Pol. J. Environ. Stud. Vol. XX, No. X (XXXX), 1-22
DOI: *10.15244/pjoes/221414* ONLINE PUBLICATION DATE: 2026-09-18

Original Research

A Study on the Carbon Emission Reduction Effects and Spatial Heterogeneity of Livestock Manure Fertilizer Substitution Driven by the Rural Revitalization Strategy in China

Qi Qi*

Party School of Liaoning Provincial Party Committee, Shenyang, 110004, China

Received: 08 February 2026
Accepted: 04 May 2026

Abstract

Promoting manure-based fertilizer substitution is important for nutrient recycling and agricultural carbon mitigation under China's Rural Revitalization Strategy and dual-carbon agenda. Using provincial panel data for 31 provinces in mainland China from 2017 to 2024, this study develops an integrated framework to estimate livestock manure resources, manure-borne nutrient supply, and the technical carbon-mitigation potential of mineral fertilizer substitution. Dagum Gini decomposition, global Moran's I, and a Spatial Durbin Model are used to examine inequality, spatial dependence, and driving factors. Results show that national manure resources and nutrient supply followed a decline–rebound pattern, while carbon-mitigation potential increased after 2019 and remained relatively high. Interprovincial inequality was moderate to high, and mitigation outcomes exhibited significant positive spatial dependence. Manure resource intensity was the main local driver of mitigation, whereas the effects of fertilizer intensity and mechanization showed clear regional heterogeneity. By linking nutrient cycling with carbon mitigation in a spatial framework, this study provides evidence for differentiated regional policies on manure resource utilization in China.

Keywords: livestock and poultry manure, nutrient supply, mineral fertilizer substitution, carbon-mitigation potential, Dagum Gini decomposition, spatial autocorrelation, Spatial Durbin Model

Introduction

Livestock production provides essential foods such as meat, eggs, and dairy, but it also generates massive quantities of manure every year. When improperly managed, livestock manure becomes a major source of agricultural non-point pollution, posing serious threats to air, water, and soil environments [1]. Its adverse impacts include increased greenhouse gas (GHG) emissions, land degradation, eutrophication of water bodies, and public health risks [2]. Evidence suggests that in low- and middle-income countries, pollution associated with livestock waste has become an important contributing factor to gastrointestinal diseases among rural residents [3]. Therefore, the safe handling and effective utilization

*e-mail: wuxiaorui1995@126.com

of livestock manure have emerged as a critical bottleneck for advancing green agricultural development and strengthening environmental governance.

At the same time, livestock manure is rich in organic matter as well as key nutrients, and thus represents a valuable agricultural resource [4]. A growing body of research shows that, after appropriate treatment, manure can partially replace mineral fertilizers as a nutrient source for crop growth and can also be converted into clean energy through technologies such as anaerobic digestion [5]. For example, biogas produced by co-digesting livestock manure with crop residues can be used for rural cooking and electricity generation, reducing the consumption of firewood and coal while lowering direct methane emissions and reducing dependence on fossil energy [6]. In this sense, transforming livestock manure from “waste” into “resource” is of substantial significance for improving agro-ecological quality and promoting circular nutrient use [7]. This approach is also closely aligned with the goals of China’s Rural Revitalization Strategy, particularly those related to ecological livability and green development [8]. The Chinese government has attached great importance to manure resource utilization. It has treated this issue as a key component of rural environmental remediation and sustainable agricultural policy, and has issued a series of policy documents to promote implementation [9]. According to the Ministry of Agriculture and Rural Affairs, the national comprehensive utilization rate of livestock manure reached 75% by 2020 [6]. However, as the world’s largest producer of livestock products, China still faces considerable environmental pressure due to the enormous annual volume of manure generated. The government has set a target of increasing the manure resource utilization rate to 80% by 2025, yet substantial efforts are still required to achieve this goal [3]. Therefore, under the Rural Revitalization Strategy, accelerating the harmless treatment and resource-oriented utilization of livestock manure is of great practical importance. It can improve rural living environments, support the green transition in agriculture, and promote the development of a circular rural bioeconomy.

Manure resource utilization is also closely connected to China’s “dual-carbon” targets [10]. Agricultural activities constitute an important source of GHG emissions, and methane (CH_4) and nitrous oxide (N_2O) emissions arising from enteric fermentation and manure management exert particularly pronounced climate impacts [11]. It has been estimated that the global food system contributes roughly one-third of anthropogenic GHG emissions, and emissions associated with livestock products are approximately twice those from plant-based foods [12]. Livestock production plays a pivotal role in agricultural and rural GHG mitigation. It accounts for about half of the technical mitigation potential in the land-use sector. Emissions can be reduced through sustainable husbandry practices, enhanced grassland carbon sequestration, and improved manure management [13]. Some studies have emphasized that accelerating cleaner production in the livestock sector and strengthening manure emission reduction are crucial for achieving China’s strategic targets of peaking carbon emissions by 2030 and reaching carbon neutrality by 2060 [14, 15]. More specifically, promoting manure nutrients as substitutes for mineral fertilizers represents an important mitigation pathway in agriculture [16]. On the one hand, the use of organic fertilizers can reduce reliance on the energy-intensive production of synthetic fertilizers, thereby lowering CO_2 emissions at the source. On the other hand, organic amendments can improve soil nutrient use efficiency and reduce N_2O emissions following fertilizer application [17]. Research indicates that in double-cropping rice systems and similar settings, partial substitution of mineral fertilizers with organic fertilizers can reduce soil N_2O emissions by approximately 70% [18]. Moreover, improved manure treatment and utilization can directly curb methane leakage during manure storage and stockpiling. For example, anaerobic digestion of manure not only avoids direct methane emissions but also produces renewable energy. Data show that by 2018 China had built nearly 40 million biogas projects of various scales, generating more than 11 billion cubic meters of biogas annually for cooking, electricity generation, and heating[6]. Biogas utilization helps mitigate GHG emissions, substitutes for part of fossil fuel consumption, and enables effective treatment of livestock manure and crop residues. Therefore, manure resource utilization has substantial potential for agricultural emission reduction and carbon sequestration. Recent carbon-assessment studies also suggest that evaluating mitigation-related outcomes at broader spatial scales requires appropriate modeling frameworks and careful attention to spatial heterogeneity and data quality. For example, Drygval et al. assessed organic carbon stocks at the landscape level using the InVEST model and highlighted the importance of spatial scale, temporal coverage, and input-data quality in carbon-related evaluations [19]. This potential extends from fertilizer substitution to bioenergy development. It is therefore widely regarded as a key pathway for advancing the “dual-carbon” agenda in agriculture and rural areas.

Over the past five years, research and practice related to livestock manure resource utilization have advanced rapidly both domestically and internationally. Globally, there is growing consensus that “manure should no longer be treated as waste but as a resource,” and the concepts of circular agriculture and the bioeconomy have gained traction [20]. Many studies have focused on diversified technologies and models for manure utilization. For example, livestock manure can be combined with urban organic wastes to produce biomethane and organic fertilizers, thereby linking energy generation with nutrient cycling [21]. Common approaches include composting, anaerobic digestion, solid–liquid separation, land application of digestate, and nutrient recovery technologies. For example, recovering phosphorus from livestock wastewater via chemical precipitation to produce struvite fertilizer is considered an advanced option for improving nutrient recycling efficiency. Meanwhile, governments in many countries are establishing incentive policies and regulatory frameworks to facilitate the safe circulation of manure-derived fertilizer products as market commodities. Under the dual drivers of policy and technological innovation, manure resource utilization rates in developed countries have increased markedly in recent years, and some regions have achieved near-zero discharge with full return-to-land use. Developing countries are also drawing on these experiences to explore locally appropriate circular agriculture models. The literature widely emphasizes that efficient manure nutrient recycling requires coordinated efforts across technological, economic, social, and policy dimensions. Karakulov et al. showed that the adoption of climate-smart technologies can simultaneously improve yields, farm income, and resource-use efficiency, while also supporting environmentally sustainable agricultural development, highlighting the importance of integrated policy, technology, and management interventions [22]. Sadeghpour et al. comprehensively reviewed the critical role of livestock manure in the circular economy, highlighting major recent progress in technologies for producing fertilizers and energy from manure, as well as policy initiatives encouraging manure return-to-land and bioenergy utilization [23]. Notably, some researchers have proposed incorporating manure-related emission reductions into market-based mechanisms such as carbon trading, using carbon-credit incentives to further stimulate manure resource utilization [23]. In terms of nutrient cycling efficiency, the intensification and regional concentration of livestock production have increasingly led to the decoupling of crop and livestock systems, making it difficult to utilize manure locally and resulting in declining nutrient use efficiency. Consequently, an expanding body of research advocates re-integrating cropping and livestock production and strengthening nutrient balance management at regional scales. Some estimates suggest that more than 90% of cropland nutrients in China came from organic fertilizers in the 1950s, whereas mineral fertilizers dominate today. Given the still-low manure utilization rate, stronger crop–livestock integration is needed to improve nutrient recycling efficiency [24]. In China, since launching the national action plan for manure resource utilization in 2017, the government has invested heavily in manure treatment facilities and socialized service systems nationwide, promoting nearby and local land application of livestock waste [2]. Many studies evaluating these measures report that pollution emission intensities from livestock manure have declined in recent years, and that policy-driven adoption of supporting manure treatment infrastructure among large-scale farms has increased substantially. Meanwhile, field experiments and modeling studies have expanded to explore how to further enhance fertilizer substitution effects and reduce GHG emissions. Related field evidence also shows that organic amendments can generate persistent agronomic and soil-quality benefits. Wijitkosum et al. reported that a one-time application of biochar, either alone or combined with compost, improved soil properties and maize yield across five consecutive cultivation cycles, suggesting that organic inputs can provide sustained support for nutrient retention and crop performance [25]. For instance, He et al. analyzed 137 experimental sites worldwide and found that replacing mineral fertilizers with organic fertilizers can significantly reduce soil N_2O emissions. However, such substitution may increase CH_4 emissions in anaerobic environments such as paddy fields. Therefore, organic fertilizer types and substitution rates should be optimized to avoid increasing overall warming effects [17]. Overall, existing research has explored manure resource utilization from engineering technologies and management models to policy mechanisms. This body of work provides robust scientific support for reducing agricultural waste and promoting resource recycling, and it also indicates the considerable potential of manure resource utilization to improve nutrient use efficiency, reduce mineral fertilizer use, alleviate environmental pollution, and advance rural sustainable development. However, most of this literature either emphasizes resource accounting and utilization performance or focuses on emission outcomes alone, without jointly examining substitution-based carbon mitigation and its spatial heterogeneity at the national scale.

Despite substantial progress in the literature, important gaps remain in existing national-scale assessments. Most previous studies have focused on manure generation, nutrient-resource accounting, agricultural emissions, or policy evolution separately. Although these studies provide valuable evidence on manure utilization and environmental performance, they rarely integrate manure resource endowment, manure-borne nutrient supply, and the carbon-mitigation potential of mineral fertilizer substitution within a single analytical framework. In addition, national-scale evidence remains limited on how such mitigation potential varies across provinces, how large the resulting regional disparities are, and whether these differences are shaped by spatial dependence and spillover effects. As a result, the nationwide mitigation contribution of manure-based fertilizer substitution and its spatially differentiated policy implications are still not fully understood.

To address these gaps, this study uses provincial panel data for 31 provinces in mainland China from 2017 to 2024 and makes three main contributions. First, it moves beyond separate assessments of manure resources or agricultural emissions by integrating manure generation, manure-borne nutrient supply, and carbon-mitigation potential from mineral fertilizer substitution into one unified framework. Second, it goes beyond aggregate national accounting by identifying interprovincial inequality and spatial clustering through

Dagum Gini decomposition and Moran's I. Third, it extends existing national-scale assessments by applying a Spatial Durbin Model to reveal both local drivers and spatial spillover effects of manure-based fertilizer substitution. By linking nutrient cycling with carbon mitigation in a spatially explicit framework, this study provides new evidence for region-specific policies under China's Rural Revitalization Strategy and dual-carbon agenda.

