig. S1). Consequently, each province's survey data includes only representative points, which may not comprehensively cover the full farm size information for all livestock types (small-, medium-, and large-sizes). This limitation constrains the ability to fully elucidate the variations in farm characteristics across different livestock scales. To address this, the Census data were supplemented with Cost and Benefit Yearbook data and literature to enhance the dataset on livestock production system performance. For instance, the crude protein content of feed (in Table S2), were not directly available from the survey and were instead sourced from other literature. This may introduce a degree of error, as feeding practices can vary significantly within farms of similar size. However, these data were the best available for the study, and uncertainty analyses were conducted to assess how variations in feed quality assumptions might affect the model results.

To quantify this, 10,000 Monte Carlo simulations were performed in Matlab 2021b to assess uncertainties in livestock production and environmental performance, as well as in the cost-benefit analysis under PCA scenario. We calculated the 95% confidence intervals for all results (Fig. S21-22 and Supplementary Data 1-12). Table S29 provides the coefficients of variation (CV) for activity data and parameters related to livestock production, environmental performance, and cost-benefit analysis. The CVs exceeding 30% in our Monte Carlo analysis indicate moderate to high levels of uncertainty, reflecting the intrinsic variability in livestock systems, spatial heterogeneity, and parameter uncertainty associated with literature-derived inputs. CVs within the 30-50% range are frequently observed in environmental modeling and benefit valuation studies (Chang et al., 2021; IPCC, 2019), especially those that incorporate empirical data and large-scale assumptions. Despite this variability, the directional trends and relative improvements, such as N loss reduction and increased NUE, remain consistent across simulations. As such, while the absolute magnitudes of economic and environmental benefits carry uncertainty, the results should be interpreted as indicative of potential outcomes, with emphasis placed on the robustness of relative patterns rather than precise numerical estimates.

2.6 Sensitivity analysis

The nation average N loss intensity was selected as the adjustment threshold for several reasons. First, the regression curves did not exhibit a distinct empirical inflection point to define an optimal farm size, and extrapolating toward the theoretical minimum N loss intensity could lead to unrealistic or unattainable farm size targets. Second, the national average provides a practical and policy-relevant benchmark, suitable for setting national mitigation targets and guiding resource allocation strategies. Third, this average was derived from a comprehensive dataset encompassing 360,000 livestock farms, offering a robust representation of typical performance across China. Finally, due to limited availability of disaggregated regional data and considerable spatial heterogeneity in factors such as climate and land availability, it is not currently feasible to define region-specific optimal farm size with sufficient confidence.

To assess the robustness of the adjusted (PCA) scenario, a sensitivity analysis was conducted using a one-at-a-time (OAT) approach (Hamby, 1994), focusing on the threshold of N loss intensity used to determine farm-size target. In the baseline PCA scenario, farms were adjusted to achieve national average N loss intensity, assuming this represents a policy-feasible and broadly applicable target.

To test the sensitivity of this assumption, an alternative adjustment scenario was introduced using the national median N loss intensity as the threshold. This more conservative benchmark captures a lower emission intensity level and reflects potential variability in policy stringency or implementation flexibility. The stability of environmental and production outcomes under different levels of adjustment ambition was evaluated by comparing the resulting changes in N losses, manure recycling, and livestock production between the two scenarios. Detailed results of this sensitivity analysis are provided in the Supplementary Discussion and Fig. S23.

3. Results and Discussion

3.1 Nitrogen use efficiency and farm size

In this study, we analyzed four livestock production systems: pig, dairy cattle, layer, and broiler chicken. NUE increases significantly with farm size for all livestock, particularly in pig and dairy cattle systems (Fig. 1). In the pig systems, larger farms demonstrate more efficient feed use with lower crude protein levels, while excessively large farms experience a decline in livestock yield (Fig. S2). Small-scale pig farms often rely on locally sourced corn, bran, and byproducts mixed with commercial premixes, leading to nutrient excess and resource wastage (Fang and Fuller, 1998). Additionally, the use of the same feed throughout the entire growth period on most small farms results in nutrient surplus, as crude protein levels should be decrease progressively from the growing to fattening stages (NRC, 2012; Presto Åkerfeldt et al., 2019). Larger farms tend to adopt more advanced feeding technologies and equipment, enabling stage-specific rationing that better matches animals' changing nutritional requirements across production phases and thereby reduces feed intake per head (Presto Åkerfeldt et al., 2019) (Table S8). Medium-scale farms dominate the pig production sector, making up 66% of the total (Fig. S3), while super-large farms with over 10,000 heads remain relatively rare. The Southeast region raises more pigs than the Northwest region (Fig. S4). The distribution of pig farm sizes across regions shows limited variation, except in Xinjiang, where large-scale farming is more prevalent due to the availability of extensive land and abundant crop feed. The NUE for pigs in Xinjiang is relatively high, reaching 25%, supported by policies and funding that promote large-scale farming (Fig. S2i). Pig NUE is also high in central and southern regions, such as Sichuan, where pig production systems exhibit higher yields (Fig. S2a). Sichuan, as a national hub for high-quality commercial pigs, has a higher degree of modernization and intensification.

