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# Diagnosing spatial decoupling of manure and crop nutrients in China: drivers and multi-objective optimization for sustainable redistribution

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China's uneven farming distribution creates significant mismatches between manure nutrients and crop demands, causing pollution in surplus areas and deficits in agricultural heartlands. This study diagnosed the distribution and drivers of nitrogen (N) and phosphorus (P) nutrient mismatches, and developed a Non-dominated Sorting Genetic Algorithm II (NSGA-II) optimization model for interprovincial manure redistribution, which minimizes transport distance and application-phase greenhouse gas (GHG) emissions while respecting ecological thresholds across China. China shows a regional N/P imbalance, with surpluses in the west and deficits in densely populated and grain-producing regions, dominated by a nitrogen gap. Nutrient surpluses are jointly driven by regional socio-economic development, cropping structure, and manure management efficiency. Strategic redistribution of  $0.300 \times 10^6$  tons of N and  $0.047 \times 10^6$  tons of P to recipient provinces reduced land carrying capacity saturation rates (LCCSRs) of surplus regions to safe levels and decreased the national average LCCSRs by 39.3% for N and 24.1% for P. Simultaneously, the increase in GHG emissions was controlled to within 8.5%. This study offers theoretical and practical optimization tools for sustainable manure management under China's carbon neutrality, advancing nutrient goals and establishing quantitative bases for regional circular agriculture and ecological sustainability.

China's livestock sector has expanded significantly, supporting  $8.26 \times 10^9$  heads and generating  $3.80 \times 10^9$  tons of manure by 2023-half of the global total<sup>1-3</sup>. However, the resource utilization rate remains below 60% in many regions<sup>1,4,5</sup>, creating both challenges and opportunities: while the abundant manure nutrients could serve as valuable crop fertilizers, their potential is undermined by significant spatial disparities in production and utilization. Approximately 70% of China's breeding industry is concentrated in 10 out of 34 provinces, creating a mismatch with crop production areas that exacerbates manure allocation difficulties<sup>4-6</sup>. This imbalance has led to regional over-application, resulting in environmental pollution through soil and water contamination<sup>4,5,7</sup>. In response, national policies have set ambitious targets, such as achieving over 80% manure utilization by 2025<sup>8</sup>.

However, significant barriers remain in achieving sustainable manure management. Key knowledge gaps persist regarding the spatial distribution of nutrient flows between livestock production and crop demand systems, along with an insufficient understanding of the drivers behind these imbalances. The challenges are compounded by wide regional variations in manure treatment efficiency (ranging from <30% to >70% nutrient recovery) and divergent crop nutrient needs shaped by heterogeneous climatic conditions, diverse topography, and uneven economic development<sup>9-13</sup>. Collectively, these factors generate a complex agricultural dichotomy: intensive livestock production regions exhibit nutrient surpluses with associated environmental pollution, while crop cultivation areas suffer from nutrient deficiencies leading to soil degradation and yield constraints<sup>14-16</sup>.

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Three aspects are crucial for optimizing manure redistribution. First, assessing land carrying capacity is essential to avoid exceeding ecological limits<sup>17,18</sup>. Second, accurate quantification of regional manure nutrient availability is needed. While baseline manure output can be readily calculated from statistical data<sup>1,13,19,20</sup>, actual nutrient content varies significantly by livestock species, breeding scale, manure treatment methods, and application patterns<sup>21–23</sup>. The National Pollution Survey data, which provides spatially explicit information on breeding details and manure management practices across China's counties and districts<sup>24</sup>, currently serves as the most comprehensive dataset for such analysis. Third, agricultural and food systems are major drivers of global climate change, with the Food and Agriculture Organization reporting that greenhouse gas (GHG) emissions from agricultural land account for over 30.0% of total anthropogenic emissions globally<sup>25</sup>. Thus, the variation in GHG emissions from manure application, influenced by diverse crop and soil types across regions<sup>26,27</sup>, must be integrated to ensure low-carbon sustainability.

Despite recognition of these aspects, current manure allocation practices remain fragmented, often relying on single indicators or manual distribution approaches. While several studies have sought to enhance manure management at the household or farm scale—for instance, through targeted subsidies for organic fertilizer use or standardization of management techniques<sup>5,28,29</sup>—these interventions remain constrained by the lack of regional data on nutrient demand and application. As a result, practices default to local disposal, failing to resolve the fundamental spatial mismatch between livestock production and cropland availability, let alone incorporate low-carbon manure application practices. Indeed, improving feed conversion efficiency, advancing manure treatment technologies, and adjusting livestock production structures can reduce GHG emissions from the livestock sector<sup>30–32</sup>. However, such strategies focus mainly on emissions during manure generation and collection, overlooking both the GHG impacts from field application and the need for region-specific management<sup>26,27</sup>. Overall, approaches that address only one or two dimensions prove inadequate for managing the complexity of interregional nutrient flows or balancing multiple objectives such as nutrient equilibrium and ecological constraints. This analysis underscores a critical research gap: the absence of an integrated spatial optimization framework that can jointly address nutrient balance, land carrying capacity, and GHG trade-offs across provinces. Such a framework is essential to move beyond localized or single-objective solutions and achieve system-level sustainability<sup>33–35</sup>.

With technological advancements, sophisticated algorithms such as the Non-dominated Sorting Genetic Algorithm II (NSGA-II) have emerged as an effective tool for tackling the complexity of resource distribution problems. The NSGA-II, with its mechanisms of fast non-dominated sorting and crowding distance calculation, can efficiently identify and maintain the Pareto front and thereby achieve dynamic balance across multiple objectives<sup>36–38</sup>. This algorithm has been extensively applied to multi-objective optimization problems across various domains, including agricultural yield optimization and irrigation system design<sup>39–41</sup>. Notably, its effectiveness in handling spatial distribution problems has been well-documented<sup>42–44</sup>. These capabilities render NSGA-II particularly well-suited for regional manure allocation.

**Table 1 | Nutrient supply from livestock manure in China**

Type	Nitrogen		Phosphorus	
	Supply (10 <sup>6</sup> tons)	Proportion (%)	Supply (10 <sup>6</sup> tons)	Proportion (%)
Pig	2.04	29.4	0.348	29.6
Beef cattle	1.97	28.4	0.300	25.6
Dairy cattle	0.468	6.70	0.089	7.60
Poultry	2.46	35.5	0.437	37.2
Total	6.94	100.0	1.18	100.0

Thus, this study aims to diagnose the spatial decoupling of manure nutrients and crop demand across China, and then to explore optimization strategies to balance national nutrients employing the NSGA-II algorithm. For this purpose, the study seeks to: (1) quantify provincial-scale livestock manure nutrient availability and crop demand; (2) analyze the spatial patterns and driving mechanisms of nutrient surpluses and deficits; and (3) build an NSGA-II model to determine optimal spatial allocation pathways that efficiently transfer manure nutrients from surplus to deficit regions, minimizing transport distance and associated GHG emissions while optimizing land carrying capacity nationwide. This research provides scientific knowledge for manure management and a systematic data-driven approach to support sustainable livestock-agricultural systems through improved nutrient recycling.