Data Sources and Methods

Study Area and Data Sources

This study covers 31 provincial-level administrative units in mainland China (provinces, autonomous regions, and municipalities) over the period 2017-2024. The study period begins in 2017 because this year marks an important policy turning point in China's nationwide promotion of livestock manure resource utilization. Therefore, the 2017-2024 window is particularly suitable for examining the recent evolution of manure-based fertilizer substitution and carbon-mitigation potential under the combined context of the Rural Revitalization Strategy and the strengthening of green agricultural policies. All data were obtained from official and publicly available statistical sources in China. Livestock data, including the stocks and slaughter numbers of major livestock and poultry categories, were collected from the China Rural Statistical Yearbook (2018–2025 editions). Crop production data, mainly crop planting areas, were obtained from the China Statistical Yearbook (2018–2025 editions). Other coefficients required for indicator accounting were taken from authoritative domestic and international studies and are reported with citations in the subsequent calculation steps (Table 1).

Accounting for Livestock Manure, Nutrient Resources, and Carbon Mitigation Potential

In terms of accounting boundary and objects, the total livestock manure resource in this study refers to the annual amount of manure excreted by major livestock and poultry categories in each province, measured on a fresh-weight basis. The nutrient resources refer to the contents of nitrogen (N), phosphorus (P), and potassium (K) contained in the above manure, quantified as pure nutrients. The carbon-mitigation potential refers to the avoided carbon emissions from mineral fertilizer production and application under a nutrient-equivalent substitution scenario, in which recoverable manure nutrients are assumed to substitute the same amounts of mineral fertilizer nutrients. This scenario is intended to measure the technical potential or upper-bound mitigation space of manure-based fertilizer substitution, rather than the actually realized mitigation under current logistical, behavioral, and agronomic constraints. To ensure consistency across provinces and years, all nutrient contents and emission factors were converted and expressed in terms of N, P_2O_5, and K_2O, and the same accounting conventions were applied throughout the interprovincial and intertemporal comparisons.

Total Manure Resource

The total manure resource was estimated based on livestock and poultry populations and corresponding manure generation coefficients. Let i denote province, t denote year, and s denote livestock type. The major livestock and poultry categories considered in this study include cattle, horses, donkeys, mules, pigs, sheep, and poultry. The total manure excretion in province i and year t, denoted as M_{it}, can be expressed as the sum over livestock types:

$$M_{it} = \sum_{s} (C_{its} \times d_s \times h_s) \tag{1}$$

where M_{it} is the total livestock manure resource (t); C_{its} is the population of livestock type s in province i and year t (10^4 head or 10^4 birds); d_s is the daily manure excretion of livestock type s ($kg \cdot d^{-1}$); and h_s is the feeding (raising) cycle of livestock type s (days).

Nutrient Resources

Nutrient resources were calculated by linking manure production to nutrient content coefficients. Let

Table 1. Feeding cycle, daily manure excretion, and nutrient contents of different livestock categories[27].

Livestock type	Feeding cycle (days)	Daily excretion (kg/day)	N (%)	P (%)	K (%)
Cattle	300	18.00	0.38	0.10	0.23
Horse	365	10.20	0.44	0.13	0.38
Donkey	365	8.56	0.49	0.19	0.54
Mule	365	8.56	0.31	0.16	0.23
Sheep	365	2.00	1.01	0.22	0.53
Pig	180	2.44	0.55	0.25	0.30
Poultry	55	0.12	1.03	0.37	0.72

θ_s^N, θ_s^P, and θ_s^K denote the unit content coefficients of N, P, and K in manure from livestock type *s*, respectively. Then the N, P, and K nutrient resources in province *i* and year *t* can be estimated as:

$$N_{it} = \sum_s (Q_{its} \cdot \delta_s) \cdot \theta_s^N \tag{2}$$

$$P_{it} = \sum_s (Q_{its} \cdot \delta_s) \cdot \theta_s^P \times 2.29 \tag{3}$$

$$K_{it} = \sum_s (Q_{its} \cdot \delta_s) \cdot \theta_s^K \times 1.20 \tag{4}$$

To ensure consistency with mineral fertilizer substitution accounting, phosphorus and potassium were converted into effective nutrient amounts expressed as P_2O_5 and K_2O. Specifically, 2.29 is the conversion factor from elemental P to P_2O_5, and 1.20 is the conversion factor from elemental K to K_2O [26]. In the above equations, Q_{its} denotes the livestock quantity basis used in the calculation, and δ_s represents the corresponding conversion factor used to align the livestock quantity with annual manure production for type *s*.

Carbon Mitigation Potential from Mineral Fertilizer Substitution

This study treats manure recycling as a nutrient-equivalent substitution scenario for mineral fertilizer nutrients. Specifically, the pure nutrients N, P2O5, and K2O contained in manure are assumed to replace the same amounts of effective nutrients in nitrogen, phosphate, and potash fertilizers, respectively. This assumption is used to construct a standardized technical-potential benchmark, rather than to imply that full substitution is achieved in practice. In reality, the extent of substitution may be constrained by manure collection and transport costs, farmer adoption, treatment capacity, and spatial mismatches between manure supply and cropland nutrient demand. The emission factors for N, P, and K fertilizers are set to 2.116, 0.636, and 0.180, respectively [27]. Therefore, the carbon mitigation potential in province *i* and year *t*, denoted by ER_{it}, can be calculated as:

$$ER_{it} = N_{it} \times 2.116 + P_{it} \times 0.636 + K_{it} \times 0.180 \tag{5}$$

where ER_{it} represents the carbon mitigation potential. This accounting framework reflects the marginal contribution of "substitution as mitigation" under the technical-potential scenario: each additional unit of recoverable manure nutrient, if used to substitute an equivalent unit of mineral fertilizer nutrient input, avoids the corresponding carbon emissions generated during mineral fertilizer production, transportation, and application.

Dagum Gini Decomposition and Identification of the Sources of Regional Disparities

This study measures interprovincial inequality in carbon-mitigation potential and decomposes its sources. The aim is to reveal the extent of spatial imbalance and its structural determinants in China's livestock-manure fertilization pathway. Although the conventional Gini coefficient can quantify the magnitude of overall inequality, it cannot clearly distinguish whether such inequality mainly stems from within-region differences or between-region differences. Moreover, when regional distributions overlap, standard decomposition approaches may lead to interpretational bias. Therefore, this study adopts the Dagum Gini coefficient and its decomposition framework, which allows for distributional overlap and rigorously decomposes overall inequality into three components: within-region inequality, net between-region inequality, and transvariation intensity [28]. This structured decomposition helps identify the dominant contributors to overall inequality and provides a basis for subsequent heterogeneity analysis and policy discussion.

The inequality object is provincial carbon mitigation potential. Let CE_{it} denote the carbon mitigation potential in province *i* in year *t*, *n* the number of provinces, and μ_t the national mean of CE_{it} in year *t*. The overall Dagum Gini coefficient in year *t* is defined as:

$$G_t = \frac{1}{2n^2\mu_t} \sum_{i=1}^{n} \sum_{j=1}^{n} | CE_{it} - CE_{jt} | \tag{6}$$

This index captures the relative dispersion of provincial carbon mitigation potential normalized by the national mean; a larger value indicates greater interprovincial inequality. To examine dynamic evolution, this study computes G_t annually and further decomposes it to identify how the sources of inequality change over time.

To enhance the structural and policy relevance of inequality interpretation, the 31 provinces are grouped into three macro-regions-eastern, central and western China. Suppose the sample is partitioned into *K* regional groups. Group *k* contains n_k provinces and has group mean μ_{kt}. Then the overall Gini coefficient can be decomposed as:

$$G_t = G_{wt} + G_{nbt} + G_{tt} \tag{7}$$

where G_{wt} denotes the contribution of within-region inequality, G_{nbt} the contribution of net between-region inequality, and G_{tt} the contribution of transvariation intensity. Within-region inequality reflects the average disparity among provinces within the same region. It is computed by first obtaining the within-group Gini coefficient for each region and then aggregating them using weights that account for regional size and mean level. The within-group Gini coefficient for region *k* is:

$$G_{kt} = \frac{1}{2n_k^2\mu_{kt}} \sum_{i\in k} \sum_{j\in k} | CE_{it} - CE_{jt} | \quad (8)$$

Accordingly, the within-region contribution is:

$$G_{wt} = \sum_{k=1}^{K} \left(\frac{n_k\mu_{kt}}{n\mu_t} \right) G_{kt} \quad (9)$$

where the weight $\frac{n_k\mu_{kt}}{n\mu_t}$ jointly reflects the region's population share (number of provinces) and its mean mitigation level relative to the national total, ensuring comparability and additivity of regional contributions to overall inequality.

In the Dagum framework, between-region inequality is further decomposed into net between-region inequality and transvariation intensity. Net between-region inequality captures the separable differences in mean levels and relative positions across regions, whereas transvariation intensity captures the additional inequality generated by distributional overlap between regions. To implement this split, the cross-group inequality between any two regions k and h is first calculated. The between-group Gini coefficient is defined as:

$$G_{kht} = \frac{1}{n_k n_h(\mu_{kt} + \mu_{ht})} \sum_{i\in k} \sum_{j\in h} | CE_{it} - CE_{jt} | \quad (10)$$

Dagum's method further introduces a relative impact coefficient D_{kbt} to measure the degree of overlap and net dominance between the two regional distributions. Intuitively, when the distributions of two regions overlap less and the disparity is largely attributable to differences in overall levels, D_{kbt} tends to be larger and the between-region inequality is primarily explained by the net difference. Conversely, when the distributions overlap substantially and mean gaps alone cannot explain the disparity, D_{kbt} tends to be smaller and the contribution of transvariation intensity increases. Accordingly, net between-region inequality and transvariation intensity can be expressed as:

$$G_{nbt} = \sum_{k=1}^{K} \sum_{h=1, h\neq k}^{K} \frac{n_k n_h(\mu_{kt} + \mu_{ht})}{2n^2\mu_t} G_{kht}\, D_{kht} \quad (11)$$

$$G_{tt} = \sum_{k=1}^{K} \sum_{h=1, h\neq k}^{K} \frac{n_k n_h(\mu_{kt} + \mu_{ht})}{2n^2\mu_t} G_{kht}\, (1 - D_{kht}) \quad (12)$$

This decomposition enables not only the quantification of overall inequality, but also a structured interpretation of whether inequality is dominated by within-region disparities or net between-region gaps, and how much is attributable to distributional overlap (transvariation). In turn, it provides more informative evidence for understanding the mechanisms behind the spatial disparities in carbon mitigation potential from livestock manure fertilization.

Spatial Autocorrelation Analysis

To test whether the carbon mitigation potential generated by livestock manure fertilization exhibits spatial clustering or dispersion across provinces, this study conducts a global spatial autocorrelation test at the provincial scale [29]. Global spatial autocorrelation measures the overall strength of spatial dependence in the study variable across the entire spatial domain and helps determine whether high (or low) values tend to co-occur in geographically adjacent areas. The results provide a statistical basis for whether a spatial econometric specification should be introduced and how such models should be formulated. Carbon-mitigation potential is strongly influenced by regional resource endowments. In addition, policy diffusion and factor mobility may induce cross-provincial linkages. Therefore, global spatial autocorrelation tests are used to identify spatial dependence more rigorously.