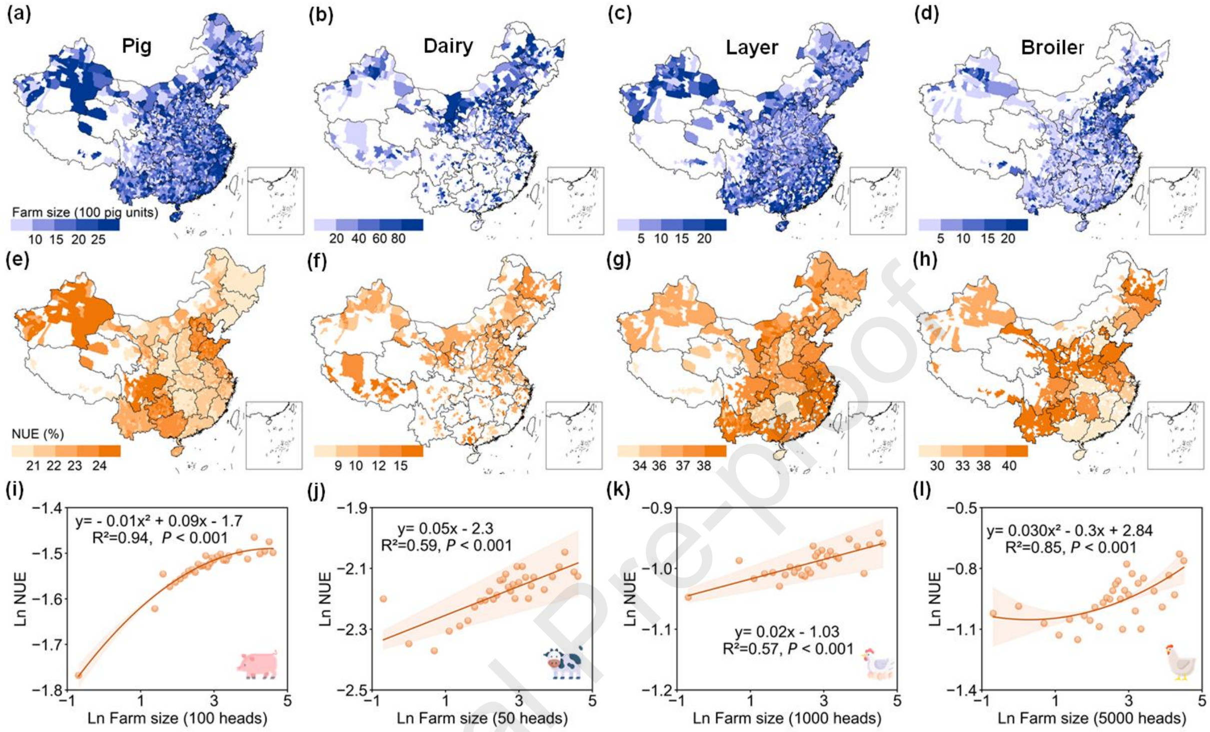

Fig. 1. NUE changes with farm size in all livestock systems. a-d, Average farm size of the county for pig, dairy cattle, layer, and broiler chickens, respectively. **e-h,** NUE of the county for pig, dairy cattle, layer, and broiler chickens, respectively. **i-l,** Relationship between livestock NUE and farm size in pig, dairy cattle, layer, and broiler chicken production systems, respectively. Each dot in i-l represents the mean of variables within a specific farm size group for each livestock type (Grouping criteria for each livestock production system are provided in Tables S4-7). The shaded area in the figure represents the 95% confidence interval. The base map was applied from the Database of Global Administrative Areas (GADM; https://gadm.org/).

Among all livestock, dairy cattle exhibit the lowest NUE at 12%. This is mainly due to their low feed conversion efficiency, as they consume substantial amounts of cellulose-rich feed like as grass and straw. The low NUE of dairy cattle arises from their high feed conversion rate (the amount of feed required to produce a unit of product) (Mottet et al., 2017), with 80% of their feed being cellulose-based, and their feed's relatively low crude protein content (FAO, 2022b). Additionally, only milk production was considered as the output in the dairy cattle system, excluding meat production from the analysis. Large-scale dairy cattle operations exhibit considerably higher productivity than small- and medium-scale farms, due to increased inputs such as concentrate feed, fixed assets, and expenses related to medical care and vaccinations (Yu and Peixin, 2021). Dairy cattle constitute 34% of large farms, encompassing the Large, Very Large, and Super Large farm categories (Table S1, and Fig. S3b). However, the Northern and Northwest regions show relatively high percentages of large dairy farming (40% and 37%, respectively). This is due to the abundant forage resources, favorable climate, and substantial dairy cattle populations in these regions. Furthermore, national policies and financial support have fostered the development of high-quality, standardized grazing areas, promoting large-scale dairy farming in these regions.

The NUE of chicken (37%) is substantially higher compared to pig (22%) and dairy cattle (12%), largely (2018; Mottet et al., 2017) due to the high proportion of easily digestible concentrate crops in their feed composition. Broiler chicken systems exhibit the highest NUE and the largest proportion (91%) of large-scale farming, indicating that broilers are particularly suited for large-scale and standardized farming practices, especially in the Northern region, where super-large farms account for 16% of production. In contrast, the proportion of large-scale farming in layer production systems is relatively low (22%, Fig. S3c). Despite the Northern region being the primary egg-producing area in China, with provinces such as Shandong, Hebei, Henan, and Hubei contributing to 40% of the country's egg production (Table S33), the average size of layer farms in these areas remains small (Fig. 1c and Fig. S3c). This is primarily due to high population density, limited and fragmented land availability, and smaller farming areas, which constrain the farm size in these regions.

Livestock farm sizes exhibit regional variations, influenced by rearing practices and socio-economic indicators (Pan et al., 2021). There is a positive relationship between rural per capita disposable income, urbanization rate, and farm size at the county level (Fig. S4). Higher levels of economic development and urbanization provide the necessary support to large-scale equipment, technology, and other operational costs. Increased investment in equipment, technology, and management expertise facilitates the development of high-quality, large-scale livestock farms (Hu and Yu, 2022). Additionally, the relationship between livestock farm size and cropland farm size follows an inverted-U shape, suggesting that an appropriate cropland farm size may benefit the expansion of livestock farm size at the county level. Given that the recoupling of crops and livestock also follows an inverted-U shape with cropland farm size (Jin et al., 2021), an optimal cropland farm size would not only enhance NUE in livestock production but also improve manure recycling for crops.