## Results and discussion

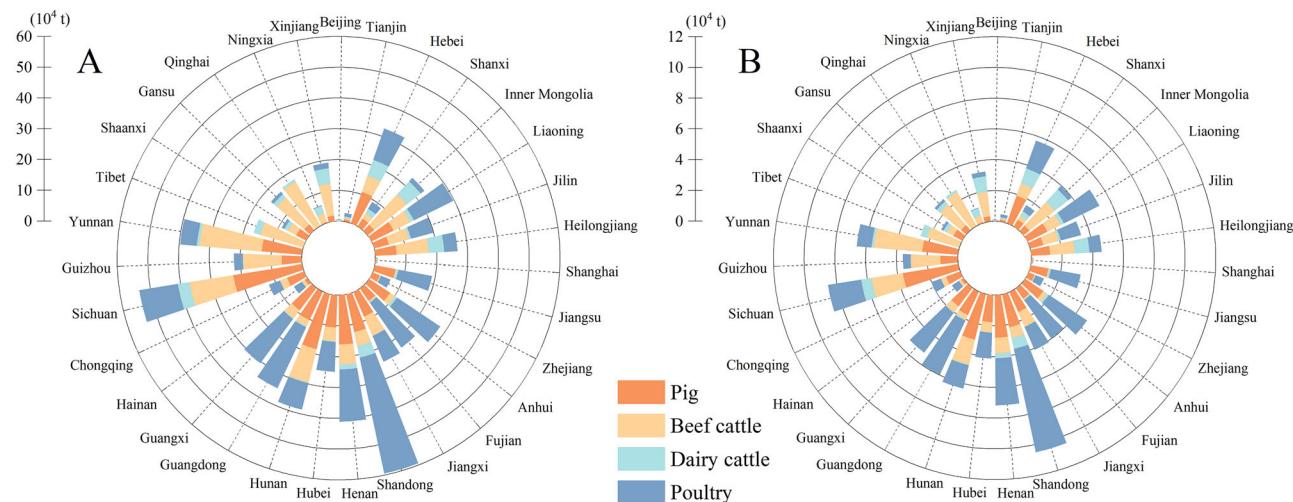
### Nutrient supply from livestock manure in provinces of China

In 2020, livestock manure from 31 provinces in China provided substantial nutrient supplies, yielding  $6.94 \times 10^6$  tons of N and  $1.17 \times 10^6$  tons of P. The N supply was significantly higher than that of P, consistent with previous research results<sup>18,45</sup>. Among all livestock types, as shown in Table 1, poultry manure contributed the highest amounts of both N and P nutrients, with supplies of  $2.46 \times 10^6$  and  $0.437 \times 10^6$  tons, respectively, representing 35.5% and 37.2% of respective totals. Pig and beef cattle manure were the dominant nutrient sources, contributing 29.4% and 28.4% of total nitrogen (N), and 29.6% and 25.6% of total phosphorus (P), respectively. Dairy cattle manure, however, supplied the least—only  $0.468 \times 10^6$  tons of N (6.75% of total N) and  $0.089 \times 10^6$  tons of P (7.61% of total P). This ranking of nutrient contributions across livestock categories aligns with previous studies<sup>46,47</sup>. To quantitatively compare their nutrient contributions, this study normalized the livestock populations into pig-equivalent units based on standard manure excretion coefficients, which account for these species-specific differences. The results showed that poultry and pigs constituted the largest shares, at 37.0% and 34.7% of the total pig-equivalent units, respectively, followed by beef cattle (23.4%) and dairy cattle (4.80%). This indicates that the difference in manure nutrient contributions is largely proportional to the relative breeding scale of each livestock type, with poultry and pigs dominating in most provinces. Beyond scale, nutrient composition per unit manure also varies significantly: poultry excreta are typically more concentrated due to high-efficiency feed and unique physiology, whereas dairy cattle—often raised in extensive systems with higher roughage intake and lower feed conversion efficiency—produce manure with lower nutrient density<sup>47</sup>.

The provincial-scale analysis identified clear geographic concentrations in nutrient supply patterns (Fig. 1). Three provinces, including Shandong, Sichuan, and Henan, emerged as dominant nutrient hotspots, collectively contributing 22.2% (N) and 22.4% (P) of national totals, with individual nutrient supply substantially exceeding regional averages. This discrepancy is closely related to the agricultural structure and the breeding industry scale in these provinces<sup>48</sup>. Notably, Shandong and Sichuan lead in poultry and pig breeding volumes, respectively, while Henan ranks among China's top four for both pig and poultry categories (Supplementary Table 1). In contrast to major agricultural provinces, urban-focused municipalities, including Beijing, Shanghai, and Tianjin, maintain minimal contributions (0.583% N and 0.599% P), aligning with their limited livestock production. Other provinces exhibited varying nutrient outputs commensurate with their production scales. For example, Hebei's elevated outputs reflect its large operations, while Yunnan's substantial contribution stems from its leading beef cattle inventory. Overall, the regional disparity in nutrient supply not only reflects the varying scales of livestock farming across provinces but also underscores the profound influence of agricultural structure on manure nutrient availability.

### Nutrient demand of crops in provinces of China

In 2020, the total nutrient demand of crops in China for N and P reached 24.3 and  $6.46 \times 10^6$  tons, respectively (Table 2), reflecting an



**Fig. 1 | Nutrient supply from livestock manure in provinces of China in 2020. A is for nitrogen and B is for phosphorus.**

**Table 2 | Nutrient demand for different types of crops in China**

Crop type	Nitrogen	Phosphorus			
	Demand (10 <sup>6</sup> tons)	Proportion (%)	Demand (10 <sup>6</sup> tons)	Proportion (%)	
Food crop	Rice	4.66	19.2	1.69	26.3
	Wheat	4.03	16.6	1.34	20.8
	Maize	6.00	24.7	0.782	12.1
	Millet	0.088	0.360	0.0100	0.160
	Sorghum	0.057	0.240	0.0150	0.240
	Beans	1.59	6.54	0.165	2.55
	Potato	0.143	0.590	0.0250	0.390
	Other	0.112	0.460	0.0540	0.830
Economic crop and vegetable	Peanut	1.28	5.26	0.157	2.44
	Rapeseed	0.604	2.49	0.379	5.87
	Other	0.192	0.79	0.070	1.09
	Cotton	0.691	2.85	0.180	2.78
	Sugar crops	0.252	1.04	0.025	0.380
	Tobacco leaves	0.081	0.340	0.011	0.170
	Tea leaves	0.188	0.770	0.026	0.400
	Vegetables	2.74	11.3	0.754	11.7
	Melons and fruits	0.365	1.50	0.218	3.37
	Garden fruits	0.973	4.01	0.330	5.12
	Planted woodland	0.217	0.900	0.217	3.37
Total	24.3	100	6.46	100	

increase of 3.68 and  $1.9 \times 10^6$  tons compared with 2017<sup>45</sup>. Food crops, including rice, wheat, and maize, accounted for the majority of these demands. Specifically, the N and P demands from these crops constituted 68.7% ( $16.7 \times 10^6$  tons) and 63.3% ( $4.09 \times 10^6$  tons) of the total, respectively. Maize had the highest N demand at  $6.00 \times 10^6$  tons (24.7% of the national total), followed by rice (19.2%) and wheat (16.6%). This nutrient demand structure highlights the dominant role of staple crops in China's agricultural system. Moreover, the extensive cropland area of three major grain crops, approximately  $41.3 \times 10^6$  ha<sup>49</sup>, further emphasizes their critical dependence on fertilizer resources for food security. Economic crops and vegetables also exhibited considerable nutrient demand, accounting for about one-tenth of the total (Table 2). This reflects the dual trends of agricultural diversification and farmers' economic optimization strategies.

The spatial distribution of agricultural planting structures, defined by the composition and layout of major crop types, significantly influences regional disparities in nutrient demand. Major grain-producing provinces, including Heilongjiang, Sichuan, and Henan, exhibit substantially higher N and P requirements compared to other regions. As shown in Fig. 2, Heilongjiang had the highest nutrient demand nationwide, with N and P reaching  $1.55$  and  $0.331 \times 10^6$  tons, respectively, accounting for 9.92% and 8.70% of the national totals. Sichuan and Henan follow closely in nutrient requirements. This pronounced demand pattern primarily stems from two key factors: the extensive cropland area in these provinces and their grain-centric agricultural systems, where intensive crop production drives substantial nutrient consumption. In contrast, provinces with highly urbanized areas like Beijing and Shanghai show considerably lower N and P demands ( $0.035 \times 10^6$  tons N and  $0.009 \times 10^6$  tons P) due to limited cropland.