The spatial autocorrelation test is performed on provincial carbon mitigation potential in year t, denoted as ER_{it}. To maintain comparability across years and reduce scale effects, the global spatial autocorrelation index is computed using the mean-centered variable. Moran's I is adopted as the global indicator. Let n be the number of provinces, $\bar{ER}_t$ the sample mean in year t, w_{ij} the $(i\cdot j)$ element of the spatial weight matrix, and $S_0 = \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}$. Then the global Moran's I in year $t$is defined as:

$$I_t = \frac{n}{S_0} \cdot \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\,(ER_{it} - \bar{ER}_t)(ER_{jt} - \bar{ER}_t)}{\sum_{i=1}^{n}(ER_{it} - \bar{ER}_t)^2} \quad (13)$$

When I_t>0, carbon mitigation potential exhibits positive spatial autocorrelation, implying spatial clustering where high values are adjacent to high values and low values are adjacent to low values. When I_t<0, the pattern indicates negative spatial autocorrelation, i.e., spatial dispersion where high values tend to be adjacent to low values. When I_t is close to zero, there is no evident overall spatial dependence.

The spatial weight matrix $W = [w_{ij}]$ is used to characterize the interprovincial spatial linkage structure. The baseline specification adopts a geographic contiguity (adjacency) matrix: $w_{ij} = 1$ if provinces i and j share a common border, and $w_{ij} = 0$ otherwise, with $w_{ii} = 0$. To avoid incomparability caused by differences in the number of neighbors across provinces, the matrix is row-standardized so that the weights in each row sum to one. This ensures a consistent interpretation of spatial lag terms. Considering that spatial dependence may be sensitive to weight-matrix design, this study further employs an economic–geographic distance weight matrix as an alternative specification for robustness and comparison.

Spatial Durbin Model

Building on the global spatial autocorrelation tests, this study employs a Spatial Durbin Model (SDM) to identify the determinants and spatial spillover effects of carbon-mitigation potential associated with livestock manure fertilization [30]. The choice of SDM is motivated by both the research objective and the likely data-generating process. This study is concerned not only with whether mitigation outcomes in one province are affected by those in neighboring provinces, but also with whether neighboring provinces' explanatory variables – such as manure resource intensity, fertilizer input intensity, and agricultural development conditions – generate cross-provincial spillover effects. Compared with the SAR model, which mainly captures spatial dependence in the dependent variable, and the SEM model, which mainly addresses spatial correlation in the error term, the SDM allows both the spatial lag of the dependent variable and the spatial lags of explanatory variables to be estimated simultaneously. It is therefore more appropriate for examining the spatial transmission mechanisms underlying manure-based fertilizer substitution.

In addition, the preceding Moran's I results confirm significant spatial dependence in provincial carbon-mitigation potential, and the empirical setting suggests that policy diffusion, factor mobility, service-network extension, and cropping-pattern linkages may all operate across provincial boundaries. Under such conditions, restricting the model to SAR or SEM may overlook relevant explanatory spillovers. The SDM therefore provides a more flexible and informative framework for this study.

The dependent variable is the provincial carbon mitigation potential generated by manure nutrient recycling in year *t*, denoted as ER_{it}. The key explanatory variable is manure resource intensity, which captures the manure resource supply per unit of cropland and thus reflects the potential mitigation endowment from nutrient substitution. Control variables are consistent with those in the non-spatial specifications, accounting for fertilizer input intensity, economic scale, agricultural production conditions, industrial structure, and urbanization. To reduce distortions caused by scale differences and extreme values, the dependent variable and selected control variables are transformed into logarithmic form where appropriate. The transformation depends on variable distributions and model specifications. All spatial models and benchmark (non-spatial) models are estimated under consistent definitions and transformations to ensure comparability.

The baseline panel SDM is specified as:

$$ER_{it} = \rho \sum_{j=1}^{n} w_{ij}\, ER_{jt} + X_{it}\beta + \sum_{j=1}^{n} w_{ij}\, X_{jt}\theta + \mu_i + \tau_t + \varepsilon_{it} \tag{14}$$

where n denotes the number of provinces; w_{ij} is the $(i{\cdot}j)$ element of the spatial weight matrix; ρ is the spatial autoregressive coefficient of the dependent variable, capturing the overall transmission from neighboring provinces' mitigation levels to the focal province; X_{it} is a vector of explanatory variables including manure resource intensity and all controls; β measures the local (within-province) effects of explanatory variables; $\sum_j w_{ij} X_{ij}$ denotes the spatially lagged explanatory variables; and θ captures spatial spillover effects, i.e., how changes in neighboring provinces' covariates affect local mitigation outcomes. μ_i represents province fixed effects controlling for time-invariant unobserved factors such as geographic endowments, long-run institutional environments, and agricultural baseline conditions. τ_t denotes year fixed effects absorbing nationwide common shocks including macro policies, technological progress, and market fluctuations. ε_{it} is the idiosyncratic error term.

The spatial weight matrix $W = [w_{ij}]$ characterizes interprovincial spatial connectivity. The baseline specification uses a geographic contiguity (adjacency) matrix, while an economic-distance-based weight matrix is used as an alternative for comparison to examine the robustness of spatial effects.

Regional Classification

For the Dagum Gini decomposition and regional heterogeneity analysis, this study adopts the widely used three-region classification of China – eastern, central, and western China – to reflect structural differences in resource endowments, livestock production layout, agricultural production conditions, and socio-economic development stages.

The eastern region includes Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan. The central region includes Shanxi, Anhui, Jiangxi, Henan, Hubei, Liaoning, Jilin, Heilongjiang, and Hunan. The western region includes Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Tibet, Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang.

Results and Discussion

National Livestock Manure Resources and Nutrient Supply in China

Based on the accounting results for 2017–2024, China's total livestock manure resources remained at a relatively high level nationwide and exhibited a clear "decline-rebound-slight fallback at the end" trajectory. Total manure resources decreased from 12.09×10^8 t in 2017 to a period low of 10.98×10^8 t in 2019, then increased year by year and reached a stage peak of 13.24×10^8 t in 2023, before slightly declining to 12.80×10^8 t in 2024. Overall, fluctuations were relatively limited during the study period. However, the observed phase-based swings suggest that changes in the scale and structure of livestock production had a non-negligible effect on manure resource supply (Fig. 1a).

From a regional perspective, manure resource supply displays a stable gradient pattern, with the Western region consistently contributing the largest share, followed by the Eastern and Central regions. Using the 2017–2024 mean shares, the West accounts for 45.72% of national manure resources, while the East and Central regions contribute 30.76% and 23.52%, respectively. This distribution implies substantial spatial concentration of manure resource supply: major resource-producing provinces are more heavily clustered in the West, whereas the Central and Eastern regions occupy intermediate positions in terms of total volumes. The practical use of manure resources is constrained by cropland nutrient absorption capacity, transport radius, and treatment infrastructure. Therefore, this pattern of resource concentration underscores the need to strengthen both cross-regional coordination and local absorption capacity.

With respect to nutrient resources, the national stock of manure-borne nutrients (N+P+K) follows a trajectory broadly consistent with that of total manure resources, also showing a "decline–rebound–slight end-of-period fallback" pattern. Total nutrient resources decreased from 16.77×10^6 t in 2017 to 15.22×10^6 t in 2019, rebounded markedly after 2020, and peaked at 18.36×10^6 t in 2023, before declining to 17.85×10^6 t in 2024. In terms of composition, the national nutrient structure is relatively stable over the study period: nitrogen accounts for approximately 40.10%, while phosphorus and potassium contribute about 31.59% and 28.31%, respectively. This indicates that livestock manure provides a relatively balanced composite nutrient supply, with nitrogen maintaining a persistent comparative advantage (Fig. 1b; Fig. 1c).

Notably, the regional shares of "total manure volume" and "nutrient resources" are not fully aligned, reflecting differences in livestock species composition and manure nutrient contents across regions. The East contributes 30.76% of total manure resources but accounts for 33.67% of total nutrient resources; in contrast, the West contributes 45.72% of manure resources but only 41.96% of nutrient resources. Further, using "nutrient load intensity per unit manure" to measure nutrient density, the national average is approximately 13.90 kg/t, compared with about 15.20 kg/t in the East, 14.40 kg/t in the Central region, and 12.80 kg/t in the West. These results suggest that the East does not dominate in total manure volume, but it has a higher nutrient density per unit of manure. By contrast, the West contributes more to the national supply mainly through larger manure volumes, while its nutrient density is comparatively lower.

Carbon Mitigation Potential from Livestock Manure Fertilization in China

National carbon mitigation decreased from 1.84×10^7 t in 2017 to a period low of 1.68×10^7 t in 2019, representing a 9.06% decline relative to 2017. It then entered an upward trajectory, increasing continuously during 2021–2023 and reaching a peak of 2.02×10^7 t in 2023, which is 20.47% higher than the 2019 level. In 2024, mitigation slightly fell to 1.96×10^7 t, a 2.89% decrease

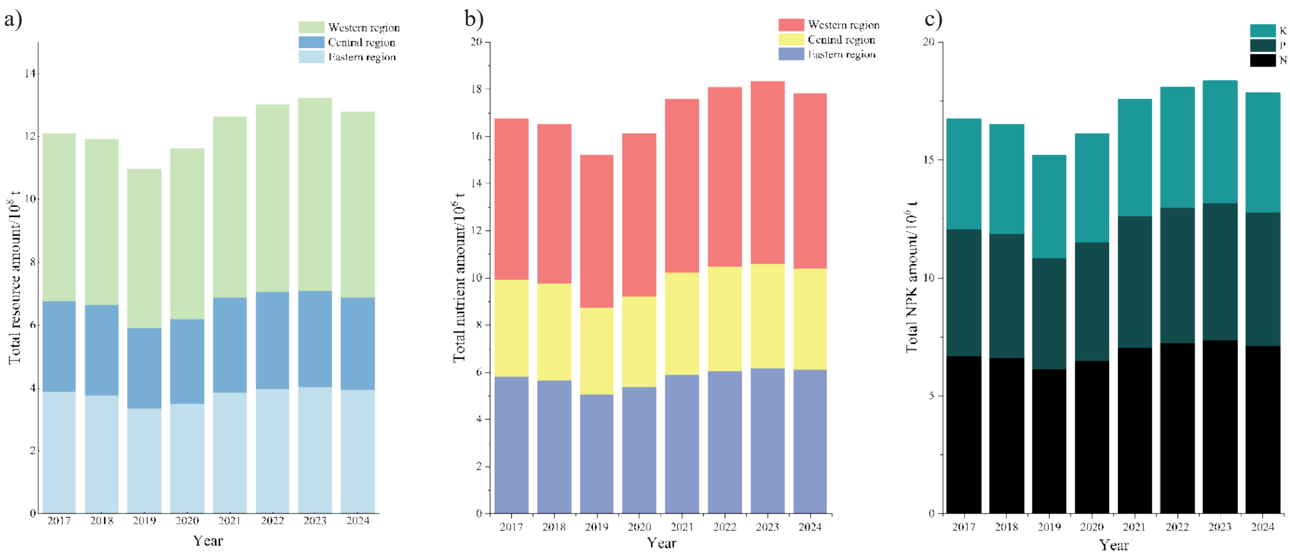

Fig. 1. Total Manure Resources and Total Nutrient Content from Livestock and Poultry.

compared with 2023. Overall, carbon mitigation remained at a relatively high level throughout the study period, and fluctuations were modest. This pattern indicates that year-to-year changes in national mitigation outcomes were jointly shaped by manure nutrient supply and the substitution space for mineral fertilizers.

From a regional perspective, carbon mitigation exhibits a stable spatial gradient pattern characterized by "high in the West, second in the East, and moderate in the Central region." In cumulative terms over 2017–2024, the Western region contributed $6.40×10^7$ t, the Eastern region contributed $4.99×10^7$ t, and the Central region contributed $3.63×10^7$ t. Across all years, the Western region consistently provided the largest contribution, suggesting that both the scale of manure resource supply and the spatial alignment between manure-derived nutrients and mineral fertilizer substitution opportunities are more concentrated in the West. Meanwhile, although the Eastern region may not dominate in total manure resources, its relatively higher agricultural input intensity and stronger substitution demand still translate into a stable and non-negligible mitigation contribution.