3.2 Manure recycle

The manure recycling ratios for different livestock types show distinct patterns with respect to farm size (Fig. 2). For pigs and broiler chickens, manure recycling ratios increase significantly with farm size, with the change being more pronounced for pigs and relatively minor for broiler chickens. The manure recycling ratio for broiler chickens is high (49%) and exhibits minimal variation across farm sizes. The distribution of broiler farms (Fig. 1d) aligns closely with the main distribution of cropland in the Northern and Northeast regions (Fig. S5), where abundant cropland resources make it easier to absorb the manure produced by broilers. Dairy cattle also have a high manure recycling ratio (49%), with farming concentrated in regions with abundant cropland and grassland, facilitating manure recycling. While the relationship between farm size and manure recycling ratio for dairy cattle is not strong, there is a trend of increased recycling as farm size increases. Additionally, manure produced by grazing dairy cattle is directly deposited on grasslands, contributing to the recycling process. In contrast, the manure recycling ratio for layer chickens is relatively low (39%) and does not show a significant relationship with farm size. This is due to the scattered distribution of layer farms, with large-scale farming concentrated in the Central and Southern regions (Fig. 1c), where cropland resources are limited (Fig. S6), resulting in insufficient agricultural land for effective manure recycling.

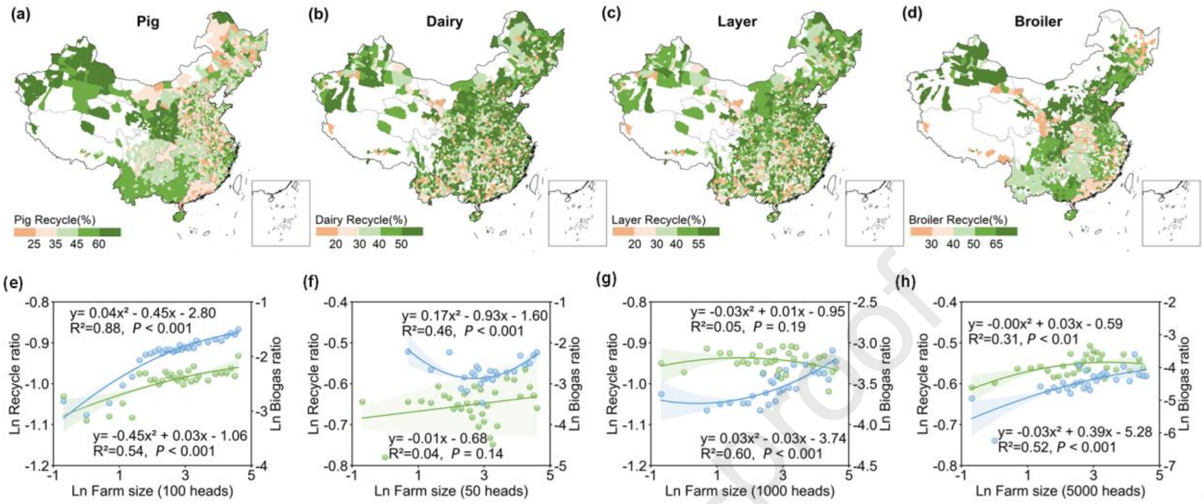

Figure 2. Ratio of manure recycled as organic manure and being used for biogas under different farm sizes. a-d, the manure recycling ratio for pig, dairy cattle, layer and broiler chickens, respectively. **e-h,** the relationship between manure recycling ratio, biogas ratio and farm size for pig, dairy cattle, layer and broiler chickens, respectively. The green and blue lines represent the manure recycling ratio and the biogas ratio, respectively. The shaded area in the figure represents the 95% confidence interval. The shaded area in the figure represents the 95% confidence interval. The base map was applied from the Database of Global Administrative Areas (GADM; https://gadm.org/).

For pigs, the manure recycling ratio (38%) increases significantly with farm size. As farm size grows, pig farms tend to invest more in manure treatment infrastructure, leading to higher manure resource utilization (Jing et al., 2020; Wang and Yang, 2017; Yu et al., 2012). Large farms produce more concentrated manure, and government policies emphasize the importance of proper manure management (GOSC, 2013): It is recommended that livestock farms, based on their size and pollution control needs, establish facilities such as composting, organic fertilizer production, and biogas generation to ensure comprehensive manure utilization. Farms that outsource these tasks to third parties are not required to set up their own facilities. Biogas production primarily relies on anaerobic fermentation technology, which converts organic waste into methane. The digestate produced during fermentation can still be used as organic fertilizer, which can be recycled to agricultural land.

The proportion of manure bio-gasification across all livestock production systems increase notably with farm size. This increase is largely due to the substantial initial investment required for anaerobic fermentation technology, which demands high technical expertise (Pan et al., 2021), which are more accessible to medium- and large-scale farms. Larger farms are more likely to invest in such technologies and infrastructure, enabling centralized manure treatment and energy recovery (Wei et al., 2016). Specifically, pig manure is the primary feedstock for biogas production in China, exhibiting the highest bio-gasification ratios (Fig. S7). By contrast, dairy cattle farms show lower and dispersed biogas utilization, partly due to the greater prevalence of grazing-based production. Bio-gasification ratios for broiler and layer chickens are also relatively low. Additionally, significant regional variations are observed, with higher biogas utilization ratios in the central and southern regions (Fig. S8), while the northern regions show lower ratios. For instance, in pig production systems, the biogas utilization ratio is much higher in the Southwest (32.4%), Central and Southern (14.4%), and Eastern China (15.1%) regions, compared to the Northwest (6.6%), Northeast (1.7%), and Northern (6.8%) regions. The colder climate in the northern region is not conducive to biogas generation, while the warmer temperatures in the southern region are more suitable for anaerobic biogas fermentation (Dongmei et al., 2019). The promotion of rural biogas energy development and utilization has led to the widespread adoption of anaerobic biogas digesters on farms in the southern region.