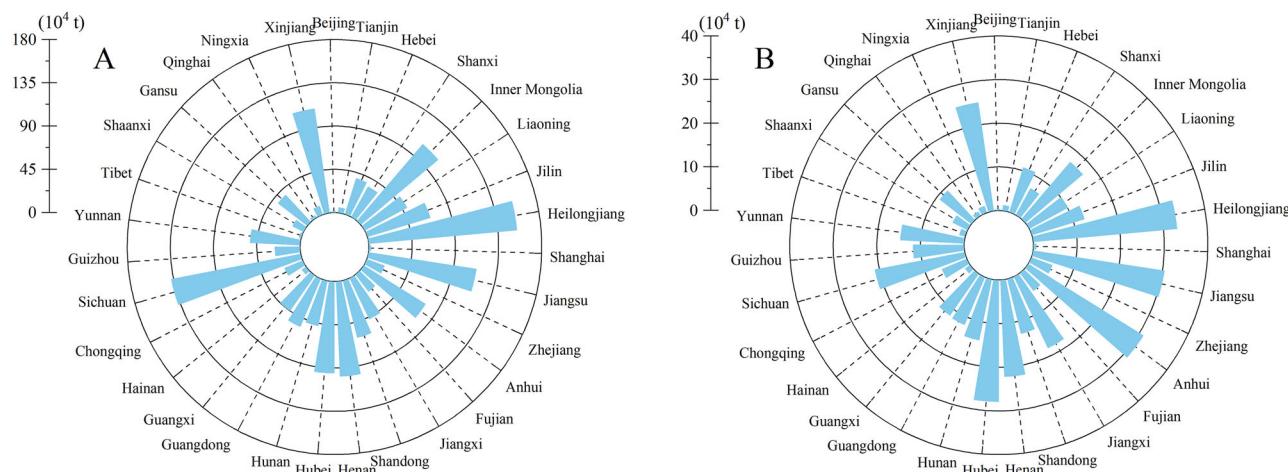


Fig. 2 | Crop nutrient demand in provinces of China in 2020. A is for nitrogen and B is for phosphorus.

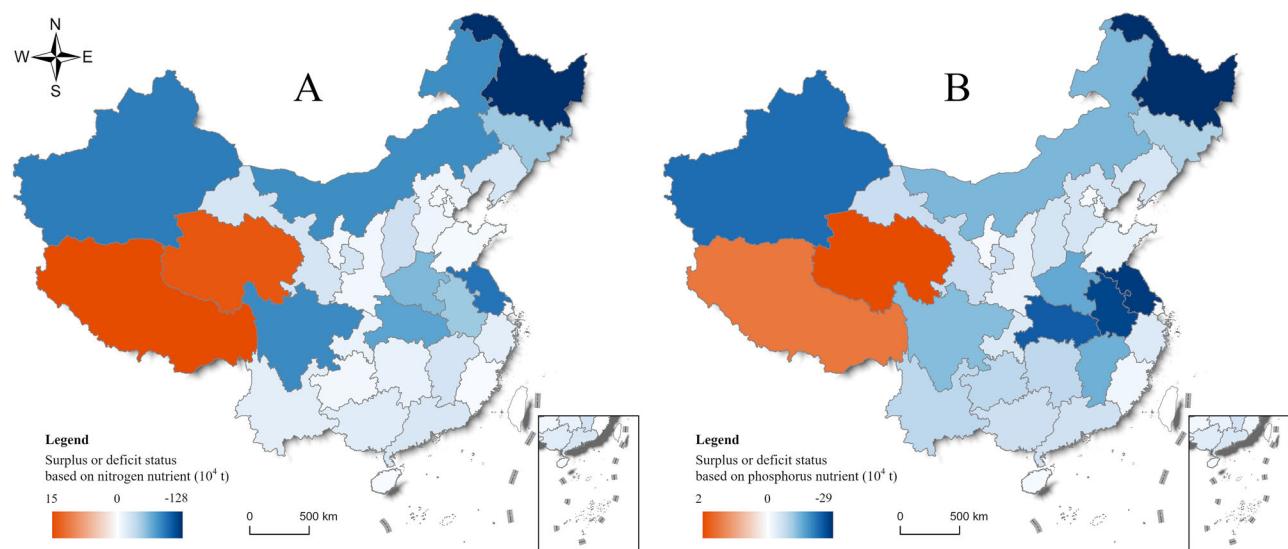


Fig. 3 | Nutrient surplus and deficit status in provinces of China in 2020. A is for nitrogen and B is for phosphorus.

Notably, these urbanized regions exhibit distinct nutrient utilization patterns characterized by both reduced total demand and enhanced land-use efficiency through specialized cultivation of high-value crops such as vegetables and fruit trees. This is reflected in their nutrient demand per unit cropland area (128.5–151.9 kg/ha for N; 25.2–31.1 kg/ha for P), which exceeds that of grain-producing provinces (67.3–139.4 kg/ha for N; 15.1–22.2 kg/ha for P), consistent with the findings reported by Zhu et al.<sup>45</sup>. Such pronounced regional disparities not only reflect fundamental differences in agricultural systems but also underscore the tight coupling between production patterns and nutrient requirements. Therefore, region-specific and crop-specific fertilizer application protocols should be developed according to differentiated nutritional requirements.

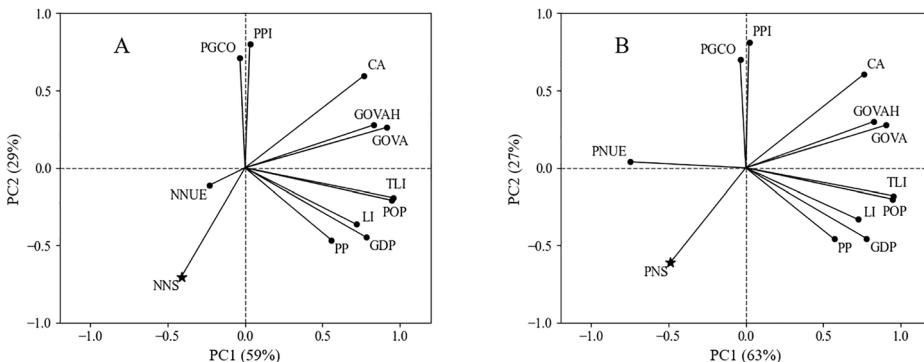
#### Spatial patterns and driving mechanisms of nutrient surpluses and deficits

**Regional imbalance in nutrient surpluses and deficits analysis.** The spatial heterogeneity of regional nutrient balance in China reveals a significant mismatch between livestock manure nutrient supply and crop demand, characterized by distinct regional surpluses and deficits (Fig. 3). Western provinces such as Qinghai and Tibet exhibit notable advantages in livestock industry development due to their vast land areas, low population density, and abundant grassland resources<sup>50,51</sup>. These

conditions facilitate large-scale livestock farming and the accumulation of manure-derived nutrients. However, the plateau continental climate prevailing in this region, marked by persistently low temperatures, limited annual precipitation, and a sparse, fragmented distribution of cropland—significantly restricts grain production capacity<sup>52–54</sup>. Taking Qinghai as a representative case, cropland accounted for only 0.8% of the province's total land area in 2020, and agricultural productivity was markedly below the national average<sup>55,56</sup>. As a result, crop nutrient uptake remained minimal, leading to substantial nutrient surpluses— $0.144 \times 10^6$  tons for N and  $0.016 \times 10^6$  tons for P. A similar pattern was observed in Tibet, which reported N and P surpluses of  $0.146 \times 10^6$  tons and  $0.013 \times 10^6$  tons, respectively. These figures reflect a typical “high supply-low demand” structural surplus pattern. A parallel nutrient surplus pattern was observed in Fujian Province, a southeastern coastal region with extensive livestock production ( $1.04 \times 10^9$  heads, ranking 6th nationally). Despite its relatively high level of economic development, Fujian has limited cropland resources, and crop nutrient demand remains low ( $0.234 \times 10^6$  tons, ranking 23rd nationally). The province exhibits a modest N nutrient surplus of  $0.010 \times 10^6$  tons.