At the interprovincial level, carbon mitigation displays pronounced clustering and differentiation. High-mitigation provinces are mainly concentrated in Southwest China, South China, and several major agricultural provinces, whereas low-mitigation provinces tend to be municipalities or regions with relatively smaller livestock sectors. Taking 2024 as an example, the top five provinces in terms of mitigation were Guangxi, Sichuan, Shandong, Yunnan, and Hubei, while the bottom five were Beijing, Tianjin, Inner Mongolia, Zhejiang, and Ningxia. In the same year, the gap between the highest and lowest values exceeded two orders of magnitude. The top five provinces accounted for 32.49% of the national total, and the top ten contributed 55.86%. These figures indicate that mitigation potential is highly concentrated in a small subset of provinces (Fig. 2).

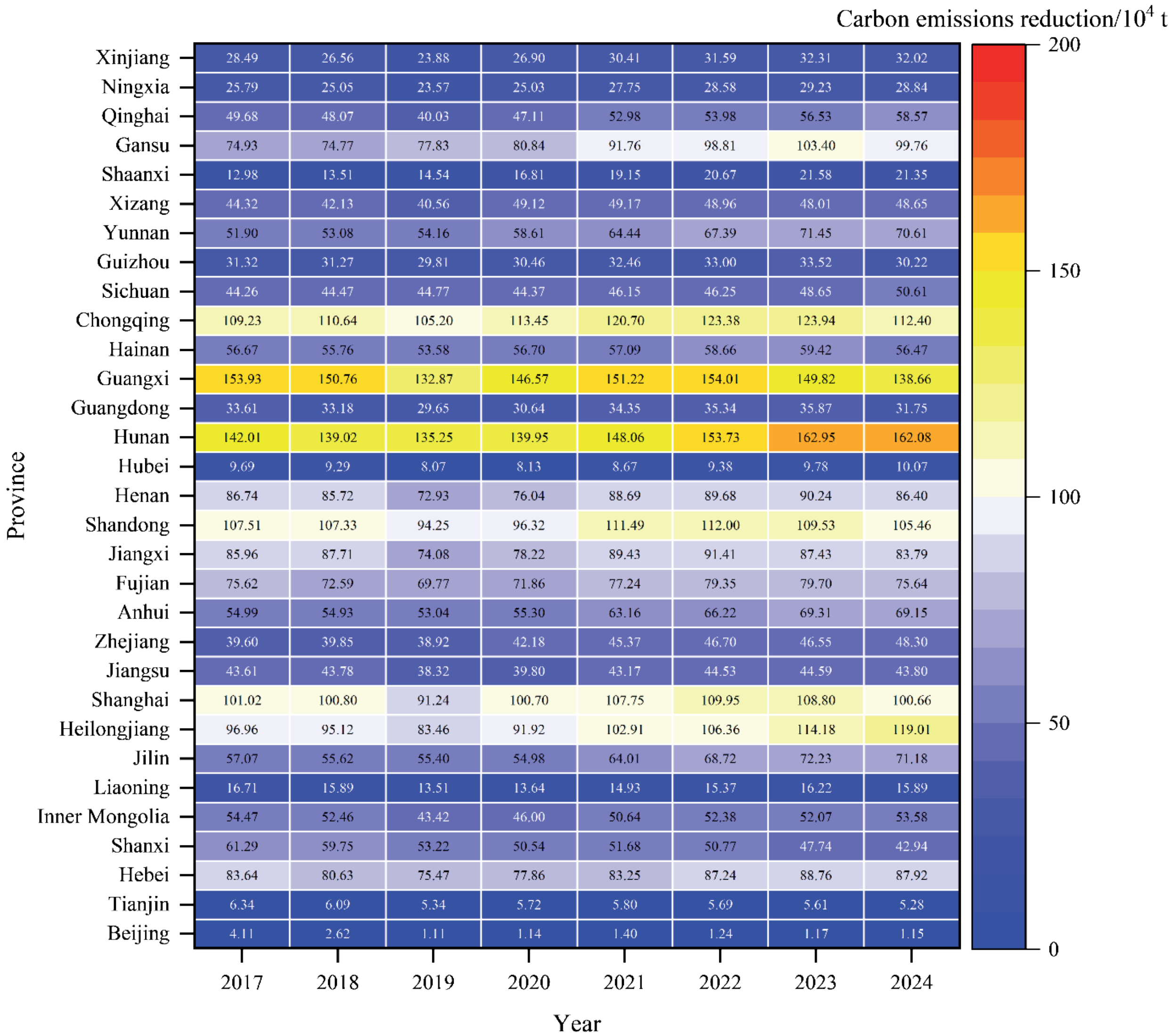

Fig. 2. Carbon Emission Reduction from Fertilizer-Oriented Utilization of Livestock and Poultry Manure across 31 Provinces in China.

Dagum Gini Coefficient and Decomposition of Inequality Sources

Interprovincial disparities in carbon mitigation from fertilizer-oriented utilization of livestock manure in China during 2017–2024 are generally moderate-to-high and remain relatively stable. The overall Dagum Gini coefficient fluctuates slightly between 0.347 and 0.353, reaching a stage high of 0.353 in 2018 and declining to 0.347 in 2024. This indicates a mild convergence in interprovincial differences toward the end of the study period, while the overall unequal pattern has not fundamentally changed.

Decomposition results show that the overall inequality is jointly determined by within-region inequality (G_w), net between-region inequality (G_b), and transvariation intensity (G_t), and the contribution structure of these components remains broadly stable over time. Within-region inequality contributes G_w = 0.121–0.122, staying at a nearly fixed level across years, suggesting strong persistence in the internal disparity structure among provinces within the Eastern, Central, and Western regions. In contrast, net between-region inequality exhibits more pronounced phase-based variation, with G_b = 0.093–0.103; it rises to 0.102 and 0.103 in 2019 and 2021, respectively, but equals 0.093 in both 2017 and 2024. This pattern implies a temporary widening of interregional gaps in the middle of the study period, followed by a subsequent narrowing, returning by the end of the period to a level broadly comparable to the beginning. Transvariation intensity (G_t) also shows slight fluctuations, peaking in 2017 and reaching its lowest value in 2021. This result indicates a certain degree of cross-overlap in the regional distributions of mitigation outcomes. In other words, some provinces have mitigation levels that are above or below the typical level of their own region. Therefore, regional boundaries do not fully separate provincial distributions, and overlap persists.

A further comparison of the within-region Gini coefficients across the three major regions reveals marked differences in internal inequality and clear evolutionary directions. Within the Eastern region, the Gini coefficient is relatively high and increases steadily from 0.361 in 2017 to 0.387 in 2024, indicating intensifying divergence in mitigation potential among eastern provinces and a widening gap between leading and lagging provinces. Within the Western region, the internal Gini coefficient remains high but declines gradually from 0.386 to 0.372, suggesting a modest convergence in internal disparities. Within the Central region, internal inequality declines most substantially, falling from 0.165 in 2017 to 0.123 in 2024, indicating that differences in mitigation potential among central provinces have narrowed markedly over the study period and the internal distribution has become more balanced (Table 2).

Global Spatial Autocorrelation

Global Moran's I tests based on provincial carbon mitigation data for 2017–2024 indicate that carbon mitigation from fertilizer-oriented utilization of livestock manure exhibits significant positive spatial autocorrelation at the national scale. In other words, provinces with high mitigation levels tend to be geographically adjacent to, or more closely connected (in an economic-geographic sense) with, other high-mitigation provinces, while low-mitigation provinces display similar clustering patterns. Using a spatial contiguity (adjacency) matrix, Moran's I fluctuates between 0.222 and 0.247. For all years, the z-statistics are positive and fall within 2.154~2.364, with p-values ranging from 0.016 to 0.009; thus, the null of spatial randomness is rejected at conventional significance levels. This suggests that mitigation is not randomly distributed, but instead follows a stable spatial clustering pattern. Under contiguity weights, Moran's I reaches a stage high of 0.247 in 2019 and, although it declines thereafter, remains at a relatively high level (0.226~0.244), implying that clustering intensity persists throughout the study period with only minor fluctuations.

Under the economic–geographic weight matrix, Moran's I is also positive and significant in most years. This suggests that spatial dependence in mitigation

Table 2. Dagum Gini coefficient, decomposition components, and within-region inequality by macro-region.

Year	Overall	G_w	G_b	G_t	Eastern	Central	Western
2017	0.351	0.121	0.093	0.137	0.361	0.165	0.386
2018	0.353	0.122	0.097	0.134	0.368	0.167	0.385
2019	0.351	0.121	0.102	0.128	0.376	0.142	0.377
2020	0.352	0.122	0.099	0.131	0.378	0.136	0.377
2021	0.351	0.121	0.103	0.127	0.377	0.148	0.374
2022	0.351	0.121	0.101	0.128	0.379	0.142	0.374
2023	0.350	0.122	0.097	0.131	0.384	0.133	0.373
2024	0.347	0.121	0.093	0.133	0.387	0.123	0.372

outcomes is shaped not only by geographic proximity, but also by interprovincial linkages such as factor mobility, industrial connections, regional coordination, and policy diffusion. Notably, the magnitude of spatial correlation under economic–geographic weights is generally lower than that under contiguity weights, yet significance remains robust. This implies that spatial clustering in mitigation is driven primarily by geographic proximity, while a non-negligible component can also be attributed to correlation along interprovincial linkage networks. By 2024, Moran's I under the economic–geographic matrix declines to 0.032; although it still passes the significance test, the strength of spatial dependence weakens, which may indicate that the synchrony of mitigation outcomes associated with interprovincial linkages diminishes toward the end of the period, or that rising within-region heterogeneity partially dilutes the statistical strength of cross-provincial associations.

Taken together, results from both weight matrices confirm that carbon mitigation from fertilizer-oriented utilization of livestock manure in China exhibits significant and persistent spatial clustering over 2017–2024, jointly shaped by geographic adjacency and economic–geographic linkages. This finding provides essential statistical justification for employing spatial econometric models to identify determinants and spatial spillover effects. When spatial dependence is present, ignoring the spatial correlation structure may lead to underestimation or misinterpretation of the marginal effects of key drivers and their cross-provincial transmission pathways (Table 3).

Spatial Durbin Model Estimation and Decomposition of Spatial Spillover Effects

The SDM specification is particularly useful in this context because it allows the analysis to distinguish local effects from explanatory spillovers transmitted through neighboring provinces. The Spatial Durbin Model (SDM) estimates indicate that carbon mitigation is shaped not only by local determinants but also by significant spatial dependence and spatial spillovers for selected covariates. The spatially lagged dependent variable term (Wy) is 0.167 and significantly positive, implying that a province's mitigation level increases with higher mitigation in neighboring provinces. This confirms a clear positive spatial dependence in mitigation outcomes, consistent with the preceding global Moran's I tests.

Regarding local explanatory variables, manure resource intensity exerts a significantly positive effect on carbon mitigation, suggesting that stronger manure resource endowment expands the scope for mineral fertilizer substitution and thus increases realizable mitigation at the provincial level – making it a key driver of higher mitigation outcomes. Mineral fertilizer application intensity is also significantly positive, indicating that, conditional on resource availability, provinces with higher fertilizer input intensity have greater potential substitution volumes and therefore larger mitigation space. Among the control variables, only ln (agricultural GDP) shows a weakly significant negative local effect, whereas agricultural mechanization, urbanization rate, and cropping structure are not statistically significant in their local terms. This suggests that once spatial interactions are explicitly modeled, the marginal explanatory power of these factors for local mitigation is limited, or their effects may operate through more complex indirect transmission channels.

Turning to the spatially lagged explanatory variables, several covariates show significant spillover effects. The spatial lag of fertilizer application intensity has a significantly positive effect on local mitigation. This suggests that higher fertilizer input intensity in neighboring provinces raises mitigation in the focal province. This may operate through mechanisms such as regional convergence in input-use patterns, technology diffusion, and policy coordination, whereby fertilizer substitution and manure utilization advance in a spatially synchronized manner. In contrast, the spatial lag of ln(agricultural GDP) is significantly

Table 3. Global Moran's I of provincial carbon mitigation potential under different spatial weight matrices.