3.3 Nitrogen loss from livestock production

In 2017, the four main livestock production types in China resulted in a total N loss of 2.3 Tg (1 Tg = 10^{12} g), which includes NH_3-N, N_2O-N, N loss to water, and other forms of nitrogen. The contributions from pigs, dairy cattle, layer chickens, and broiler chickens were 1.0, 0.5, 0.5, and 0.3 Tg, respectively (Fig. S9). The distribution of N loss was as follows: 1.2 Tg from NH_3-N, 0.1 Tg from N_2O-N, 0.3 Tg N from N loss to water and 0.6 Tg from other sources. The Eastern, and Central and Southern regions exhibited the highest N losses, with totals of 0.66 Tg and 0.63 Tg, respectively, substantially higher than losses in other regions (Fig. S10a). This pattern is primarily driven by the concentration of intensive livestock production in these regions. At the provincial level, Henan, Guangdong, and Shandong provinces bear a large portion of the manure burden and have the highest N losses (Fig. S10), reflecting their roles as major livestock-producing provinces, particularly for pigs and chickens. However, regional differences in manure recycling capacity reflect structural constraints in crop-livestock integration, which are closely associated with variations in manure handling pressure and N loss intensity. Henan and Shandong, as major crop-growing provinces, have relatively high manure recycling ratios (55% and 50%, respectively), which help mitigate the N load by meeting the demand for organic fertilizer. In contrast, Guangdong has a relatively lower manure recycling ratio (32%) and thus experiences higher N losses. Therefore, effective manure treatment techniques must be urgently implemented in Guangdong to address this issue.

The Central and Southern region is responsible for large N losses from pig production (Figs. S9-10). Guangdong, as a major pig farming province, produced 46 Gg N (1 Gg=10^9 g) from meat production, resulting in 120 Gg of N losses and placing considerable environmental pressure on surrounding terrestrial and aquatic ecosystems. In contrast, N losses in dairy farming are more evenly distributed, with no significant regional differences, which is consistent with a more spatially dispersed production structure of dairy farms. In layer chicken production, the sector is highly concentrated in key egg-producing provinces such as Henan, Shandong, Hubei, and Hebei, which are also experiencing substantial N losses. These provinces collectively account for 37% of the country’s total egg-laying N losses, producing 50, 48, 48, and 41 Gg of N losses, respectively. Although these provinces are characterized by large production volumes, their average farm sizes are predominantly small to medium, with relatively moderate levels of mechanization and management. Their N loss intensities are close to the national average (1.0 kg N per kg product N), at 1.0, 0.8, 1.2, and 1.0 kg N per kg product N, respectively. Among these provinces, Shandong exhibits a slightly larger average farm size than Henan, Hubei, and Hebei (Fig.1c), which is associated with a lower N loss intensity. Overall, these provinces present hotpots for N loss mitigation, where reductions in total N losses are constrained by production scale but could be effectively achieved through improvements in farm size and associated improved management.

N loss intensities differ substantially across livestock systems, reflecting inherent differences in production efficiency and management requirements. N loss intensities in both layer and broiler chicken production systems are relatively low, at 1.0 and 0.7 kg N per kg product N, respectively, owing to their higher NUE. In contrast, dairy farming exhibits the highest N loss intensity, at 3.9 kg N per kg product N, which is attributed to lower feed conversion efficiency and longer production cycles (Uwizeye et al., 2020). Across all livestock systems, N loss intensity decreases as farm size increases. This pattern is primarily driven by improvements in management efficiency and technology adoption on larger farms. Larger farms typically b investment more in mechanical equipment, technology, and veterinary services (Fig. S11), which can replace labor (Fig. S12), improve farm efficiency, and reduce N losses (Wei et al., 2016; Wei et al., 2018). In pig, layer chicken and broiler chicken systems, N loss intensity stabilizes as farm size grows larger, particularly in the pig and layer chicken production systems. Beyond a certain farm size, further expansion does not lead to significant reductions in N losses, and excessively large farms may experience diminishing net profits (Fig. S13). For dairy farming, increasing farm size significantly reduces N loss intensity and enhances farming efficiency. However, because dairy farming often involves grazing, excessively large farms may strain grassland carrying capacities, potentially leading to land degradation (Bardgett et al., 2021; Bilotta et al., 2007). Overall, these results indicate that reductions in N loss intensity are driven by scale-related improvements in management and technology rather than farm size alone, and that maintaining an appropriate farm size by balancing efficiency gains against environmental and land constraints is critical for sustainable livestock production.

3.4 Optimizing farm size for different livestock systems

Optimizing farm size based on the emission characteristics of livestock can substantially improve resource efficiency. The adjustment strategy aims to minimize total N loss, including N_2 emissions. Although N_2 does directly threaten the environment or ecosystem, reducing its emissions can enhance the effectiveness of N components in resource utilization. The adjustment strategy for the Optimized scenario (PCA) recommends consolidating farm sizes for all livestock production systems, as N loss intensity decreases with increasing farm size (Fig. 3). However, excessively large farm sizes may lead to diminishing net profits or pose the risk of manure accumulation, so maintaining an optimal farm size is crucial for ensuring sustainable agricultural production. Under the PCA scenario, consolidation is recommended for farms that exceed the national average N loss intensity while falling below the corresponding optimal farm size. This approach avoids the risks associated with excessively large farms. Farm size consolidation is implemented at the county level to ensure practical feasibility, avoid cross-regional management complexities, and mitigate challenges associated with excessive livestock waste concentration. Detailed information on the adjustment scheme can be found in the Methods section.