In contrast, central China (Henan, Hubei), eastern China (Jiangsu, Anhui), and northeastern China (Heilongjiang, Jilin) face widespread nutrient deficits exacerbated by high population densities and substantial

**Fig. 4 | Principal component loadings of driving factors related to nutrient surpluses.** A is for nitrogen and B is for phosphorus. *NNS* N nutrient surplus, *PNS* P nutrient surplus, *NNUE* N nutrient utilization efficiency, *PNUE* P nutrient utilization efficiency, *PGCO* Proportion of grain crops output, *PPI* Proportion of primary industry, *CA* Cropland area, *GOVAH* Gross output value of animal husbandry, *GOVA* Gross output value of agriculture, *TLI* Total livestock inventory, *POP* Population, *GDP* Gross Domestic product, *PP* Proportion of poultry, *LI* Livestock intensity.



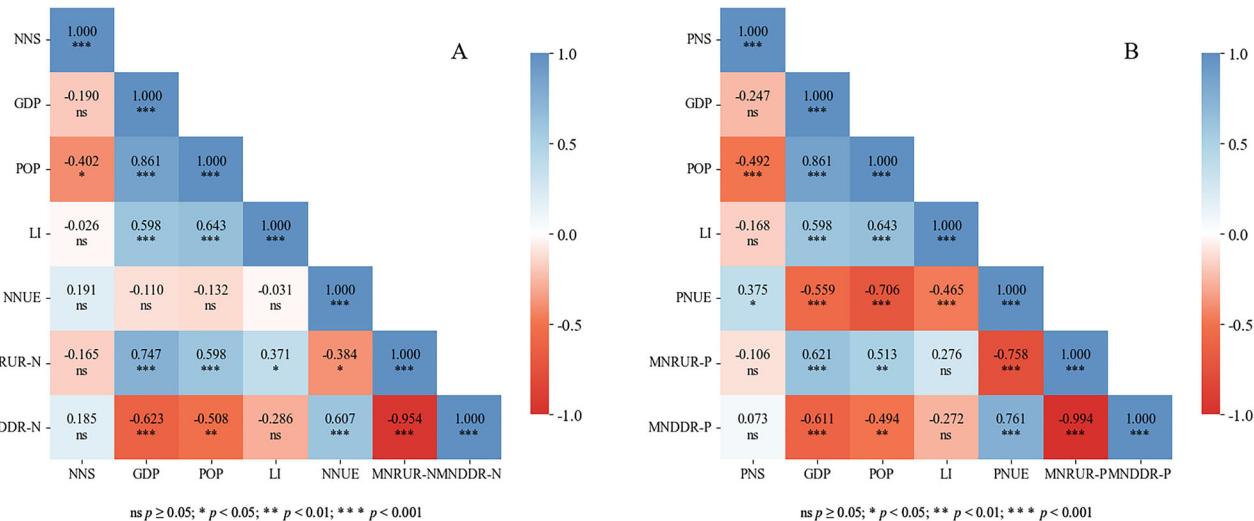
agricultural demands. Henan Province, a critical national grain production base, sustains extensive cereal cultivation, with wheat and maize yields ranking among the highest nationwide<sup>57,58</sup>, driving substantial nutrient demand. Similarly, Hubei Province's prevalent double-cropping rice systems exhibit high N and P uptake throughout the growth cycle<sup>41,59,60</sup>. However, limited land resources restrict livestock development in these regions, hindering effective organic fertilizer supplementation and worsening nutrient supply-demand imbalances<sup>61</sup>. In northeastern China, Heilongjiang and Jilin provinces—key national commodity grain bases—maintain vast croplands with high yields but face persistent nutrient shortage<sup>13,62</sup>. However, chronic over-cultivation of chernozem soils under unsustainable “high extraction-low replenishment” practices has degraded soil fertility and exacerbated erosion<sup>63,64</sup>, increasing reliance on external nutrient inputs. Concurrently, the decoupling of planting and breeding industries has drastically reduced manure application<sup>23</sup>, exacerbating regional N-P deficits. Notably, Heilongjiang exhibits the most severe deficits nationwide, with N and P deficits reaching  $1.28 \times 10^6$  tons (14.3% of the national total) and  $0.286 \times 10^6$  tons (10.7% of the national total), respectively.

From a national perspective, the imbalance between supply and demand of N and P is highly consistent, but the spatial gap of nitrogen is more prominent. Calculations reveal total national deficits of  $8.69 \times 10^6$  tons for N and  $2.66 \times 10^6$  tons for P, with the N exceeding P by  $6.05 \times 10^6$  tons. This disparity primarily stems from provincial variations in cropping systems and agricultural structures. Crop-specific nutrient acquisition patterns exhibit marked divergence, particularly in N and P use efficiency. As China's predominant staple crops, rice and wheat have high nitrogen requirements and exhibit strong yield dependence on N availability<sup>65,66</sup>. In contrast, phosphorus is more closely associated with early-stage physiological processes such as root development and cell division, making its demand more prominent in certain vegetables and cash crops<sup>12,67</sup>. In 2020, the planting area of cereal crops in China accounted for 69.7% of the total cropland area for all crops, far exceeding that of cash crops and vegetables, and thereby driving a much greater national demand for N than for P<sup>56</sup>. Moreover, soils exhibit a measurable P accumulation effect, which further explains why the national N deficit generally surpasses that of P<sup>68</sup>. These findings suggest that nutrient imbalances in China have evolved beyond isolated regional issues and now represent a systemic phenomenon. The coexistence of nutrient surpluses and deficits across regions not only exacerbates environmental risks but also poses structural challenges to the country's green agricultural transition. This widespread pattern indicates that the drivers of nutrient surpluses extend well beyond natural resource constraints and are deeply rooted in broader socio-economic structures, agricultural production systems, and manure management practices.

**Analysis of the driving factors of nutrient surpluses and deficits.** To identify the key drivers of nutrient surpluses and deficits across Chinese provinces, this study applied principal component analysis (PCA) to evaluate the socio-economic, agricultural, and management-related factors influencing N and P surpluses (negative values were used to

denote nutrient deficits). Despite regional variations in natural conditions and development models, the results revealed strong consistency in the dominant controlling factors at the national scale (Fig. 4). The first principal component (PC1), representing “economic development and agricultural scale,” exhibited high positive loadings ( $>0.7$ ) for agricultural and livestock output values, GDP, population, livestock inventory and intensity, and cropland area. Notably, both N and P surpluses exhibited negative loadings on PC1, indicating that provinces with more developed and intensive agricultural systems tend to have lower nutrient surpluses or even structural deficits. This pattern is particularly evident in provinces like Jiangsu, where high GDP corresponds to substantial N and P deficits, at  $-0.947 \times 10^6$  tons and  $-0.272 \times 10^6$  tons, respectively. The second principal component (PC2) was defined by high loadings of the proportion of primary industry and grain crops output, forming a “traditional cropping structure” dimension. PC2 is also negatively correlated with nutrient surpluses, indicating that regions dominated by grain crops, which typically have high nutrient uptake capacity, tend to exhibit lower nutrient surplus levels. For instance, Heilongjiang, with grain crops accounting for 89.9% of cultivation, faces significant N and P deficits, underscoring long-term cropland depletion and soil degradation concerns. Further analysis revealed distinct drivers for N versus P surpluses and deficits: N surpluses were highly sensitive to “manure recycling efficiency,” with N nutrient utilization efficiency loading strongly (0.842) on the third principal component (PC3) as an independent driver (Supplementary Table 2). In contrast, P surpluses were jointly influenced by P nutrient utilization efficiency (PC1 loading:  $-0.750$ ) and the proportion of grain crops output (PC2 loading: 0.700). This is closely related to their distinct characteristics: N is prone to migration with water and has diverse loss pathways, whereas P is prone to enrichment in soil<sup>69–71</sup>.