Year	Contiguity Matrix			Economic–geographic Matrix		
	Moran's I	z-value	p-value	Moran's I	z-value	p-value
2017	0.222	2.154	0.016	0.045	2.263	0.012
2018	0.233	2.245	0.012	0.048	2.365	0.009
2019	0.247	2.364	0.009	0.053	2.496	0.006
2020	0.244	2.344	0.010	0.048	2.353	0.009
2021	0.238	2.291	0.011	0.047	2.322	0.010
2022	0.231	2.229	0.013	0.046	2.282	0.011
2023	0.234	2.260	0.012	0.042	2.191	0.014
2024	0.226	2.191	0.014	0.032	1.898	0.029

negative, suggesting that expansion of agricultural economic scale in surrounding areas may suppress local manure-substitution mitigation, potentially via resource "siphoning," reallocation of production factors, or changes in input structures. The spatial lag of cropping structure is significantly positive, indicating that regional linkages in cropping patterns shape the spatial distribution of mitigation. This suggests that cross-provincial externalities may arise through converging crop layouts, changes in grain–cash crop composition, and related shifts in organic fertilizer demand. By comparison, W (manure resource intensity) is not significant, indicating that manure resource endowment is more locally supplied and locally absorbed, with relatively weak cross-provincial diffusion. W(mechanization) is weakly significant and negative, while W (urbanization rate) is not significant (Table 4).

Because coefficients in spatial models cannot be interpreted directly as marginal effects, we further decompose the impacts of core variables into direct, indirect (spillover), and total effects. Results show that the direct effect of manure resource intensity is 0.173 and significantly positive. Its indirect effect is 0.086 and not significant, while the total effect is 0.259 and significantly positive. This indicates that the positive contribution of manure resource intensity operates primarily through local mechanisms, with limited spillover—consistent with the strong "place-based supply and utilization constraints" of manure resources. For fertilizer application intensity, the direct effect is 13.692 and significantly positive; however, the indirect effect is only 0.080 and not significant, and the total effect (13.773) is not statistically significant. This suggests that fertilizer intensity clearly promotes local mitigation, but its cross-provincial spillover is unstable. After spatial feedback is taken into account, the overall statistical significance becomes weaker. This implies that fertilizer intensity mainly operates through within-province substitution space rather than through a robust interprovincial transmission channel.

Effect decomposition for ln (agricultural GDP) indicates that its influence is more pronounced at the spatial level: the direct effect is 0.248, the indirect effect is 0.530, and the total effect is 0.777, all significantly positive. This implies that expansion of agricultural economic scale enhances local capacity to implement manure substitution and realize mitigation gains. It also generates significant positive spillovers to neighboring provinces. Potential mechanisms include regional agri-industrial chain collaboration, diffusion of input factors, and spillovers in service networks for manure treatment and application. In contrast, agricultural mechanization shows an overall significantly negative effect, with a direct effect of −0.284, an indirect effect of −0.957, and a total effect of −1.241. This suggests that, under current conditions, rising mechanization does not necessarily improve the accessibility or substitution efficiency of manure application to cropland. Instead, it may be associated with higher input intensity, scale-oriented production practices, or continued dependence on mineral fertilizers. Moreover, the strong spatial linkage implies that mechanization-related impacts are regionally connected, and should be interpreted in conjunction with regional machinery structure and the availability of organic fertilizer application services in subsequent discussion. Finally, the direct, indirect, and total effects of urbanization rate and cropping structure

Table 4. Baseline Spatial Durbin Model (SDM) Estimates (Coefficient Results).

Variable	Coef	Std. Err.	z-value	p-value
Constant	0.167	0.022	7.704	0.000
Manure resource intensity	13.687	2.630	5.204	0.000
Chemical fertilizer intensity	0.212	0.082	2.594	0.009
ln Agricultural GDP	-0.219	0.125	-1.751	0.080
Mechanization level	0.422	0.303	1.393	0.164
Urbanization rate	-0.283	0.439	-0.643	0.520
Cropping structure	-0.005	0.039	-0.128	0.898
W(Manure resource intensity)	-5.065	6.168	-0.821	0.412
W(Chemical fertilizer intensity)	0.275	0.126	2.191	0.028
W(ln Agricultural GDP)	-0.559	0.263	-2.125	0.034
W(Mechanization level)	-0.871	0.465	-1.872	0.061
W(Urbanization rate)	0.090	0.989	0.091	0.927
W(Cropping structure)	0.374	0.072	5.183	0.000
Wy	0.167	0.022	7.704	0.000

are not statistically significant. This suggests that, after controlling for spatial dependence and other covariates, their measurable contributions to mitigation are limited. It may also indicate that their effects are mediated through mechanisms not explicitly captured in the model (Table 5).

Robustness Checks: Variable Substitution, Alternative Spatial Weights, and Sample Exclusion

To verify the robustness of the baseline Spatial Durbin Model (SDM), this study conducts three robustness checks. First, we replace the core explanatory variable by using nutrient resource intensity instead of the baseline core variable. Second, we replace the spatial weight matrix by using an economic–geographic hybrid matrix in place of the baseline weighting scheme. Third, we replace the dependent variable by using carbon emission intensity instead of the baseline carbon mitigation indicator. Overall, the results indicate that the main conclusions remain consistent across alternative specifications, suggesting that the model identification is reasonably robust.

Under check (1), where the core explanatory variable is replaced, the coefficient on nutrient resource intensity is positive and statistically significant. This implies that whether the supply foundation is characterized by "manure resources" or by the "nutrient resources" embodied in manure, it significantly increases the realized mitigation performance associated with fertilizer-oriented manure utilization. Meanwhile, the spatially lagged dependent variable (Wy) remains significantly positive, confirming a stable spatial linkage in mitigation outcomes – i.e., mitigation changes in neighboring provinces co-move with mitigation performance in the focal province. By contrast, the spatial lag of the core explanatory variable (W(core explanatory variable)) is positive but not statistically significant, indicating that the effect of the core resource endowment still operates mainly through local mechanisms and that cross-provincial spillovers are not stable. This is consistent with the baseline inference that "resource-side effects are primarily within-province."

Under check (2), where the weight matrix is replaced with an economic–geographic hybrid matrix, the core explanatory variable remains significantly positive, indicating that the baseline conclusion does not depend on a particular spatial weighting choice. Notably, W(core explanatory variable) becomes significantly positive in this specification. This suggests that cross-provincial association effects of resource endowments are more easily detected when spatial relationships are represented by economic–geographic linkages rather than pure geographic contiguity. It further implies that resource-utilization capacity may generate externalities through regional coordination, factor mobility, and the

Table 5. Decomposed Spatial Effects.

Variable	Effect	Estimate	Std. Err.	z-value	p-value
Manure resource intensity	Direct	0.173	0.022	7.875	0.000
	Indirect	0.086	0.057	1.514	0.130
	Total	0.259	0.064	4.045	0.000
Chemical fertilizer intensity	Direct	13.692	2.535	5.402	0.000
	Indirect	0.080	8.999	0.009	0.993
	Total	13.773	9.377	1.469	0.142
ln Agricultural GDP	Direct	0.248	0.081	3.058	0.002
	Indirect	0.530	0.170	3.123	0.002
	Total	0.777	0.177	4.394	0.000
Mechanization level	Direct	-0.284	0.134	-2.121	0.034
	Indirect	-0.957	0.418	-2.293	0.022
	Total	-1.241	0.481	-2.583	0.010
Urbanization rate	Direct	0.349	0.303	1.151	0.250
	Indirect	-1.066	0.743	-1.435	0.151
	Total	-0.717	0.897	-0.799	0.424
Cropping structure	Direct	-0.284	0.445	-0.639	0.523
	Indirect	-0.023	1.465	-0.016	0.988
	Total	-0.307	1.708	-0.180	0.857

diffusion of service networks. In this setting, Wy is not significant, indicating that the statistical significance of spatial dependence differs across weight matrices: geographic contiguity better captures synchronized clustering of mitigation, whereas economic–geographic linkages better reflect cross-regional transmission of resources and structural variables. This aligns with the earlier finding that Moran's I differs in magnitude across the two types of weights.

Under check (3), where the dependent variable is replaced with carbon emission intensity, the core explanatory variable remains significantly positive, and its spatial lag W(core explanatory variable) is also significantly positive. This indicates that manure or nutrient resource endowments are closely associated with both mitigation levels and emission-intensity outcomes. The relationship also shows a non-negligible spatial linkage. In addition, Wy becomes significantly negative, implying that under an "intensity-based" metric, changes in neighboring provinces' emission intensity exert an opposite effect on the focal province. This may reflect substitution and competition effects across regions in terms of industrial division of labor, factor mobility, and governance intensity – i.e., improvements in one province may be accompanied by relative pressure or structural spillovers in neighboring areas. This result further suggests that spatial transmission directions may differ between mitigation "scale" indicators and emission "intensity" indicators, and the economic interpretation should be elaborated by considering the substantive meaning of each metric.

Regarding control variables, fertilizer application intensity is generally significant across the three robustness specifications, indicating that fertilizer input intensity remains an important determinant of mitigation-related outcomes. ln(agricultural GDP) is significantly positive in checks (1) and (2) but becomes insignificant in check (3), suggesting that agricultural economic scale is more closely associated with mitigation "scale" than with emission "intensity." Agricultural mechanization is significantly negative in check (3), and cropping structure is also significantly negative in check (3), indicating that when an intensity-based metric is used, the roles of production modes and crop-structure adjustments in improving emission intensity are more readily detected (Table 6).

To further validate the stability of "local effects versus spillovers," we decompose the spatial effects of the core explanatory variable in the robustness tests into direct, indirect, and total effects. The results show that across all three robustness settings, the direct effect of the core explanatory variable is significantly positive, and some identifiable spatial spillovers are present, indicating that the baseline conclusion is robust not only in terms of coefficient significance but also in the interpretable marginal-effect structure.

Specifically, under setting (1), the direct effect of the core explanatory variable is 0.136 (P<0.01), the indirect effect is 0.319 (P<0.05), and the total effect is 0.455 (P<0.01). This indicates that when the supply foundation is measured using an alternative resource metric, its positive role in increasing local mitigation remains clear, and a measurable cross-provincial spillover emerges – i.e., changes in neighboring regions' resource supply are associated with a sizable impact on local

Table 6. Robustness checks.

Variable	(1)	(2)	(3)
Constant	13.473 (8.770)**	0.135 (7.529)**	0.013 (63.505)**
Core explanatory variable	-11.233 (-0.183)**	10.094 (3.879)**	0.117(4.524)**
Chemical fertilizer intensity	0.396 (12.976)**	0.476 (7.298)**	-0.001 (-1.006)
ln Agricultural GDP	-0.191 (-1.634)	-0.121 (-1.038)	-0.006 (-4.696)**
Mechanization level	0.186 (1.140)	0.375 (1.269)	-0.001 (-0.325)
Urbanization rate	-0.166 (-5.570)	-0.613 (-1.482)	-0.015 (-3.431)**
Cropping structure	3.891 (1.255)	0.300 (2.017)*	0.004 (2.905)**
W(Core variable)	-1.934 (-0.324)	-13.27 (-0.757)	-0.054 (-0.884)
W(Chemical fertilizer intensity)	0.132 (1.211)	-0.351 (-1.098)	0.001 (0.997)
W(ln Agricultural GDP)	-0.329 (-1.359)	0.794 (1.200)	-0.004 (-1.561)
W(Mechanization level)	-0.685 (-1.504)	0.358 (0.236)	0.003 (0.624)
W(Urbanization rate)	0.785 (0.953)	8.504 (4.014)**	-0.007 (-0.671)
W(Cropping structure)	0.276 (3.609)**	0.119 (0.736)	-0.284 (-3.069)**

Note: *P<0.05, **P<0.01; (1) Replace core variable: Nutrient resource intensity; (2) Alternative weights: Economic–geographic composite; (3) Replace dependent variable: Carbon emission intensity mitigation. Combined with the spatial-term patterns in the regressions, this can be interpreted as follows: beyond local resource constraints, resource utilization capacity may also generate externalities through cross-regional treatment and utilization systems, diffusion of technical services, and policy coordination, although the magnitude of such externalities is weaker than local effects.