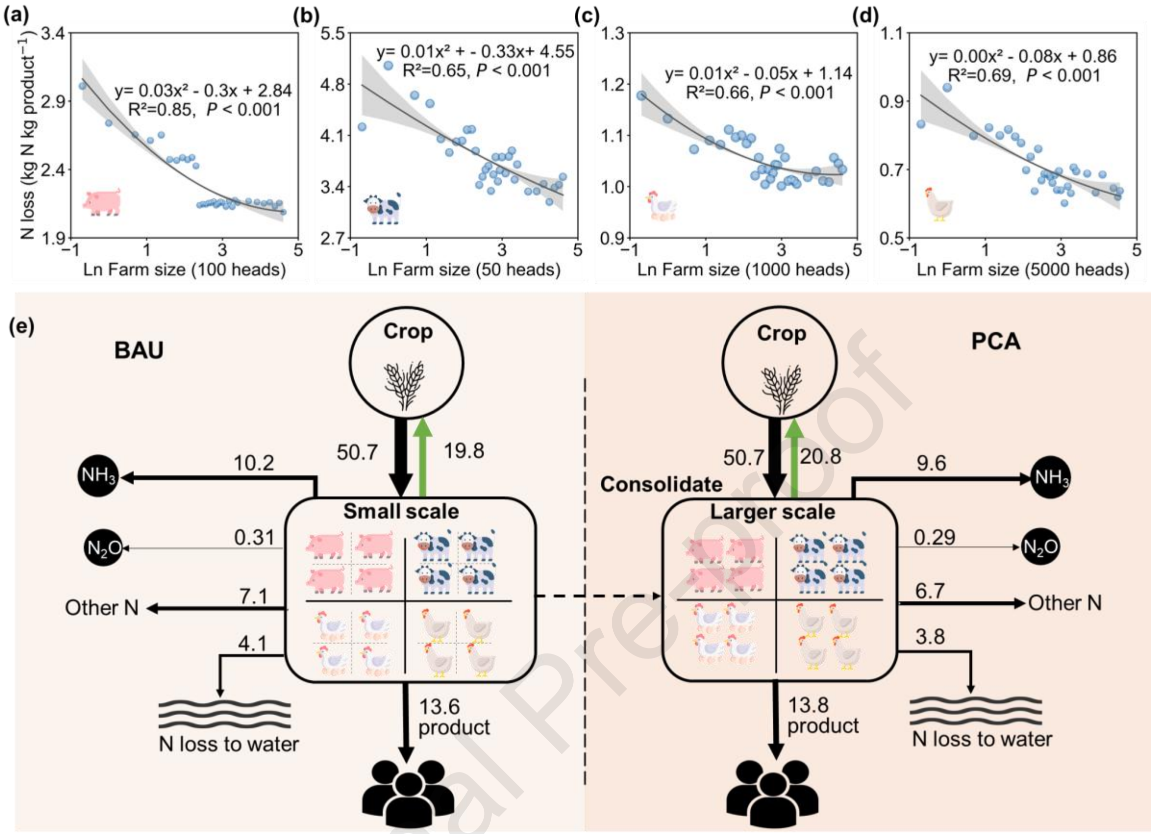

Figure 3. N losses in all livestock systems. a-d, the relationship between N loss intensity and farm size for pig, dairy cattle, layer and broiler chickens, respectively. N loss contains NH_3-N, N_2O-N, N loss to water and other N loss. The shaded area in a-b represents the 95% confidence interval. **e,** Adjusted strategy framework for all livestock. All numbers are in 10^8 kg N. BAU (business as usual) represents the baseline scenario before the consolidation of small-scale farms, whereas PCA represents the policy-constrained adjustment scenario after consolidation. The green line highlights the amount of manure returned to agricultural land, indicating enhanced and efficient manure recycling.

Based on the PCA scenario, implementing an adjusted farm size strategy would yield several benefits. With a constant feed N input, livestock N production would increase by 22 (14~29) Gg and manure N recycling to the field would rise by 100 (80~120) Gg, resulting in a 122 (109~134) Gg N reduction in N loss (Fig. 4). The reductions in NH_3, N_2O, N loss to water and other N losses would be 55, 2, 25, and 4 Gg N, respectively. Since the PCA scenario is implemented at the county level and adjusted only to the national average level, it adjusts just 16% of the intensive farms nationwide (Fig. S16). Nevertheless, this strategy would reduce national N loss by 6%, increase livestock N production by 2%, and improve manure recycling ratio by 5%. In the adjusted regions (Fig. 4), N loss would decrease by 24%, livestock N production would increase by 9%, and manure recycling would rise by 40%. The adjustment is most effective in the Central and Southern, Eastern, and Northeast regions, where N losses would be reduced by 52 Gg, 30 Gg, and 23 Gg, respectively, corresponding to reduction rates of 23%, 25%, and 24%. Among these, Henan and Guangdong provinces have the largest potential for N loss reduction, with reductions of 17 Gg and 15 Gg, respectively (Table S41). These regions, characterized by large and concentrated livestock populations, high population densities, and fragmented agricultural land, are particularly well-suited for farm size adjustment.