To elucidate the underlying mechanisms through which various driving factors influence manure nutrient surpluses, we conducted Spearman correlation analyses and used  $R^2$  to quantify the strength of these associations. As shown in Fig. 5, although some correlations were not statistically significant ( $p \geq 0.05$ ), a consistent trend was observed. Livestock intensity (LI) showed strong positive correlations with POP ( $R^2 = 0.643$ ,  $p < 0.001$ ) and GDP ( $R^2 = 0.598$ ,  $p < 0.001$ ), indicating that economically developed and densely populated regions are more likely to adopt more intensive livestock production systems. However, LI exhibited a weak positive correlation with the manure nutrient resource utilization ratio of N ( $R^2 = 0.371$ ,  $p = 0.040$ ), and was negatively correlated with the P nutrient utilization efficiency PNUE ( $R^2 = -0.465$ ,  $p < 0.001$ ). These findings suggest that while intensive livestock systems may promote manure collection and treatment, they tend to lower overall PNUE, likely owing to excessive manure generation and constrained nutrient assimilation capacity. Therefore, the impact of LI on nutrient surpluses is largely indirect-mediated through factors such as management capability, land limitations, and infrastructure development, rather than through direct enhancements in manure recycling. Moreover, both N and P surpluses were generally negatively associated with MNRUR, yet positively correlated with MNDDR.



**Fig. 5 | Spearman correlations between provincial nutrient surpluses and their driving factors across China.** A is for nitrogen and B is for phosphorus. NNS N nutrient surplus, PNS P nutrient surplus, NNUE N nutrient utilization efficiency, POP Population, GDP Gross domestic product, LI Livestock intensity.

PNUE P nutrient utilization efficiency, MNDDR-N/P Manure nutrient direct discharge ratio of N/P, MNRUR-N/P Manure nutrient resource utilization ratio of N/P, POP Population, GDP Gross domestic product, LI Livestock intensity.

These patterns imply that unregulated disposal is a key pathway contributing to nutrient surpluses. Provincial-scale observations further substantiated these findings. For instance, Jiangsu, one of China's most economically developed provinces, exhibited high MNRUR (58.1% for N and 67.9% for P), accompanied by substantial nutrient deficits, reflecting a typical "high recycling-low surplus" pattern. In contrast, less developed provinces such as Qinghai and Tibet, where the MNDDR reached 20.2% and 32.0%, respectively, reported large nutrient surpluses ( $0.144 \times 10^6$  tons N and  $0.146 \times 10^6$  tons P), highlighting the risks associated with limited treatment capacity. Notably, GDP showed a strong positive correlation with MNRUR ( $R^2 = 0.747$  for N and  $R^2 = 0.621$  for P), and a negative correlation with MNDDR ( $R^2 = -0.623$  for N and  $R^2 = -0.611$  for P), highlighting economic development's role in enabling infrastructure and management improvements that structurally mitigate nutrient surpluses<sup>7,23</sup>.

Collectively, integrated analysis reveals that China's nutrient surplus dynamics are shaped by complex interactions among multiple driving factors. Economic development establishes the fundamental capacity for waste treatment infrastructure and regulatory implementation, while cropping systems determine nutrient assimilation potential. The manure resource utilization efficiency emerges as a critical control variable that directly regulates surplus magnitude. Importantly, manure management represents a pivotal nexus connecting socio-economic development with environmental performance, uncovering an efficiency-driven transformation mechanism essential for agricultural sustainability. Nevertheless, localized improvements in manure treatment capacity cannot fully address the fundamental spatial disconnection between livestock production and crop cultivation. With severe nutrient overloads in less-intensive livestock regions coexisting with chronic deficits in major grain belts, implementing coordinated interregional manure redistribution systems becomes imperative to achieve optimal spatial allocation and enhance circular resource efficiency.

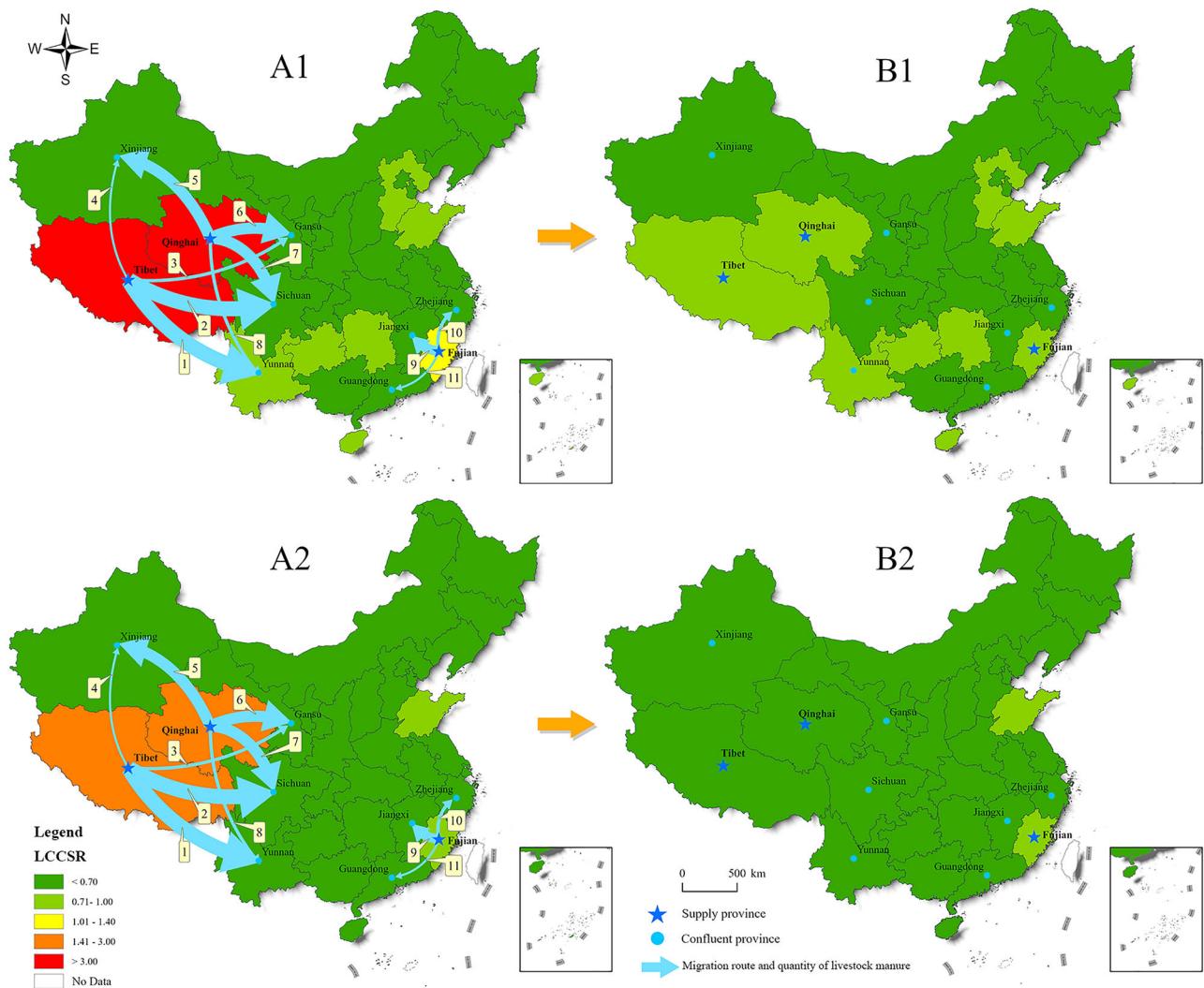
#### Manure redistribution and assessment of land carrying capacity

By conducting an in-depth analysis of nutrient status across Chinese provinces, Tibet, Qinghai, and Fujian were identified as major nutrient source provinces. Their nutrient confluent provinces were Xinjiang-Gansu-Sichuan-Yunnan, Gansu-Sichuan-Xinjiang-Yunnan, and Zhejiang-Jiangxi-Guangdong, respectively (Fig. 6A1, A2). These regions face severe nutrient overload as livestock manure production substantially exceeds local crop land assimilation capacity, potentially causing environmental hazards such as water eutrophication and also increasing the risk of accumulation of heavy metals in soils—notably copper (Cu) and zinc (Zn)<sup>2,33,74</sup>. These metals

primarily originate from livestock manure application, as they are commonly introduced through animal feed supplements<sup>14,75</sup>. The implementation of nutrient transfer strategies has proven highly effective, as shown in Fig. 6B1, B2. For Tibet, transferring  $0.146 \times 10^6$  tons of N and  $0.023 \times 10^6$  tons of P to the confluent provinces of Xinjiang, Gansu, Sichuan, and Yunnan reduced its land carrying capacity saturation rate (LCCSR) of N from 7.58 to 1.00 and its LCCSR of P from 1.91 to 0.252. Similarly, by transferring  $0.144 \times 10^6$  tons of N and  $0.022 \times 10^6$  tons of P to Gansu, Sichuan, Xinjiang, and Yunnan, Qinghai reduced its LCCSR of N and P from 6.03 to 1.00 and from 2.58 to 0.428, respectively. As a province with a mild N surplus, Fujian managed to reduce its LCCSR of N from 1.04 to 1.00 through livestock manure redistribution and appropriate nutrient transfers, thereby significantly mitigating potential environmental risks.

Our analysis reveals increased but acceptable nutrient carrying capacity across recipient provinces through interprovincial manure redistribution. Sichuan Province, a major nutrient sink, received a total of  $0.081 \times 10^6$  tons of N and  $0.013 \times 10^6$  tons of P from Tibet and Qinghai (15.1% of its original supply), increasing its LCCSR of N and P from 0.390 to 0.449 and from 0.409 to 0.471, respectively. Yunnan showed similar improvements, with total nutrients increasing from 0.397 to  $0.444 \times 10^6$  tons N and 0.066 to  $0.074 \times 10^6$  tons P, raising its LCCSR from 0.760/0.451 to 0.851/0.505 for N/P. Notably, Gansu exhibited the highest proportional reception (25.0% of original supply), with LCCSR increasing by 0.107 (N) and 0.0729 (P) to 0.537 and 0.365, demonstrating robust soil nutrient reception potential. The nutrient redistribution strategy yielded significant improvements across all recipient provinces, though with varying effectiveness. While all confluent provinces maintained LCCSR within acceptable limits post-transfer, several exhibited indices below 0.5 (half the balanced threshold of 1.00), revealing considerable remaining assimilation potential. The optimized spatial allocation reduced national average LCCSR substantially—N from 0.932 to 0.566 and P from 0.486 to 0.369, effectively mitigating regional nutrient imbalances and enhancing manure utilization efficiency.

However, the GHG emissions resulting from manure application for interprovincial nutrient transfer are significant and cannot be overlooked. This study found that, following nutrient receipt, the global warming potential (GWP) of confluent provinces varied between  $6.09 \times 10^{-5}$  and 3.72 Mt CO<sub>2</sub>-eq (Supplementary Table 3). Sichuan exhibited the most pronounced increase, with GWP rising from 44.1 to 47.8 Mt CO<sub>2</sub>-eq—an increment representing 8.44% of the province's total agricultural GHG emissions. Yunnan ranked second, with its GWP increasing from 33.1 to 35.3 Mt CO<sub>2</sub>-eq, representing 6.64% of its total agricultural GHG emissions. Given the data limitations, this study assumed that the manure nutrients



**Fig. 6 | Livestock manure redistribution strategies and LCCSR under nutrient allocation.** A Before allocation; B after allocation; A1, B1 is for nitrogen, and A2, B2 is for phosphorus. (Note: The spatial redistribution paths and quantities of livestock manure are as follows: Path 1: 9071505 NLPE; Path 2: 9046403 NLPE; Path 3: 14332

NLPE; Path 4: 7618NLPE; Path 5: 6470166 NLPE; Path 6: 6493135 NLPE; Path 7: 6484032 NLPE; Path 8: 3108 NLPE; Path 9: 2382389 NLPE; Path 10: 14867NLPE; Path 11: 6009 NLPE.

received by Sichuan and Yunnan were fully applied to paddy fields. As rice cultivation is a major contributor to  $\text{CH}_4$  emissions in agricultural systems<sup>76,77</sup>, these two provinces showed relatively greater GWP increases. Nevertheless, this generalized assumption introduced uncertainty into GHG estimates, highlighting the need for future studies to incorporate field-specific manure application data for Sichuan and Yunnan to enable more reliable assessments. In contrast, the GWP increases in other confluent provinces remained under 1% relative to their total agricultural carbon emissions, demonstrating the scheme's overall efficiency. While this study prioritizes the minimization of GHG emissions during manure redistribution and application, additional emissions derived from interprovincial transport also represent a critical component. A more accurate accounting of the associated carbon footprint and total GWP would require detailed data on vehicle types, transport routes, and distances, and potential multi-stage transportation processes related to commercial organic fertilizer distribution.

In contrast to previous national-scale nutrient management studies, such as Bai et al.<sup>78</sup>, which proposed relocating approximately 10 billion livestock to mitigate N pollution exposure, our research results quantitatively incorporate land carrying capacity constraints and GHG trade-offs into the optimization framework. While their work emphasized the spatial decoupling of livestock and cropland along with the potential health benefits of animal relocation, our analysis demonstrates that a strategic

redistribution of manure nutrients, rather than physical livestock transfer, can achieve comparable nutrient surplus reductions with only limited carbon costs. This nutrient-centered approach offers a complementary pathway toward sustainability, avoiding the socio-economic disruptions inherent in large-scale livestock relocation. Accordingly, from a policy standpoint, these results stress the need for coordinated interprovincial nutrient governance, supported by targeted measures such as organic fertilizer subsidies, investments in manure recycling technologies, and mechanization support for smallholders. These steps are essential to overcome technical and economic barriers to manure use and promote crop-livestock reintegration<sup>79,80</sup>. Furthermore, the implementation of a national nutrient balance monitoring system, along with the integration of manure management into China's carbon accounting framework, would strengthen policy coherence between nutrient recycling and carbon neutrality objectives.

This study comprehensively diagnosed the spatial decoupling of manure nutrients and crop demand across China, revealed the driving mechanisms of nutrient surpluses, and developed an NSGA-II-based optimization model to redistribute manure nutrients under ecological and GHG emission constraints. China exhibits distinct regional disparities in nutrient supply-demand patterns across provinces, primarily driven by socio-economic structures, agricultural production systems, and manure

management practices. Livestock-intensive western provinces face severe surpluses from limited cropland, while major grain-producing regions suffer deficits due to intensive cultivation and inadequate manure recycling. Economically developed areas demonstrate reduced surpluses through efficient manure utilization, while less-developed regions have a structural oversupply from high direct discharge rates. The proposed optimization strategy successfully mitigated these imbalances, reducing surplus provinces' indices to optimal levels and narrowing national nutrient deficits by 24–39%, while limiting the increase in GHG emissions to within 8.5%. This study provides a spatially explicit analytical framework that supports coordinated nutrient management and sustainable agricultural transformation in China, offering a viable pathway toward regional circular agriculture and ecological sustainability.

## Methods

The nutrient demand, manure supply, and land carrying capacity for crop fields across 31 provinces in China in 2020 were initially calculated using the methodology outlined in the *Technical Guidelines for Calculating Land Carrying Capacity of Livestock and Poultry Manure* issued by the Ministry of Agriculture and Rural Affairs of China (hereafter referred to as “the Guidelines”)<sup>31</sup>. Following this initial calculation, the analysis primarily addressed the spatial redistribution of livestock manure exceeding provincial land carrying capacity. The NSGA-II multi-objective optimization algorithm was employed to derive efficient interprovincial manure allocation pathways under the dual constraints of recipient provinces' ecological thresholds and minimal transport costs, while simultaneously minimizing GHG emissions associated with the application of surplus manure. The specific calculation steps are as follows.

### Nutrient supply estimation from livestock manure

According to the calculation method of the Guidelines and considering the primary cultivated and raised species in China, the N and P nutrient supply data from four types of livestock manure (pig, beef cattle, dairy cattle, and poultry) and the N and P nutrient demand data for plants in each province were analyzed. The pollutant coefficient method was employed to calculate the N and P resources derived from livestock manure, incorporating systematic adjustments for nutrient losses occurring during manure collection, storage, and treatment processes. The coefficients were sourced from the statistical data of China's Second National Pollution Source Census (<http://www.mee.gov.cn>), which provided the most recent provincial-level data and is considered authoritative for this purpose<sup>1,23,24,82</sup>. Among them, plants mainly involve food crops (rice, wheat, maize, millet, sorghum, beans, potatoes, and other grains), oil crops (peanuts, rapeseeds, and other oil crops), cotton, sugar crops (sugarcane, beet), tobacco leaves, tea leaves, vegetables, melons and fruits, orchard fruits, and planted woodland. Crop yields came from provincial statistical yearbooks, livestock populations from the *China Animal Husbandry and Veterinary Yearbook 2021*, and artificial woodland data from the *China Forestry and Grassland Statistical Yearbook 2020* (Supplementary Table 1). The specific calculation formulas and parameters are detailed in the Supplementary Text 1 and Tables 4–11.

### Nutrient requirements estimation for crops

Based on the recommended N and P uptake rates per 100 kg of crop yield (Supplementary Table 12), the nutrient demand for various crops in provinces of China was first calculated by multiplying crop yield by the corresponding nutrient uptake value. Subsequently, key parameters, including the proportion of manure-supplied nutrients, the fraction of manure applied, and the seasonal utilization rate of livestock manure, were collected from various publications, as summarized in Supplementary Table 13. Finally, the nutrient demand from the livestock manure was calculated using Eq. 2:

$$A = \sum (P_i \times X_i) + \sum (G \times Y) \quad (1)$$

$$D = (A \times FP \times MP) / MR \quad (2)$$

Where  $i$  represents all plant species included in the calculations.  $A$  denotes the total nutrient demand of all plant species within the region, kg.  $P_i$  represents the annual yield of the  $i$ th crop, 10<sup>2</sup> kg.  $X_i$  denotes the nutrient requirement per 100 kg of yield for the  $i$ th crop, kg.  $G$  and  $Y$  refer to the yield (m<sup>3</sup>) and nutrient demand (kg/m<sup>3</sup>) of artificial woodland.  $D$  is the amount of nutrients that plants in the region need from manure, kg.  $FP$  indicates the proportion of the total crop nutrient demand that must be met through fertilization, %.  $MP$  represents the share of manure in the total fertilization volume, %.  $MR$  denotes the livestock manure seasonal utilization, %.

### Land carrying capacity estimation for livestock manure

The land carrying capacity for livestock refers to the maximum livestock population that can be sustained on agricultural lands and woodlands under conditions that support terrestrial ecosystem stability<sup>17,23,45</sup>. In this study, livestock manure was assumed to be evenly applied across all agricultural land within each recipient province, without altering local cropping patterns or cultivation scales. Because the calculation of manure nutrient supply involves multiple animal species and manure treatment methods, the “pig equivalent” was adopted as a standard unit following the methodology in the Guidelines. All actual livestock populations were standardized into pig equivalents. Subsequently, Eqs. (3) and (4) were employed to calculate the manure nutrient supply per unit of pig equivalent and the theoretical maximum livestock population, respectively. To evaluate the land carrying capacity status, this study employed Eq. (5) to calculate the ratio of the actual livestock population to the theoretical maximum population.

$$PD = S/RE \quad (3)$$

$$CA = D/PD \quad (4)$$

$$I = RE/CA \quad (5)$$

Where  $S$  represents the nutrient supply from livestock manure, kg.  $RE$  is the number of livestock in the region converted to pig equivalent, head.  $PD$  is the nutrient supply per pig equivalent, kg.  $CA$  indicates the maximum number of pig equivalent livestock that can be maintained in the region, head.  $I$  represents the LCCSR. The LCCSR exceeding 1.0 indicates that the regional livestock population has surpassed the land's carrying capacity. The specific values for all parameters mentioned above are provided in Supplementary Table 4.

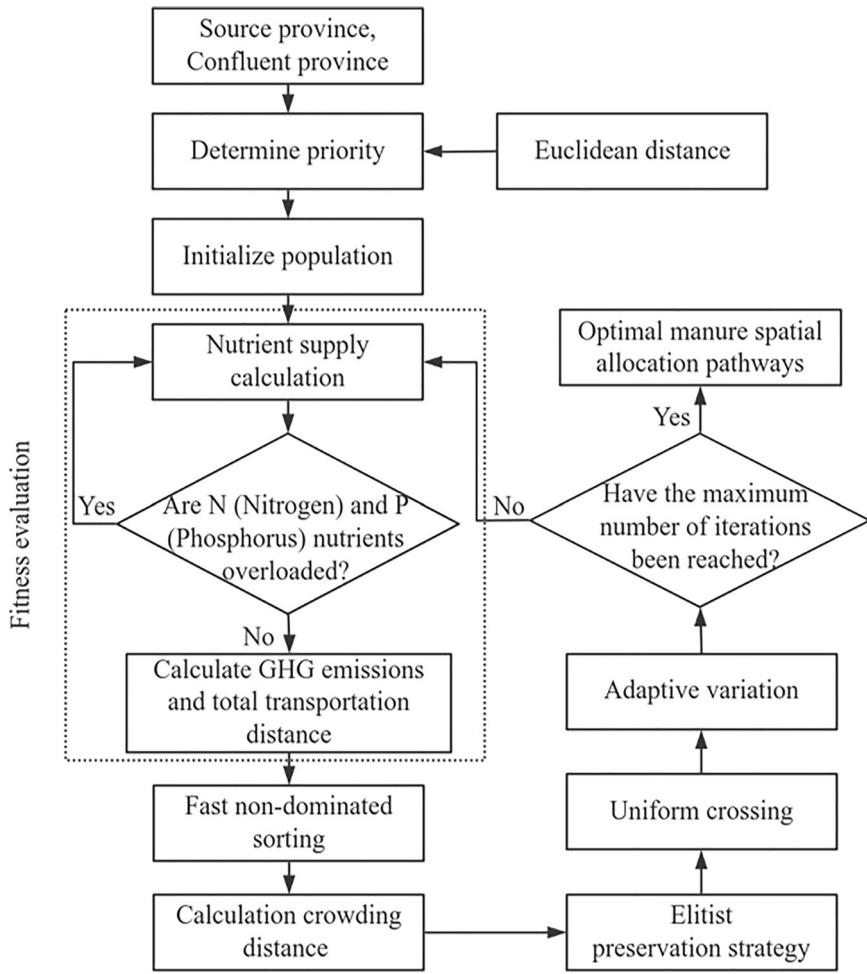
### Statistical analysis

PCA was used to identify dominant factors explaining variations in N and P surpluses and deficits across provinces of China. The input dataset included variables related to socio-economic conditions (GDP, population, proportion of primary industry), agricultural production output (gross output value of animal husbandry, gross output value of agriculture), agricultural production structure (cropland area, proportion of grain crops output, total livestock inventory, LI and proportion of poultry) and manure utilization efficiency (nutrient utilization efficiency for N and P). Spearman's correlation analysis was performed to assess monotonic associations between nutrient surpluses and deficits and key indicators, including manure management factors (manure nutrient utilization efficiency, direct discharge ratio, and resource utilization ratio), spatial distribution factors of livestock (LI), and socio-economic factors (population and GDP). Correlation coefficients with p-values less than 0.05 were considered statistically significant. The manure management factors were calculated by the ratio of the nutrient content collected under different treatment methods to the nutrients excreted by livestock. All other data were collected from *China Statistical Yearbook*<sup>49</sup>, and detailed values are summarized in Supplementary Table 14. All statistical analyses were conducted using Python 3.11.

### GHG emissions estimation from manure application to crop

Based on the preceding calculations, this study quantified the GHG emissions generated from the application of surplus manure to the croplands of

**Fig. 7** | Process flow for spatially optimized allocation of livestock manure nutrients based on the NSGA-II method.



recipient provinces, where surplus manure is defined as the amount exceeding the land carrying capacity of the source province. These emissions include both direct and indirect sources. Due to data limitations, GHG emissions were estimated according to the dominant cropping systems of the recipient provinces, with manure assumed to be applied primarily to the major crop types having the most extensive cultivation areas. The specific correspondence between provinces and applied crop types is detailed in Supplementary Table 15. Both calculation methods were grounded in a synthesis of empirically derived experimental data from prior studies conducted in China.

Direct emissions were calculated using the emission factor (EF) method, following the 2006 IPCC Guidelines for National Greenhouse Gas Inventories<sup>83</sup>. Through an extensive literature review (Supplementary Text 2), the experimental results on the GHG emissions from crops applied with livestock manure were collected. Based on these data, by using the local EF formula (Supplementary Text 3), the N<sub>2</sub>O EFs for manure applied to agricultural soils in provinces of China were estimated (Supplementary Table 15). For indirect GHG emissions, the calculation methodology involved: (1) determining N nutrient input per unit cropland area for target crops based on manure nutrient allocation in the confluent province; (2) establishing organic fertilizer application proportions by comparing these inputs with regionally recommended N application rates; and (3) estimating CH<sub>4</sub> emissions using empirical relationships between organic fertilizer application ratios and emission rates from published provincial studies. Where local experimental data were unavailable, emissions were calculated using data from neighboring provinces with similar agroecological characteristics, following the proximity principle. If the proportion of organic fertilizer application after manure transfer was below 0.1% in some

provinces, the resulting CH<sub>4</sub> emissions were considered negligible. The relevant literature data are detailed in Supplementary Tables 16 and 17.

Agricultural soil CO<sub>2</sub> emissions were excluded from analysis since farmland ecosystems typically function as carbon sinks, with photosynthesis outweighing respiration<sup>84,85</sup>. Therefore, the final GHG emissions in this study include CH<sub>4</sub> and N<sub>2</sub>O emissions. Given their different warming potentials—where 1 kg of CH<sub>4</sub> has a warming potential 25 times that of 1 kg of CO<sub>2</sub>, and 1 kg of N<sub>2</sub>O has 298 times the warming effect of 1 kg of CO<sub>2</sub><sup>86</sup>, the combined GWP of these GHGs was calculated as the evaluation index for GHG emissions.

#### Spatial allocation of livestock and poultry under multi-objective optimization

The NSGA-II is a multi-objective optimization algorithm that efficiently handles multiple objectives through strategies such as elitism and non-dominated sorting. Figure 7 illustrates the methodological framework for spatial livestock and poultry allocation developed in this study, which employs a multi-objective optimization approach. The objective is to achieve a balanced allocation of manure resources while minimizing transportation distances and the GHG emissions associated with manure application.

Initially, manure supply provinces were identified based on land carrying capacity results. Provinces exceeding their capacity were designated as supply regions, while neighboring provinces were classified as confluent regions. The interprovincial transportation priority was determined using the Euclidean distance between the centroids of provincial cropland areas. Shorter Euclidean distances were assumed to correspond to lower transportation costs and GHG emissions; thus, provinces in closer proximity

were assigned higher priority and received larger manure allocations. To balance and sustain nutrient distribution, the nutrient load per pig equivalent (NLPE) was calculated as the ratio of excess manure nutrients to the manure nutrient supply per pig equivalent (calculated by Eq. 3). The NLPE serves as the unit for spatial reallocation, which maintains consistency in nitrogen-to-phosphorus ratios and facilitates computational efficiency in the modeling process. The algorithm began with the random initialization of a population comprising 100 individuals, each representing a potential manure allocation plan. Within these individuals, genes denote the proportion of manure allocated to recipient provinces, with higher priority regions receiving larger proportions. Each iteration involves: (1) evaluating manure allocation plans for transportation distance and GWP, excluding infeasible plans exceeding recipient land carrying capacity; (2) sorting solutions via non-dominated sorting, prioritizing those with superior multi-objective performance; (3) maintaining population diversity through crowding distance calculations. Subsequent steps include elite selection, uniform crossover, and adaptive mutation. Mutation rates dynamically adjust based on fitness trends to avoid local optima and reinforce promising solutions. After 1000 iterations, the algorithm converged, yielding an optimal manure allocation scheme that minimizes emissions while enhancing resource efficiency. To verify the robustness and stability of the optimization outcomes, the NSGA-II procedure was independently repeated 60 times under identical parameter settings. The resulting minimum total GHG emissions exhibited a low average coefficient of variation (CV = 0.0097), confirming the process's high stability and convergence reliability. The manure redistribution plan with the lowest emissions was thus identified as the optimal solution for further analysis. All processes related to the data processing and model construction were conducted utilizing Python 3.11.

## Data availability

Datasets used in this study were accessed from publicly available sources. All the data supporting the findings of this study are referenced within the manuscript and in Supplementary Information.

## Code availability

The Python scripts used in the analyses are available from the corresponding author on reasonable request.

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## Author contributions

Ke Xu prepared the first draft and contributed to the research design and write-up. Qian-Qian Zhang conceived the idea and designed the study. Ya-

Ya Cai performed the research and analyzed the data. Xu-Jie Luo and Yun-Qiu Zhai conducted the data analysis. Guang-Guo Ying and Wang-Rong Liu originated the idea and contributed to research execution. All authors wrote the paper.

## Competing interests

The authors declare no competing interests.

## Additional information

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