Under setting (2) (alternative weight matrix), the direct effect is 13.51 ($P<0.01$), the indirect effect is 4.506 ($P>0.05$), and the total effect is 18.016 ($P<0.01$). This suggests that within the spatial linkage structure captured by the economic–geographic hybrid matrix, the core explanatory variable still primarily operates through local mechanisms, while the overall impact remains significant and robust. In other words, changing the weight matrix does not alter the core conclusion that the resource supply foundation is a key driver of mitigation differences. Meanwhile, the insignificant indirect effect implies that cross-provincial transmission represented by economic–geographic linkages is not necessarily stable; spillovers may materialize only under specific regional coordination contexts.

Under setting (3) (dependent variable replaced by carbon emission intensity), the direct effect is 0.013 ($P<0.01$), the indirect effect is 0.000 ($P>0.05$), and the total effect is 0.013 ($P<0.01$). This indicates that after shifting from a "mitigation-scale" metric to an "emission-intensity" metric, the core explanatory variable still exerts a stable influence on local intensity outcomes, but cross-provincial spillovers are not evident. This suggests that intensity-based indicators more strongly reflect within-province outcomes driven by production modes, input structures, and governance constraints, and their spatial diffusion is weaker than that of scale-based indicators (Table 7).

Regional Heterogeneity: Comparing Direct and Spillover Effects across Eastern, Central, and Western China

To identify regional differences in the drivers of carbon mitigation from fertilizer-oriented utilization of livestock manure, we conduct subgroup estimations for the eastern, central, and western regions. The results reveal clear regional heterogeneity.

Table 7. Summary of Robustness Results.

Robustness setting	(1)	(2)	(3)
Direct effect	0.136**	13.510**	0.013**
Indirect effect	0.319*	4.506	0.000
Total effect	0.455**	18.016**	0.013**

Note: *$P<0.05$, **$P<0.01$. (1) Replace core variable: Nutrient resource intensity; (2) Alternative weights: Economic–geographic composite; (3) Replace dependent variable: Carbon emission intensity

Manure resource intensity has a significantly positive effect in all three regions, indicating that manure resource endowment is a common driver of mitigation. The effect is strongest in the central region, suggesting that increases in resource intensity there are more readily translated into fertilizer substitution and mitigation gains. By contrast, chemical fertilizer intensity is significantly positive only in the eastern region, implying that substitution space in high-input agricultural systems is more effectively converted into mitigation potential there.

The effect of ln(agricultural GDP) differs across regions: it is significantly positive in the eastern and western regions, but significantly negative in the central region. Agricultural mechanization is negatively associated with mitigation in all three regions and is significant in the central and western regions, with the strongest negative effect in the west. In addition, urbanization rate and cropping structure are significant only in the western region, where urbanization shows a positive effect and cropping structure shows a negative effect. Overall, these results suggest that the drivers of manure-based carbon mitigation vary substantially across regions, and that differentiated regional policies are therefore needed (Table 8).

Sensitivity Analysis of Key Accounting Coefficients

To further assess the stability of the accounting results, a sensitivity analysis of key coefficients was conducted by adjusting manure-generation coefficients and nutrient-content coefficients by ±10% under separate and joint perturbation scenarios. The results show that coefficient perturbation mainly affects the absolute scale of carbon-mitigation potential, but does not materially alter its main temporal and spatial patterns.

Taking 2024 as an example, the baseline national carbon-mitigation potential was 2248.170. Under the nutrient-coefficient and manure-coefficient perturbation scenarios, the estimate increased to 2472.987 when the coefficients were adjusted upward by 10% and decreased to 2023.353 when they were adjusted downward by 10%. Under the joint perturbation scenario, the estimate increased to 2720.286 under the +10% adjustment and decreased to 1821.018 under the -10% adjustment. These results indicate that the accounting outcomes respond proportionally to coefficient changes in magnitude.

However, the core conclusions remain stable across all scenarios. The national carbon-mitigation potential still follows the same decline–rebound–slight fallback trajectory over 2017–2024, and the peak and trough years remain unchanged. At the spatial level, the broad regional gradient is consistent with the baseline results, and the top-ranking provinces in 2024 remain unchanged. Overall, moderate perturbations in key accounting coefficients do not change the main findings regarding the national evolution trend, the broad regional pattern, or the interprovincial concentration of carbon-

Table 8. Regional Heterogeneity: SDM Effect Decomposition by Macro-Region.

Variable	East	Central	West
Chemical fertilizer intensity	0.167 (5.292)**	1.396**(9.512)	0.176**(6.388)
ln Agricultural GDP	9.000 (2.073)*	1.370(0.239)	3.099(0.824)
Mechanization level	0.602 (3.831)**	-0.137*(-2.390)	0.532**(7.544)
Urbanization rate	-0.562 (-2.306)*	-0.632*(-2.447)	-0.778**(-5.543)
Cropping structure	0.645(1.171)	-0.372(-0.716)	1.444**(3.647)

Note: *P<0.05, **P<0.01.

Table 9. Coefficient sensitivity analysis of national carbon-mitigation potential and pattern stability in 2024.

Scenario	National carbon-mitigation potential	Change vs. baseline	Regional ranking	Top 5 provinces in 2024
Baseline	2248.170	0.0%	West>Central>East	Inner Mongolia, Sichuan, Shandong, Henan, Xinjiang
Nutrient +10%	2472.987	+10.0%	West>Central>East	Unchanged
Nutrient -10%	2023.353	-10.0%	West>Central>East	Unchanged
Manure +10%	2472.987	+10.0%	West>Central>East	Unchanged
Manure -10%	2023.353	-10.0%	West>Central>East	Unchanged
Joint +10%	2720.286	+21.0%	West>Central>East	Unchanged
Joint -10%	1821.018	-19.0%	West>Central>East	Unchanged

Note: Nutrient ±10% indicates a ±10% perturbation in manure nutrient-content coefficients. Manure ±10% indicates a ±10% perturbation in manure-generation coefficients. Joint ±10% indicates simultaneous ±10% perturbation in both sets of coefficients.

mitigation potential, indicating that the accounting results are reasonably robust (Table 9).

Discussion

This study reveals pronounced spatial disparities in the fertilizer-oriented utilization of livestock manure in China, a finding that is consistent with conclusions from recent international research. Some studies have noted that nearly 70% of China's livestock production capacity is concentrated in a limited number of provinces, which is not well aligned with the spatial distribution of cropping systems [31]. This mismatch results in nutrient surpluses in "manure-rich regions" and nutrient deficits in major grain-producing areas. Such cross-regional imbalance leads to excessive accumulation and over-application of manure in certain locations, thereby causing soil and water pollution; meanwhile, in other agricultural regions, mineral fertilizer application intensity remains high while inputs of soil organic matter and nutrients are insufficient, undermining soil fertility and long-term production sustainability [32]. The interregional differences in manure utilization rates identified in this study corroborate the "crop–livestock decoupling" phenomenon and underscore the need to alleviate it through cross-regional nutrient reallocation and coordination.

Interregional differences in manure utilization are also shaped by natural endowments and development levels. County-level analyses indicate that nitrogen recycling rates from manure are generally higher in northern China than in the south, which is closely related to the larger cropland base in northern regions and a stronger degree of crop–livestock integration [33]. By contrast, in southern regions characterized by high temperature and abundant rainfall, nutrient losses induced by runoff and accelerated volatilization/decomposition tend to be greater, resulting in lower manure utilization rates. In addition, regional socio-economic conditions contribute to heterogeneous manure utilization patterns across areas such as eastern China and the Northeast: regions with larger cropland scales, higher urbanization levels, and a greater share of poultry production typically exhibit higher recovery rates of manure nutrients; conversely, regions dominated by pig production often display lower utilization rates because of the substantial volume of waste generated and the greater difficulty of treatment and management. The results of this study are broadly consistent with these patterns, indicating that region-specific strategies are required for manure resource utilization. This spatial heterogeneity implies that uniform policy instruments may not be sufficiently effective; instead, improving manure utilization efficiency and achieving agricultural nutrient balance require policy designs that explicitly account for regional differences.

Accelerating the fertilizer-oriented utilization of livestock manure can deliver multiple mitigation benefits for agricultural carbon emissions through several mechanisms [17]. First, partial substitution of mineral fertilizers with organic fertilizers can directly reduce energy consumption and CO_2 emissions associated with fertilizer production and transportation [34]. Mineral fertilizer manufacturing is widely recognized as energy intensive, whereas the preparation and use of organic fertilizers typically entail lower energy demand. Thus, at the level of agricultural inputs, manure-based substitution can reduce the "embedded" industrial carbon footprint. Second, organic fertilizer application can enhance soil nutrient use efficiency and reduce nitrous oxide (N_2O) emissions driven by excessive nitrogen inputs [35]. In double-cropping rice experiments, for example, substituting mineral fertilizers with organic fertilizers has been found to significantly reduce soil N_2O emissions, with reductions of up to 70% [36]. From the perspective of crop production and soil processes, returning manure to cropland can mitigate farmland GHG emissions by improving soil quality and facilitating nutrient cycling.

It should be emphasized that the mitigation estimates in this study represent technical substitution potential under a standardized accounting scenario, rather than fully realized net mitigation under real-world implementation conditions. However, the mitigation effects of manure utilization depend on specific application conditions; across regions and management systems, outcomes may differ and can involve trade-offs. Recent meta-analyses show that replacing chemical nitrogen fertilizer with organic nitrogen fertilizer can, on average, significantly reduce soil N_2O emissions; yet, because decomposition of organic matter releases CO_2 and CH_4, the overall global warming potential (GWP) of farmland systems may sometimes increase [17]. This phenomenon is particularly evident in highly humid environments, where high-carbon organic inputs can stimulate methanogenic activity and trigger substantial CH_4 emissions. In contrast, in upland systems, net GWP can be reduced if the C:N ratio and substitution rate of organic fertilizer are appropriately controlled. For instance, some studies have optimized organic fertilizer carbon content, C:N ratio, and nitrogen substitution rates, achieving lower net GWP relative to mineral fertilizer regimes under upland conditions. These findings suggest that it is insufficient to focus solely on the average benefits of manure substitution; rather, application technologies must be optimized according to regional agro-climatic conditions to prevent potential rebounds in GHG emissions.

Further, circular utilization technologies such as anaerobic digestion can help maximize the mitigation benefits of manure management. For example, small-scale biogas systems can convert livestock manure from "waste" into "resource" while producing both organic fertilizer and biogas. This not only provides clean energy but also effectively limits direct methane leakage. Eco-circular agricultural practices in regions such as Jiangxi demonstrate substantial mitigation outcomes: centralized treatment of livestock waste with outputs of biogas and organic fertilizer can yield significant emission reductions – for instance, processing 300,000 tons of manure annually and producing 5 million m^3 of biomethane can substitute part of mineral fertilizer and fossil energy use, delivering an annual reduction of approximately 18,000 tons CO_2-equivalent. Therefore, the "agricultural circular economy" model – integrating manure resource utilization with clean energy production – offers a technological pathway that delivers co-benefits in both carbon mitigation and waste pollution control. This approach is consistent with internationally promoted nutrient-cycling concepts, whereby innovative technologies transform organic wastes such as livestock manure from environmental burdens into multi-purpose resources, thereby reducing emissions across the agri-food system [20].

The determinants of manure fertilizer utilization and its carbon mitigation effects are multifaceted, and the strength of these drivers varies considerably across regions. Using data from 2017–2024, this study finds that the interplay of natural conditions, agricultural structure, and socio-economic factors jointly shapes manure utilization patterns. International research supports this multi-factor perspective: at the national county scale, manure nutrient recycling rates are closely associated with cropland scale, modes of agricultural operation, and demographic structure [33]. Regions with larger cropland areas can more readily absorb locally generated manure nutrients and thus tend to have higher recycling rates. Higher urbanization often implies the coexistence of scaled livestock production and specialized cropping, which can increase the feasibility of manure reallocation through markets or cooperative arrangements and thereby support higher utilization rates. By contrast, regions with high livestock intensity but insufficient land for nutrient absorption are prone to manure surpluses, particularly where pig production dominates; in such cases, high treatment costs and strong odor concerns may reduce farmers' willingness to apply manure, lowering recycling rates. Rural labor aging has also been found to weaken manure utilization, potentially because older farmers are less likely to adopt new technologies and organizational modes and because labor inputs may be insufficient. The complex interactions among these factors imply that improving manure utilization requires integrated policy packages, combining technical support with behavioral guidance and incentives.

Importantly, dominant drivers differ significantly across regions, reflecting clear regional heterogeneity. Evidence suggests that in southern versus northern China – where natural conditions diverge sharply – climatic factors exert more pronounced impacts on manure utilization[33]; for example, in warm and humid southern regions, manure nutrients are more difficult to preserve and utilize effectively. In regions with large socio-economic contrasts, such as eastern China and the Southwest, socio-economic factors – including land scale and market conditions – play more prominent roles [2]. Consistent with this, the present study suggests that regional heterogeneity necessitates differentiated management strategies: in areas where natural constraints are particularly binding, policies should prioritize locally suitable small-scale manure treatment solutions and the commercialization of organic fertilizer supply; in areas where socio-economic factors dominate, policy incentives and market mechanisms should be strengthened to facilitate manure movement across farms and across regions, thereby balancing nutrient supply and demand. This finding aligns with international experience, as many countries are exploring regionally tailored agricultural waste management approaches. For example, the European Union has advocated establishing regional nutrient-trading and information platforms to encourage nutrient transfer from surplus areas to deficit areas [20]. Hence, stronger interregional cooperation and coordinated governance are essential to overcoming spatial mismatches in manure utilization.

The findings of this study carry important policy implications that resonate with the goals of ecological livability and industrial prosperity under the Rural Revitalization Strategy [37]. First, improving the fertilizer-oriented utilization rate of livestock manure is an effective pathway for reducing agricultural non-point pollution and GHG emissions, consistent with China's green development agenda [38]. In its updated Nationally Determined Contributions (NDC) and key policy documents on agricultural green development, China identifies reductions in chemical fertilizer and pesticide use, enhanced carbon sinks, and the resource utilization of wastes as priority measures, emphasizing the role of manure return-to-land in agricultural mitigation. Accordingly, the government has introduced a series of policies in recent years. For instance, the 2017 Guiding Opinions on Accelerating the Resource Utilization of Livestock and Poultry Farming Wastes set a target of achieving a comprehensive manure utilization rate above 75% by 2020; subsequent guidance in 2019 further raised the targets to 80% by 2025 and 90% by 2035 [9]. These policy measures were progressively implemented during the 2017–2024 period covered by this study. Our analysis also observes improved national manure utilization levels and a narrowing of regional disparities, reflecting the effectiveness of policy drivers.

Comparisons with international experience further indicate distinctive features of China's approach. On the one hand, China sets explicit quantitative targets and performance assessment mechanisms at the national level, mobilizing local governments and production entities to participate. On the other hand, it integrates manure resource utilization with rural eco-environmental remediation and energy substitution to achieve multiple co-benefits. For example, through government subsidies and public–private collaboration, some major livestock-producing provinces have established third-party manure treatment centers to enable centralized processing, biogas-based power generation, and organic fertilizer production. Such models not only alleviate livestock-related pollution but also supply local farmers with affordable organic fertilizers, thereby balancing economic returns with environmental benefits.

The spatial spillover effects identified in this study can be interpreted through several practical mechanisms. First, policy diffusion likely plays an important role. Since the promotion of livestock manure resource utilization in China has been strongly policy-driven, neighboring provinces often learn from each other in the design of subsidy schemes, treatment standards, and manure return-to-land programs. As a result, improvements in one province may induce similar adjustments in surrounding provinces, generating spatially correlated mitigation outcomes. Second, technology and service-network diffusion may also contribute to the observed spillovers. The treatment, processing, and field application of livestock manure increasingly rely on socialized service systems, specialized equipment, and third-party organizations. Once such technologies and service networks expand in one province, their influence may extend across provincial boundaries through demonstration effects, cross-regional business expansion, and the diffusion of technical experience, thereby affecting neighboring provinces' mitigation performance. Third, factor mobility and interprovincial production linkages provide another channel for spillovers. Changes in agricultural development conditions, input-use patterns, and the organization of crop–livestock systems in one province may influence surrounding provinces through capital flows, labor mobility, and the reallocation of production and treatment capacity. This may help explain why agricultural economic scale shows a notable spatial effect in the model. Finally, the positive spillover associated with cropping structure suggests that interprovincial similarities in crop layout and fertilizer demand also matter. When neighboring provinces exhibit converging crop patterns, they may face similar demand for manure-based fertilizers and similar constraints on substitution, which in turn produces cross-provincial externalities in mitigation outcomes. Taken together, these mechanisms suggest that manure-based carbon mitigation is shaped not only by local resource endowment, but also by broader regional coordination, market interaction, and technology diffusion processes.

A brief province-level comparison further helps illustrate the regional heterogeneity identified above. For example, Guangxi, Sichuan, Shandong, Yunnan, and Hubei ranked among the highest provinces in carbon-mitigation potential in 2024. These provinces generally combine relatively strong livestock-manure resource endowment with substantial cropland demand or stronger agricultural production capacity, allowing manure nutrients to be translated more effectively into fertilizer substitution and mitigation gains. By contrast, Beijing and Tianjin remained at the lower end of the distribution, which is closely related to their relatively limited livestock sector and smaller agricultural land base. Such province-level differences suggest that the broad east–central–west pattern is useful, but it does not fully capture the diversity of local resource conditions, agricultural structures, and substitution capacity. Therefore, regional analysis should be complemented by province-specific interpretation when formulating targeted manure-utilization policies.

The empirical findings of this study have several important policy implications. First, the significant positive spatial autocorrelation and the positive spatial dependence identified by the SDM indicate that manure-based fertilizer substitution is not only a local issue, but also a regional one. Therefore, policy should move beyond isolated provincial actions and strengthen cross-regional coordination mechanisms, including interprovincial information-sharing platforms, joint manure-treatment cooperation, and regional service networks for manure processing, transport, and field application. Such measures would help reduce fragmentation in manure utilization and improve the regional matching of nutrient supply and cropland demand.

Second, the results show that manure resource intensity is the most important local driver of carbon-mitigation potential. Policy should therefore continue to strengthen manure collection, storage, treatment, and fertilizer-oriented utilization, especially in provinces with strong livestock and poultry resource endowments. In practical terms, this requires improving county-level treatment capacity, promoting standardized manure products, and enhancing the local conversion of manure nutrients into effective fertilizer inputs so that resource advantages can be translated into actual mitigation gains.

Third, the strong regional heterogeneity suggests that a uniform policy approach would be inefficient. In the eastern region, where fertilizer intensity plays a more significant role, policy should focus on high-input agricultural systems by promoting precision substitution of mineral fertilizers, improving quality standards and certification for manure-derived fertilizers, and strengthening market channels for organic fertilizer products. In the central region, where manure resource intensity has the strongest positive effect, greater attention should be given to improving the linkage between manure supply and cropland demand, supporting county-level crop–livestock integration, and expanding local treatment and return-to-land capacity so that manure resources can be more effectively converted into realized mitigation potential. In the western region, where mechanization shows a stronger negative association, policy should prioritize investment in transport infrastructure, storage facilities, specialized manure-application machinery, and socialized service systems adapted to longer transport distances and more complex terrain, thereby reducing practical constraints on fertilizer substitution.

Finally, the decomposition of interprovincial inequality suggests that both within-region disparities and cross-regional overlap remain important. This means that policy design should not rely solely on broad east–central–west classification. Instead, macro-regional strategies should be combined with province-specific diagnosis and targeted intervention, especially for provinces whose mitigation performance deviates substantially from the typical level of their region. Provinces with relatively strong performance within otherwise lagging regions may serve as demonstration areas for policy learning, technology diffusion, and service-network expansion. In this sense, transvariation does not merely describe statistical overlap; it also signals the need for more flexible, layered, and fine-grained policy design. Such a differentiated policy framework would better support the goals of nutrient recycling, agricultural carbon mitigation, and rural revitalization in China.

Limitations

It should also be noted that this study has several limitations, which point to directions for future improvements. First, methodologically, our assessment of manure-based mitigation is a technical-potential estimate derived from statistical data and a nutrient-equivalent substitution scenario, rather than a measure of realized substitution under actual production conditions. In practice, the extent to which manure nutrients can replace mineral fertilizers depends on multiple constraints, including manure collection and transport costs, treatment and storage capacity, farmer willingness to adopt organic fertilizers, market acceptance of manure-derived fertilizer products, and spatial mismatches between manure supply and cropland nutrient demand. These behavioral, logistical, and agronomic constraints are difficult to quantify consistently at the provincial scale and were therefore not explicitly modeled in this study.

Second, the analysis primarily focuses on emission reductions in fertilizer production and application under the nutrient-equivalent substitution scenario, i.e., a technical potential assessment. However, manure collection, treatment, storage, and transportation also consume energy and generate emissions, and large-scale manure return-to-land may shift environmental pressure toward CH_4, NH_3, and other pollutants under certain conditions. Therefore, the estimates reported here should not be interpreted as a full life-cycle net mitigation effect across all emission types. Future research should combine substitution accounting with life cycle assessment (LCA) and region-specific management scenarios to evaluate the net trade-offs among different greenhouse gases and other pollutant emissions more comprehensively.

Third, this study does not provide an extensive discussion of environmental risks and supporting measures associated with manure fertilizer utilization. For example, long-term manure application may lead to the accumulation of heavy metals, residues of veterinary pharmaceuticals, and pathogen transmission in soils, which need to be controlled through pretreatment and standards-based regulation. This study focuses on macro-level nutrient and carbon effects and does not investigate these localized environmental impacts in depth; future work should complement the analysis with risk assessment and mitigation strategies. Finally, this study relies on national statistical data and findings synthesized from the literature to infer manure utilization benefits. Although this approach offers broad representativeness, manure nutrient content, soil responses, and mitigation outcomes can vary across regions, cropping systems, and crop types. The regional applicability of our conclusions requires further validation and refinement. For example, optimal manure substitution rates and management practices may differ substantially between humid southern regions with high nitrogen leaching risks and northern dryland regions with low soil organic matter. These differences imply that implementation should follow a “place-based” approach, and future studies should strengthen region- and crop-specific experiments and modeling.

In addition, the time span of this study is designed to capture the policy-intensification period after 2017. Although this window is well suited to examining recent structural changes, extending the analysis backward would help identify longer-term evolution and path dependence in manure utilization and mitigation outcomes. This should be explored in future research, subject to data comparability and parameter consistency across longer time periods.

Overall, despite these limitations, this study provides a useful reference for quantitatively understanding the mitigation potential of livestock manure fertilizer utilization in China. With the accumulation of richer data and the improvement of analytical models, further methodological refinement is feasible, enabling more scientifically robust evidence for decision-makers and supporting China’s green and low-carbon agricultural transition as well as the strategic goals of rural revitalization.