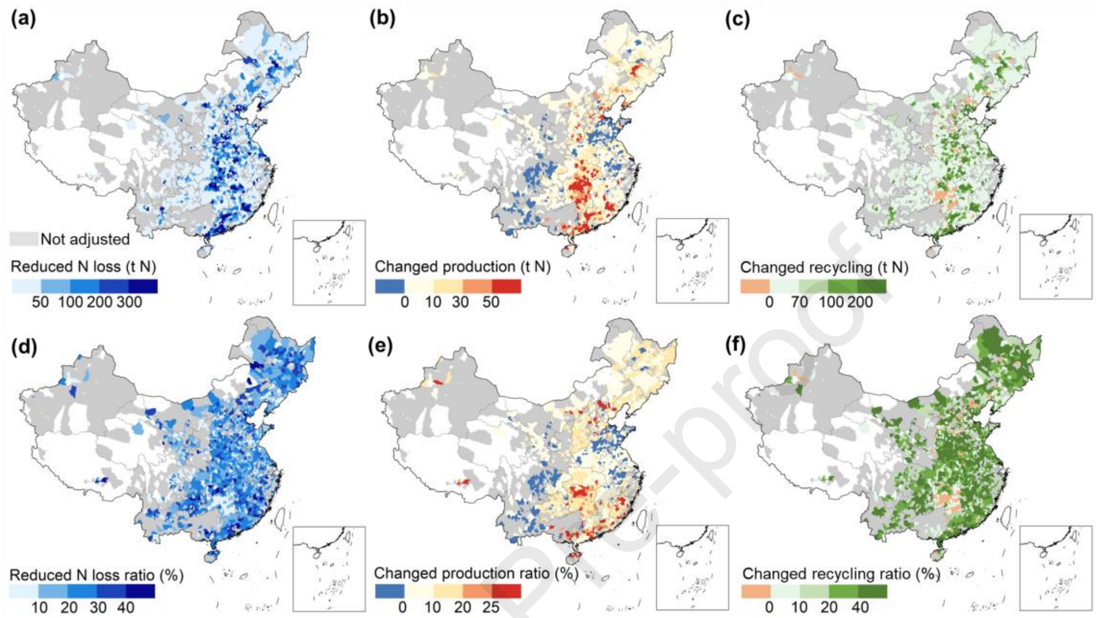

Figure 4. Changes of N losses, livestock production and manure recycle between BAU and Optimized (PCA) scenario. a-c, changes in N losses, livestock production and manure recycling under the PCA scenario. N losses include NH_3-N, N_2O-N, N loss to water, and Other N loss (including N_2, discarding N and manure utilized as fuel). Here, N_2 is also categorized as N loss. Livestock production refers to the total output of livestock products. Manure recycle denotes the amount of manure returned to agricultural land, including cropland and grassland. **d-f**, change ratio of N losses, livestock production and manure recycling under the PCA scenario. The shaded areas represent regions with livestock production but without adjustment. The base map was applied from the Database of Global Administrative Areas (GADM; https://gadm.org/).

Due to variations in livestock distributions, the adjustment areas vary notably among systems, primarily focusing on regions where small-scale livestock farming is predominant. For pig production, the PCA scenario could achieve the greatest N loss reduction (51 Gg, 19%). The adjustment is concentrated in the Eastern region (Fig. S17), where pig farming is predominant, but the farm sizes are relatively small (Fig. 1a), necessitating scientific consolidation. For dairy farming, the PCA scenario would lead to a smaller N loss reduction of 21 Gg (26%), while also increasing livestock production by 1.4 Gg (9%) and enhancing manure recycling by 19 Tg (41%). The adjustment area for dairy farming is relatively small, primarily in Northern regions (Fig. S18). For layer chicken production, adjustment is concentrated in the Central and Southern China region (Fig. S19), with reduction rates reaching 33%. In the case of broiler chicken production, adjustment primarily focuses on the Central and Southern China region (Fig. S20), where small farm sizes (Fig. 1c), low NUE (Fig. 1e), and low livestock output (Fig. S2d) prevail. Optimizing farm sizes in these regions could substantially enhance farming efficiency, reducing

N loss by 37%, while increasing livestock production by 22%, and improving manure recycling by 17%.

A comprehensive cost-benefit analysis was conducted to assess the feasibility and effectiveness of policy changes based on optimizing farm size. The cost analysis includes expenses related to dismantling old farms, constructing new ones, and the comparative difference in feed costs, newborn animal costs, fixed asset depreciation, labor, and other factors between the PCA and a "Business as Usual" (BAU) scenario (see Methods). The benefits of the PCA scenario encompass both economic and environmental aspects, including increased livestock product value and improvements in ecosystem, health, and climate. The cost-benefit analysis results show substantial economic and environmental benefits from implementing the PCA strategy. The total implementation cost was estimated at just 19 (14~25) million USD, while the benefits amounted to $1.7 (1.2~2.2) billion USD (Fig. 5). These ranges indicate variability around the central estimates, rather than precise point values. Moreover, the climate benefits considered in this analysis are limited to nitrogen-related emission changes and exclude CO_2 and CH_4 emissions. The pig production system has the highest abatement benefits with a net benefit of 1.2 billion USD. Optimizing farm size leverages scale effects, reducing rearing costs while simultaneously enhancing product output, yielding economic benefits of 0.9 billion USD. The PCA strategy for all livestock types results in improvements in environmental benefits, with ecosystem and health benefits increasing by 0.6 billion USD and 0.3 billion USD, respectively. However, one limitation of our assessment is that the climate benefits considered in this study are based solely on N loss reductions, while variations related to carbon emissions not accounted for. Overall, the cost-benefit analysis demonstrates that implementing PCA would be both economically and environmentally advantageous.

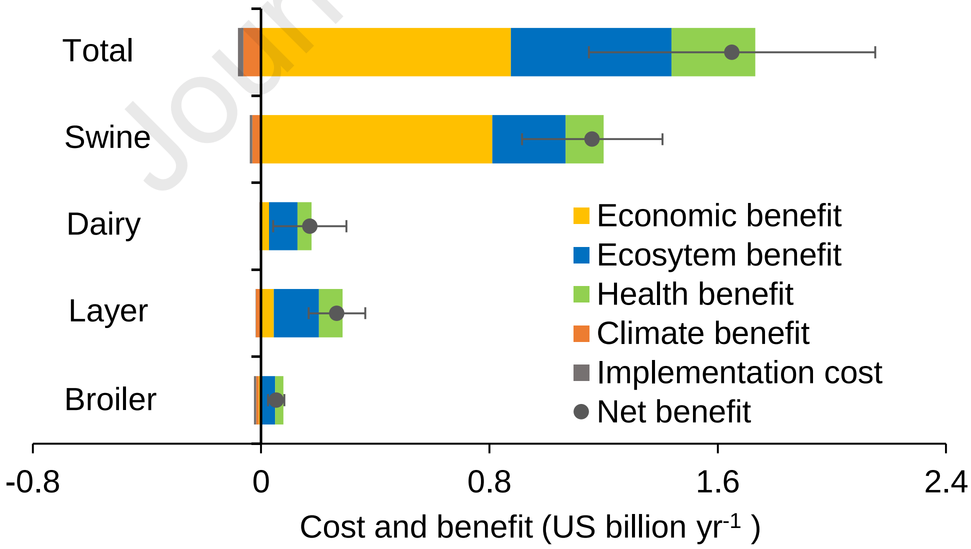

Figure 5. Costs and benefits for the PCA scenario. Data with error bars are presented as mean value with 95% confidence intervals. Economic benefits refer to the additional economic gains from increased production under the PCA scenario. Ecosystem, Health, and Climate benefits represent the benefits arising from reduced N emissions Implementation cost denotes the costs associated with consolidating small-scale farms. Net benefits are calculated as total benefits under the PCA scenario minus implementation costs.

3.5 Policy implications

As farm size increases, investments in machinery, technology, management, and disease control tend to rise (Fig. S11), enabling more scientific feed allocation and management (Hu and Yu, 2022; Wei et al., 2016). Such investments in technology and equipment are significantly negatively correlated with feed costs (Fig. S14), suggesting that technological upgrading contributes to lower input costs. Larger-scale operations generally rely on more advanced equipment and management systems, which can improve production efficiency, increase feed-use efficiency and labor productivity (Hu et al., 2017), and thereby reduce feed costs while releasing labor constraints (Fig. S12).These findings directly address the research question by demonstrating that improvements in NUE and reductions in N loss intensity are driven by scale-associated gains in management and technology, rather than farm size expansion alone. The key to expanding farm size lies in replacing manual labor with mechanization to improve productivity and profits (Wang et al., 2016) (Fig. S13). Thus, policies promoting biogas and composting initiatives are more effective for medium and large-scale farms, where knowledge of these practices is higher (Hu et al., 2022), as smaller farms typically have lower levels of policy awareness (Kuhn et al., 2020). Additionally, the state tends to subsidize medium and large farms to support specialized livestock and waste management facilities, increasing productivity and reducing pollution (Pan et al., 2016). Entrepreneurial decision-making is critical for resource allocation and the adoption of innovative solutions, enabling farms to better adapt to market demands and environmental challenges (Burton, 2014). However, excessive investment in machinery and infrastructure can lead to inefficiencies, including wasted productivity and lower cost efficiency (Xiaoxia, 2020), underscoring the importance of regions developing an optimal scale based on local advantages. This reinforces the conclusion of this study that environmental and economic benefits arise not from unlimited scale expansion, but from achieving an appropriate farm size that balances efficiency gains with management complexity and local resource constraints. Regions scale pathways aligned with their specific production conditions, institutional capacity, and development stage.

Effective disease management is crucial, as the cost of prevention is markedly lower than the economic losses, treatment expenses, and mortality costs associated with outbreaks (Hu and Yu, 2022). Large-size farms often own higher levels of technical knowledge and invest more in management and disease control (Fig. S11), and advanced manure processing technology also helps mitigate pollution and environmental risks (Kaufmann, 2015). Government policies typically offer subsidies to larger farms, encouraging the establishment of standardized operations that meet higher environmental health standards and undergo stricter regulatory oversight (Pei et al., 2021). Furthermore, large-size farming tends to focus on animal welfare by providing safer and more controlled housing conditions s to enhance animal health and product quality (Hu and Yu, 2022). However, due to their density and concentration, large-size farms are vulnerable to significant losses if faced with highly contagious diseases like avian flu, which may impact a wide area (Liu et al., 2020; Piao et al., 2024). Though the farm size itself is not the cause of disease outbreaks, the potential for large losses becomes more apparent. To combat pathogens effectively, large farms require advanced monitoring and disinfection (Hu et al., 2017), which involves substantial costs. Accordingly, scaling up livestock production must be accompanied by robust biosecurity and animal welfare safeguards, including strict disinfection protocols, personnel management, adequate space allocation, safe disposal of diseased animals and integrated waste treatment systems (Chadwick et al., 2020).

Implementing farm size management necessitates coordinated engagement across stakeholders. Government agencies should actively promote cooperative models and provide both policy and financial support to facilitate the transition from small-size to larger-size livestock farming. Target policies are required to support displaced smallholder farmers through employment transition programs and social safety nets (Pan et al., 2016). Concurrently, large-scale farms need stricter oversight and policies that support efficient manure use, transport, and application to arable lands (Feng et al., 2023). However, manure recycling also entails potential health and environmental risks, including pathogen transmission, nutrient runoff, and groundwater contamination, if manure is improperly treated or applied. Addressing these risks is therefore a prerequisite for sustainable scaling. For operators of larger farms, investment in technical capacity building and the adoption of best management practices are critical to ensure that scaling up yields both environmental and socioeconomic benefits (Chadwick et al., 2015).

While structural adjustment and the expansion of large-size farms can enhance productivity and environmental outcomes, such strategies must be accompanied by inclusive transition mechanisms to prevent the marginalization smallholders (Berdegué et al., 2025). Beyond policy design, the social and institutional feasibility of farm size management warrants careful consideration. Consolidation may lead to the displacement or exit of small-scale farmers who lack capital, access to credit, or the capacity to comply with increasing technical and regulatory requirements, potentially exacerbating rural inequality if not adequately managed (Hazell et al., 2010). At the same time, effective implementation of coordinated consolidation requires substantial governance capacity, including cross-sectoral coordination, monitoring, and enforcement, which may vary considerably across regions (Pretty et al., 2018). Differences in local administrative capacity, infrastructure, market access, and extension services further imply that the feasibility and outcomes of farm size management are likely to be spatially heterogeneous. Consequently, policy approaches should be adapted to regional conditions and institutional readiness, rather than assuming uniform implementation potential. To promote equitable participation, we propose several policy instruments to promote equitable participation: (1) Incentivizing cooperatives and contract-based partnerships to enable shared manure management and resource utilization (Shi et al., 2023); (2) Expanding training and extension services to improve smallholders' access to circular agriculture technologies (Jin et al., 2021). Enhancing livestock N efficiency and environmental performance should not come at the expense of rural social stability. Policies must be designed to align environmental goals with social equity, ensuring that vulnerable stakeholders are supported throughout the transition toward adjusted farm structures.

The inclusion of N_2 in total nitrogen loss follows a mass-balance and NUE perspective commonly applied in livestock systems (Oenema et al., 2006; Neysari et al., 2023), in which N loss is defined as nitrogen no longer available for productive use. From this perspective, N_2 represents a terminal loss of nitrogen from the agro-food system that reduces NUE, although it does not cause direct environmental harm. Accordingly, the aggregation of different nitrogen pathways into a single N loss intensity indicator is intended to reflect system-level nitrogen efficiency rather than equivalent environmental impacts. Reactive nitrogen forms (e.g., NH_3, N_2O, and nitrate) have well-documented environmental consequences, whereas N_2 is environmentally benign. Therefore, reductions in total N loss should not be interpreted as proportional reductions in environmental damage, and potential trade-offs among nitrogen loss pathways should be considered when interpreting mitigation outcomes.