Conclusions

This study quantifies China’s livestock-manure nutrient supply and the associated carbon mitigation potential from nutrient-equivalent substitution of mineral fertilizers over 2017–2024, and demonstrates that both resources and mitigation benefits are spatially uneven. National manure resources and nutrient supply exhibit a “decline–rebound–slight fallback” trajectory, while nutrient composition remains stable, indicating that manure constitutes a reliable composite nutrient source for supporting fertilizer reduction and nutrient cycling. The estimated mitigation potential rebounds after 2019 and is highly concentrated across a small number of provinces, implying that prioritizing key regions and key links of the manure collection–treatment–application chain can yield sizable marginal mitigation gains.

Spatial diagnostics and SDM estimates further confirm that mitigation outcomes display significant positive spatial dependence, highlighting the relevance of interprovincial linkages and potential policy/technology diffusion. Manure resource intensity is a robust driver of mitigation, dominated by local effects, consistent with the place-based nature of manure supply and on-site nutrient absorption constraints. Strong regional heterogeneity underscores the need for differentiated policy packages: manure effects are stronger in Central China; fertilizer intensity is significant mainly in the East, reflecting larger substitution room; and mechanization tends to depress mitigation, especially in Central and Western regions. Accordingly, advancing crop–livestock integration, strengthening manure treatment and socialized application services, and improving cross-regional nutrient coordination are essential to translating technical potential into realizable mitigation under the Rural Revitalization and dual-carbon agendas.

Acknowledgments

This study was supported by the National Key Research and Development Program of China (Grant No. 2023YFD1501001).

AI Usage Disclosure Statement

During the preparation of this work the authors used OpenAI ChatGPT-5.3 in order to assist in English language editing, grammatical correction and manuscript polishing. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Conflict of Interest

The authors declare no conflict of interest.

References

1. CAI Y., ZHANG F., DENG X. Recoupled crop-livestock system can potentially reduce agricultural greenhouse gas emissions by over 40% in China. Environmental Impact Assessment Review, **112**, 107756, **2025**.

2. LIN H., JIAO H., LIN H., XU X. The Evolution of Policies for the Resource Utilization of Livestock Manure in China. Agriculture-Basel, **15** (2), 153, **2025**.
3. DELAHOY M.J., WODNIK B., MCALILEY L., PENAKALAPATI G., SWARTHOUT J., FREEMAN M.C., LEVY K. Pathogens transmitted in animal feces in low- and middle-income countries. International Journal of Hygiene and Environmental Health, **221** (4), 661, **2018**.
4. DENONCOURT C., CHANTIGNY M.H., ANGERS D.A., MAILLARD É., HALDE C. Animal manure application promotes nitrogen and organic carbon accumulation in soil organic matter fractions: A global meta-analysis. Science of The Total Environment, **996**, 180097, **2025**.
5. WELDESEMAYAT SILESHI G., BARRIOS E., LEHMANN J., TUBIELLO F.N. An organic matter database (OMD): consolidating global residue data from agriculture, fisheries, forestry and related industries. Earth System Science Data, **17**, (2), 369, **2025**.
6. HUANG X., WANG S., SHI Z., FANG L., YIN C. Challenges and strategies for biogas production in the circular agricultural waste utilization model: A case study in rural China. Energy, **241**, 122889, **2022**.
7. KLEINMAN P.J.A., SPIEGAL S.A., SILVIERA M.L., BAKER J.M., DELL C.J., BITTMAN S., CIBIN R., VADAS P.A., BUSER M.D., TSEGAYE T. Envisioning the manureshed: Toward comprehensive integration of modern crop and animal production. Journal of Environmental Quality, **51** (4), 481, **2022**.
8. LI X.-S., GU M.-H., CHEN N., LIU Y.-X., NONG M.-L., LI Y.-M., ZHANG Y., WEN Q.-J., WANG Y.-L., LIU W., HE L.-S. Research on the revitalization of rural talents under the strategy of rural revitalization. Asian Agricultural Research, **13** (6), 6, **2021**.
9. ZHANG X., JIN W., DU L. Analysis of the Fertilizer and Energy Utilization Potential of Livestock and Poultry Manure Resources-A Case Study Concerning Liaoning Province, China. Sustainability, **17** (6), 2612, **2025**.
10. SUN J., LI M., ZHAI N., MU H., LI W., LIU H. Enhancing carbon neutrality through blue carbon fisheries: Spatial analysis in Shandong. Regional Studies in Marine Science, **85**, 104125, **2025**.
11. FRANK S., LESSA DERCI AUGUSTYNCZIK A., HAVLíK P., BOERE E., ERMOLIEVA T., FRICKO O., DI FULVIO F., GUSTI M., KRISZTIN T., LAURI P., PALAZZO A., WöGERER M. Enhanced agricultural carbon sinks provide benefits for farmers and the climate. Nature Food, **5** (9), 742, **2024**.
12. ZHU Z., WANG Y., YAN T., ZHANG Z., WANG S., DONG H. Greenhouse gas emissions from livestock in China and mitigation options within the context of carbon neutrality. Engineering Agriculture, **10** (2), 226, **2023**.
13. HAO D., WANG R., GAO C., SONG X., LIU W., HU G. Spatial-Temporal Characteristics and Influence Factors of Carbon Emission from Livestock Industry in China. International Journal of Environmental Research and Public Health, **19** (22), 14837, **2022**.
14. WANG F., PEI X., ZHOU L. Trend and inequality in livestock CO_2 emission intensity: Evidence from 341 prefecture-level cities from 2006 to 2022 in China. Environmental Research, **284**, 122209, **2025**.
15. HE D., DENG X., WANG X., ZHANG F. Livestock greenhouse gas emission and mitigation potential in China. Journal of Environmental Management, **348**, 119494, **2023**.
16. SPIEGAL S., KLEINMAN P.J.A., ENDALE D.M., BRYANT R.B., DELL C., GOSLEE S., MEINEN R.J., FLYNN K.C., BAKER J.M., BROWNING D.M., MCCARTY G., BITTMAN S., CARTER J., CAVIGELLI M., DUNCAN E., GOWDA P., LI X., PONCE-CAMPOS G.E., CIBIN R., SILVEIRA M.L., SMITH D.R., ARTHUR D.K., YANG Q. Manuresheds: Advancing nutrient recycling in US agriculture. Agricultural Systems, **182**, 102813, **2020**.
17. HE Z., DING B., PEI S., CAO H., LIANG J., LI Z. The impact of organic fertilizer replacement on greenhouse gas emissions and its influencing factors. Science of The Total Environment, **905**, 166917, **2023**.
18. NIU J., SAEED Q., WANG W., ZHANG R., LIU L., LV F., XU J., HAN Y., ZHANG P., HU C., XU H., SUN B., YANG X., ZHANG S. Manure replacing synthetic fertilizer improves crop yield sustainability and reduces carbon footprint under winter wheat–summer maize cropping system. Journal of Environmental Management, **358**, 120936, **2024**.
19. DRYGVAL P., DRYGVAL A., TABUNSHCHIK V. Assessment of Organic Carbon Stocks at Landscape Levels Using the InVEST Software. Civil Engineering Journal, **11** (3), 1145, **2025**.
20. ARSIC M., ABDALLA A.L., DONG H., LOYON L., PACKER A.P.C., SAHA C.K., SI B., MEO ZILIO D., AMON B.R. Circular bioeconomy approaches for livestock manure and post-consumer wastes: opportunities for biofertilizers and bioenergy. Animal Frontiers, **15** (4), 54, **2025**.
21. KARUNANITHI R., SZOGI A.A., BOLAN N., NAIDU R., LOGANATHAN P., HUNT P.G., VANOTTI M.B., SAINT C.P., OK Y.S., KRISHNAMOORTHY S. Chapter Three - Phosphorus Recovery and Reuse from Waste Streams. Advances in Agronomy, pp. 173, **2015**.
22. KARAKULOV F., MENGLIKULOV B., MAMASADIKOV A., KHOLBUTAEVA S., MUKHTOROV A., ABDULKHAEVA G., GAFUROVA D., RUZIYEV S., ABLATDINOV S., DURMANOV A. The Impact of Climate-Smart Technology Adoption on Agricultural Productivity and Environmental Sustainability. Emerging Science Journal, **9** (6), 3087, **2025**.
23. SADEGHPOUR A., AFSHAR R.K. Livestock manure: From waste to resource in a circular economy. Journal of Agriculture and Food Research, **17**, 101255, **2024**.
24. WEI S., ZHU Z., ZHAO J., CHADWICK D.R., DONG H. Policies and regulations for promoting manure management for sustainable livestock production in China: a review. ENGINEERING Agriculture, **8** (1), 45, **2021**.
25. WIJITKOSUM S., SRIBURI T., TOONSIRI P. Effect of One-Time Application of Biochar and Compost on Soil and Maize During 5-Time Consecutive Periods of Crop Cultivation. Emerging Science Journal, **9** (1), 114, **2025**.
26. LI M., ZHANG X., WANG Y., HOU J., TIAN X., ZHANG W., TANG K.H.D., ZHANG Z., MEI C., LI R. Microbial mechanisms driving carbon emissions and humification in inoculant-enhanced swine manure composting: Insights into inoculation timing. Journal of Environmental Chemical Engineering, **14** (2), 121298, **2026**.
27. XU S.-Q., CHEN W.-J., XIE L.-Q., CHAI S.-Y., JIA K.-X., WEI Y.-Q. Organic waste resources and nutrient utilization potential in China. Journal of Plant Nutrition and Fertilizers, **28** (8), 1341, **2022**.
28. QIN Q., YAN H., LIU J., CHEN X., YE B. China's agricultural GHG emission efficiency: regional disparity and spatial dynamic evolution. Environmental Geochemistry and Health, **44** (9), 2863, **2022**.

29. YANG M., CHU J., LI Z., LIU X., YU F., SUN F. An Examination of Regional Variations in Pesticide Usage and Grain Yield in China Before and After the Double Reduction Policy's Adoption. Polish Journal of Environmental Studies, **32** (2), 1887, **2023**.
30. DEBARSY N., LE GALLO J. Identification of Spatial Spillovers: Do's and Don'ts. Journal of Economic Surveys, **39** (5), 2152, **2025**.
31. XU K., ZHANG Q.-Q., CAI Y.-Y., LUO X.-J., ZHAI Y.-Q., LIU W.-R., YING G.-G. Diagnosing spatial decoupling of manure and crop nutrients in China: drivers and multi-objective optimization for sustainable redistribution. npj Sustainable Agriculture, **4** (1), 11, **2026**.
32. HE T., ZHANG W., ZHANG H., SHENG J. Estimation of Manure Emissions Issued from Different Chinese Livestock Species: Potential of Future Production. Agriculture, **13** (11), 2143, **2023**.
33. CHEN B., GU B., ZHANG X., CHENG L., WANG C., DONG H., ROS G.H., DE VRIES W., WANG M. Drivers of livestock manure nitrogen recycling on county scale in China. Journal of Environmental Management, **380**, 125075, **2025**.
34. CHAO Z., ZHU Z., LI Y. Spatial-temporal characteristics and influencing factors of farmland carbon emissions in Guangdong Province, China. Frontiers in Environmental Science, **12**, **2025**.
35. HATANO R. Study on the occurrence, impact, and mitigation of soil-derived environmental loads in agricultural ecosystems. Soil Science and Plant Nutrition, **71** (4), 371, **2025**.
36. YU K., FANG X., ZHANG Y., MIAO Y., LIU S., ZOU J. Low greenhouse gases emissions associated with high nitrogen use efficiency under optimized fertilization regimes in double-rice cropping systems. Applied Soil Ecology, **160**, 103846, **2021**.
37. YIN J., WANG J., LI Y., ZHANG Y. China's rural revitalization in the context of rural depopulation: Challenges, opportunities and responses. Journal of Rural Studies, **123**, 103985, **2026**.
38. LIU Y., HU S., CHEN N., RAN Z. Multifunctional rural areal system transformation and rural revitalization. Agricultural Environment and Sustainability, **1** (1), 100007, **2026**.