It is important to clarify that emphasizing farm size in this study does not imply that scale expansion or further intensification should be regarded as a desirable mitigation strategy. From a planetary health perspective, recent literature highlights that efficiency gains alone are insufficient to reduce environmental pressures without constraints on aggregate production (Willett et al., 2019) (Clark et al., 2020). Accordingly, the PCA scenario is designed as a benchmark-based, policy-constrained adjustment rather than a formal adjustment in the strict sense. It focuses on consolidating excessively small farms toward a farm size associated with the national average N loss intensity, which serves as a pragmatic policy reference reflecting prevailing regulatory norm, rather than a theoretical system optimum. In this context, farm size should be interpreted as a structural proxy capturing a suite of co-varying factors, including capital intensity, access to technology, management capacity, regulatory compliance, and spatial organization, rather than as a purely causal management variable (Herrero et al., 2020). The observed relationships between larger farm size, higher NUE, and lower N loss intensity therefore reflect the combined effects of these underlying factors, such as improved feeding practices, manure management infrastructure, and environmental control technologies, rather than farm size alone. Importantly, environmental benefits arise when structural consolidation is accompanied by appropriate technological, managerial, and institutional support (Pretty et al., 2018). Farm size should thus be viewed as an emergent characteristic of broader system-level transformations, rather than a standalone policy lever for nitrogen mitigation.

The data presented in this study primarily focus on intensive farms, rather than traditional backyard livestock farms, which hold even greater potential for management. In 2017, traditional farming still accounted for a substantial portion of livestock farming, with the products of backyard livestock comprising 55% of the total. For instance, backyard pig production represented 59% of the overall pig production, a significantly higher percentage than in advanced countries like America (Robinson et al., 2014), where it is just 2%. Traditional farming practices generally lack modern manure treatment equipment, resulting in inefficient manure storage with higher N losses. However, due to the limited available data on traditional farms, this study was unable to comprehensively analyze the N loss on traditional farms. The second pollution census of traditional livestock data is only available at the county level, posing constraints on conducting the extensive analysis. Moreover, the adjustment strategy in this study focused on county boundaries, without considering adjustment between countries and within regions, which may limit the potential for N loss reduction. However, this strategy remains viable and beneficial as it enhances resource allocation within counties, reduces transportation costs, mitigates the risk of cross-regional pollution transfer, and guarantees a stable supply of local livestock products. Meanwhile, the adjustment strategy focused on county boundaries can help avoid the issue where excessive manure production in a particular area may exceed the capacity of surrounding agricultural land to absorb.

3.6 Limitations

This study relies on questionnaire-based information from the national pollution census, which involves large-scale manual reporting and may introduce reporting or estimation uncertainty, particularly for manure management practices and their relative proportions (Table S3). While these data reasonably capture overall patterns and trends in livestock management, uncertainty remains at the individual-farm level; this limitation is addressed through uncertainty analysis to enhance the robustness of the results. The assumption of constant total feed N input between the BAU and PCA scenarios is a deliberate constraint designed to isolate the effects of structural consolidation and efficiency improvement from changes in aggregate production or market dynamics. In addition, restricting consolidation to the county level reflects administrative feasibility and likely results in conservative estimates of mitigation potential, as cross-county reallocation could further reduce N losses but faces institutional barriers. Together, these assumptions frame the PCA scenario as a realistic policy benchmark, and the results should be interpreted as achievable improvements under current governance conditions rather than upper-bound mitigation potentials. Moreover, this study focuses on nitrogen flows and does not explicitly account for co-existing contaminants in livestock manure, such as antibiotics or heavy metals, which may interact with nitrogen management and pose additional environmental risks. Addressing these co-contaminants would require additional data and modeling frameworks beyond the scope of this study, but represents an important direction for future research.

4. Conclusion

In this study, we found that increasing farm size substantially improved NUE and decreased N loss intensity across all livestock categories, while the manure N recycled varies between different livestock types. While increasing farm size could enhance feed utilization efficiency, it also poses certain risks, such as increasing the spatial mismatch between cropland areas and livestock. Hence, pursuing farm size expansion without an underlying strategy is not advisable. Instead, it is imperative to develop an adjusted approach based on a comprehensive analysis of N utilization characteristics and N emission features for each specific livestock category. Optimizing farm size according to the N loss intensity function, which is derived from the regression relationship between N emissions and farm size, could achieve a synergistic improvement by combining reduction in N losses, increased production, and enhanced manure N recycling ratios. We emphasize the importance of assessing N utilization indicators while considering food security and environmental protection to optimize farming levels in each region. Furthermore, livestock farm size is constrained by natural and economic factors, showing an inverted U-shaped relationship with cropland farm size. Therefore, promoting an appropriate farm size should be tailored to local conditions and aligned with the corresponding cropland farm size to foster sustainable agricultural development.

Data availability

Data supporting the findings of this study are available within the article, a separate source data file and its supplementary information files. Any additional data required for reanalysis are available from the corresponding author upon reasonable request.

Declaration of competing interest

All authors have no conflicts of interest to report.

Supporting Information

The Supporting Information is available.

Supplementary Methods of statistical analysis, Supplementary Discussion of intrinsic mechanism of farm size impacting on livestock production and environmental performances, and additional figures and tables mentioned in the text (PDF). Supplementary Data of uncertainty results analysis and unit livestock farm demolition cost in Dataset (XLSX).

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Highlights:

1. Livestock NUE rises and N loss intensity decreases with farm size.
2. Manure recycling ratios vary with farm size across different livestock types.
3. Optimizing farm size for 16% of intensive farms could reduce N losses by 1.2 Tg.
4. Farm size optimization improves societal and environment benefits.

Declaration of Interest Statement

☒ 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.

☐ The author is an Editorial Board Member/Editor-in-Chief/Associate Editor/Guest Editor for this journal and was not involved in the editorial review or the decision to publish this article.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: