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Interprovincial supply chains reshape the pattern of nitrogen deposition in China

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Abstract. China faces severe atmospheric nitrogen deposition, with domestic consumption acting as a hidden key driver. Domestic interprovincial supply chains can reshape deposition patterns by reallocating emission burdens across provinces, yet its role in China's nitrogen deposition remains poorly understood. Here, we quantify how domestic consumption reshapes China's nitrogen deposition pattern by combining multi-regional input–output (MRIO) analysis with GEOS-Chem simulations. We find that domestic consumption was responsible for 10.5 kg N ha^{-1} yr^{-1} of China's nitrogen deposition in 2017, accounting for 67% of the national total. Reduced nitrogen (NH_x) and wet deposition dominate this footprint, reflecting the strong influence of agricultural NH_3 emissions and precipitation-driven removal. Among all consumption demand categories, investment accounts for the largest share, followed by household and government consumption. We find a clear spatial mismatch that the provinces with high consumption affordabilities tend to net outsource emissions, while the provinces with intensive agricultural and industrial productions tend to be with net emission inflows. Sectorally, NH_3 emissions are emitted from livestock and crop production, mainly driven by domestic demand for food and agricultural products. In contrast, NO_x emissions mainly originate from transport, power generation, and heavy industry, driven by consumption demand for infrastructure investment, manufactured goods, transport services, and energy-intensive products. Our findings show that interprovincial supply chains reshape China's nitrogen deposition pattern by transferring emission burdens from developed coastal provinces to inland agricultural and industrial regions. Effective mitigation therefore requires coordinated strategies that combine production-side emission controls with consumption-based responsibility sharing.

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1 Introduction

Since the industrial revolution, atmospheric inputs of reactive nitrogen (N_r) have increased markedly as a result of intensified human influence on the nitrogen cycle (Galloway et al., 2008; Schlesinger, 2009). Anthropogenic ammonia (NH_3) emissions are mostly from agricultural activities, while nitrogen oxides (NO_x) are mainly from fossil fuel combustion in processes such as power generation, transportation, and industrial energy use (Fowler et al., 2013; Galloway et al., 2008; Gruber and Galloway, 2008). Emitted N_r then undergoes atmospheric physical and chemical processes, forming reduced (NH_x) and oxidized (NO_y) species. These species are subsequently removed from the atmosphere via wet and dry deposition onto terrestrial and aquatic surfaces (Dentener et al., 2006; Jacob, 1999; Vet et al., 2014). When N_r inputs exceed ecosystem uptake capacity, the excessive nitrogen can acidify soils, accelerate eutrophication in aquatic systems, reduce biological diversity, and contribute to human health risks (Duce et al., 2008; Erisman et al., 2013; Sutton et al., 2011). Atmospheric nitrogen deposition rates over China are among the highest reported worldwide (Jia et al., 2014; Liu et al., 2013; Lu and Tian, 2007; Zhao et al., 2017). Observational studies based on the Nationwide Nitrogen Deposition Monitoring Network (NNDMN) reported an average total inorganic nitrogen deposition flux of approximately 40 kg N ha^{-1} yr^{-1} across China during 2010–2014, substantially higher than the levels reported by comparable networks in Japan, Europe, and North America (Xu et al., 2015). Although recent emission control policies have stabilized or slightly reduced national-average nitrogen deposition in China (Liu et al., 2024; Yu et al., 2019), deposition levels in many regions still remain among the highest worldwide (Liu et al., 2013; Liu et al., 2024; Xu et al., 2015). This persistent pressure calls for a deeper understanding of the hidden drivers beyond direct emission sources (Gu et al., 2015).

The share of final consumption expenditure in China's GDP was 56.6% in 2024, and contributed 52% to the overall economic growth in 2025, highlighting the central and increasing role of domestic consumption in the national economy (National Bureau of Statistics of China, 2026; World Bank, 2026). Despite its importance, domestic consumption is often overlooked as a driver of N_r emissions and subsequent deposition in China (Huo et al., 2014; Leach et al., 2012). Direct emissions are generated during household activities, including small scale fertilizer application, residential fossil fuel use for cooking and heating, and private transportation (Huo et al., 2014; Leach et al., 2012; Peng et al.,

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2019). More important are the indirect emissions embedded in supply chains, which refer to emissions released during upstream production and transportation processes for satisfying consumption demand from households, governments, and investment activities (Huo et al., 2014; Wang et al., 2017; Zhao et al., 2015). For instance, urban demand for meat drives livestock production in rural areas, leading to NH_3 emissions from manure (Guo et al., 2017; Xian et al., 2021; Xu et al., 2017). Likewise, demand for manufactured goods can induce NO_x emissions from energy-intensive industrial production and transport activities (Huo et al., 2014; Wang et al., 2017; Zhao et al., 2015). Previous studies have revealed the importance of consumption-based accounting in quantifying China's greenhouse gas and air pollutant footprints (Huo et al., 2014; Mi et al., 2016; Wang et al., 2017), but its specific role in driving nitrogen deposition remains inadequately quantified. Given the vast heterogeneity in provincial consumption patterns, economic structures, and environmental vulnerabilities across China, a detailed province-scale analysis is essential. Such an analysis would not only help clarify the key drivers behind deposition hotspots, but also provide a reference for designing effective and regionally differentiated mitigation policies.

This study quantifies the role of domestic consumption in driving provincial nitrogen deposition in China, using 2017 as the reference year, as it represents the latest year with complete data availability for all required analytical inputs. This study focuses on 31 Chinese mainland provinces (Fig. S1), excluding Hong Kong, Macao, and Taiwan because the required data are unavailable. For this study, the domestic consumption types considered include investment, government consumption, and household consumption. First, a multi-regional input-output (MRIO) framework is used to trace province- and sector-specific emissions of atmospheric pollutants embodied in interprovincial trade. Then, using the GEOS-Chem atmospheric chemical transport model, we simulate the resulting nitrogen deposition from these consumption-related emissions. This work offers a consumption-based perspective on the drivers of nitrogen deposition in China, with findings to inform environmental and nitrogen deposition management and facilitate the formulation of coordinated emission mitigation policies.

2 Methods

2.1 Calculation of Emissions Driven by Domestic Consumption

To trace the atmospheric pollutant emissions attributed to domestic consumption, we applied MRIO analysis across Chinese provinces. The MRIO table captures economic flows among regions and

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sectors, enabling attribution of emissions from producers to consumers. Our analysis uses China's 2017 provincial MRIO table from the Carbon Emission Accounts and Datasets (CEADs; https://www.ceads.net/) (Zheng et al., 2021), covering 42 economic sectors across Chinese provinces.

The fundamental input-output model is expressed as:

$$\mathbf{X} = \mathbf{AX} + \mathbf{Y}, \tag{1}$$

where **X** denotes the vector of total economic output, with x_i^r denoting the economic output of sector i in province r. **A** is the direct technical coefficient matrix, in which a_{ij}^{rs} measures the economic input from sector i in province r required per unit of economic output of sector j in province s. **Y** denotes the final demand vector, and y_i^r specifies the final demand for output produced by sector i in province r. In this analysis, final demand is divided into investment, government consumption, and household consumption.

Equation (1) can be rearranged as:

$$\mathbf{X} = (\mathbf{I} - \mathbf{A})^{-1} \cdot \mathbf{Y} = \mathbf{L} \cdot \mathbf{Y}, \tag{2}$$

where $\mathbf{I}$ is the identity matrix and $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$ denotes the Leontief inverse. It captures the complete supply-chain production requirements induced by final demand and can be expanded as $\mathbf{L} = \mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \ldots$, where $\mathbf{I}$ represents the direct production requirements needed to satisfy final demand, $\mathbf{A}$ represents first-order supplier inputs, $\mathbf{A}^2$ represents second-order supplier inputs, and the remaining higher-order terms represent more distant upstream production requirements.

Thus, the emission of pollutant k generated in province m to satisfy final demand of province n is calculated as:

$$E_{k,m\leftarrow n} = \boldsymbol{f}_m^k \boldsymbol{L}^{\boldsymbol{mn}} \boldsymbol{y}_n \tag{3}$$

where $\boldsymbol{f}_m^k$ denotes the emission intensity vector of pollutant k across all sectors in province m. $\mathbf{L}^{mn}$ is the corresponding block of the Leontief inverse matrix, showing requirements in province m induced by the final demand of province n, while $\boldsymbol{y}_n$ represents final demand across all sectors in province n. Here, our provincial emission inventory were merged by combining provincial emission totals from Multi-resolution Emission Inventory for China (MEIC) (Li et al., 2017; Zheng et al., 2018) with sectoral shares from Greenhouse Gas–Air Pollution Interactions and Synergies (GAINS) (Amann et al., 2011). For a better sectoral representation of NH_3 emissions, the agricultural NH_3 emissions were further replaced with the inventory from Chen et al. (Chen et al., 2021). Details for our merged

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emission inventory can be found in Supplementary Text S1 and sectoral details are listed in Tables S1–S3.

To evaluate the role of a specific province in interprovincial emission transfer, we define the bilateral net emission transfer associated with province n in the trade relationship between provinces m and n as:

$$\Delta E_{k,mn}^{(n)} = E_{k,m\leftarrow n} - E_{k,n\leftarrow m}. \quad (4)$$

A positive value of $\Delta E_{k,mn}^{(n)}$ indicates that, in the bilateral relationship between provinces m and n, final demand in province n drives more emissions in province m than final demand in province m drives in province n. Conversely, a negative value indicates that province n bears more emissions driven by province m than it outsources to province m in this bilateral relationship.

Thus, the overall net emission transfer of province n with all other provinces is calculated as:

$$\Delta E_{k,n} = \sum_{\mathrm{m}\neq\mathrm{n}} (E_{k,m\leftarrow n} - E_{k,n\leftarrow m}) \quad (5)$$

This overall metric is equivalent to the difference between consumption-based and production-based emissions of province n for pollutant k.

2.2 Simulation of Nitrogen Deposition

We further quantified the contribution of domestic consumption to nitrogen deposition with GEOS-Chem version 14.0.1. This three-dimensional atmospheric chemistry model has been widely applied to studies of nitrogen deposition over China (Wang et al., 2013; Zhao et al., 2017). GEOS-Chem simulates the transport and chemical transformation of emitted NH_3 and NO_x into reduced and oxidized nitrogen species, which are subsequently removed through dry deposition and wet scavenging processes.

We conducted a control simulation and a set of sensitivity simulations, with detailed emission settings summarized in Table S4. Consumption-based emissions were gridded following the corresponding spatial patterns in MEIC. All simulations used GEOS-FP meteorological fields supplied at 3-hour intervals by NASA's Global Modeling and Assimilation Office (GMAO). For each simulation group, boundary conditions for the high-resolution nested simulation were generated from a global simulation conducted at 2° × 2.5° horizontal resolution, with the nested-grid simulation covering East Asia at a horizontal resolution of 0.25° × 0.3125°. The simulations were conducted for four representative months in 2017, i.e., January, April, July, and

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October. Each nested simulation included a 10-day spin-up to reduce the influence of initial conditions within the regional domain. For each domestic consumption-related category, its contribution to nitrogen deposition was calculated as the control simulation result minus the corresponding sensitivity simulation result, in which emissions associated with that category were removed according to Table S4.

3 Results

3.1 Spatial distribution of domestic consumption-related nitrogen deposition

Fig. 1a shows that domestic consumption causes approximately 10.5 kg N ha^{-1} yr^{-1} of nitrogen deposition over China in 2017, accounting for 67% of the national total nitrogen deposition budget. By contrasting Fig. 1b and c, we find that NH_x is identified as the dominant component of domestic consumption-driven nitrogen deposition, reaching 5.9 kg N ha^{-1} yr^{-1}. This reflects the strong influence of domestic demand for food and agricultural products, which stimulates upstream NH_3 emissions generated through manure management and the agricultural use of fertilizers. By contrasting Fig. 1d and g, we find that wet deposition has a higher contribution (6.1 kg N ha^{-1} yr^{-1}) than dry deposition (4.4 kg N ha^{-1} yr^{-1}). Spatially, domestic consumption-driven nitrogen deposition and its components show a pronounced east-to-west decreasing gradient (Fig. 1a-i). High deposition is mainly concentrated in densely populated and agriculturally or industrially intensive provinces, such as Shandong, Hebei, Henan, Jiangsu, and Sichuan. The high deposition in Sichuan is not only resulted from intensive agricultural production, especially livestock production and grain cultivation, but also from its basin topography, which favors pollutant accumulation and efficient wet scavenging.

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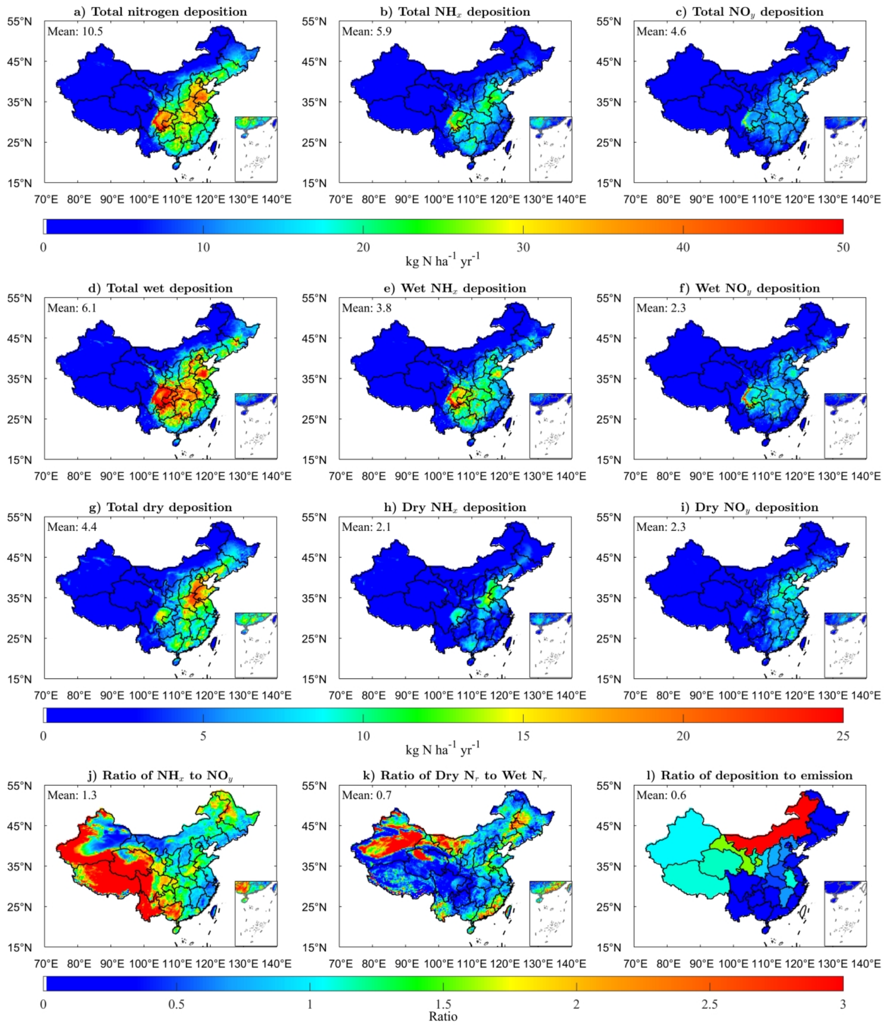

Fig. 1. The spatial distributions of domestic consumption-driven nitrogen deposition in China in 2017. (a–c) Spatial distributions of total nitrogen deposition (a), reduced nitrogen deposition (NH_x) (b), and oxidized nitrogen deposition (NO_y) (c) driven by domestic consumption. (d–f) Spatial distributions of total wet deposition (d), wet NH_x deposition (e), and wet NO_y deposition (f). (g–i) Spatial distributions of total dry deposition (g), dry NH_x deposition (h), and dry NO_y deposition (i). (j–l) Ratios of NH_x to NO_y deposition (j), dry to wet N_r deposition (k), and domestic consumption-related nitrogen deposition to precursor emissions (l). The national mean result is shown on the upper left corner of each panel.

Fig. 1j–l further shows three ratios related with domestic consumption-driven nitrogen deposition. The ratio of NH_x to NO_y in Fig. 1j reflects the differences in emission sources, with a national mean of 1.3,

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indicating the dominance of NH_x deposition. Higher NH_x to NO_y ratio is observed in western and some agricultural provinces, such as Tibetan Plateau and southwestern China, especially Tibet and western Sichuan, suggesting a dominant contribution from agricultural sources. Fig. 1k shows that the dry to wet N_r deposition ratio has a national mean of 0.7, confirming that wet deposition is the dominant removal pathway of N_r. This is apparent in regions with sufficient precipitation, such as southern China, the Yangtze River basin, and the Sichuan Basin. In contrast, relatively high dry to wet N_r deposition ratio exists in northern and northwestern China due to the dry weather. Fig. 1l further evaluates the balance between the amount of domestic consumption-related N_r deposited within a province and the amount emitted from that province with a source – receptor indicator, where values greater than 1 indicate that the province acts as a net N_r receptor, while values less than 1 indicate that it acts as a net N_r sourcer. The national mean ratio of 0.6 indicates that, at the national scale, domestic consumption-related N_r deposition is lower than the corresponding precursor emissions, which is comparable to previous estimates (Chen et al., 2023; Ge et al., 2020). Meanwhile, the strong inter-provincial heterogeneity implies substantial spatial reallocation of N_r via atmospheric transport. Provinces such as Inner Mongolia and Gansu act as net N_r receptors, meaning they receive more Nr from domestic consumption via atmospheric transport compared with their local emissions. By contrast, Sichuan, Yunnan, and Xinjiang tend to be net N_r sourcers, where a larger fraction of locally emitted N_r is deposited downwind rather than retained locally.

3.2 Contribution from different consumption types

Domestic consumption in our study includes three parts, i.e., investment, government consumption, and household consumption. Fig. 2a and b show that investment is the dominant contributor in domestic consumption-driven nitrogen deposition, accounting for 66.7% of NH_x deposition and 57.9% of NO_y deposition. This results from the fact that investment is responsible for 62.9% of domestic consumption volume. The contribution from investment is distinct in central, eastern, and southern China, with pronounced hotspots in Sichuan, Henan, Shandong, Hebei, and the middle and lower Yangtze River region (Fig. S2). Investment accounts for the largest share of final consumption among the three categories, combined with its reliance on multiple emission-intensive upstream production chains, including construction, infrastructure, energy-intensive industry, and agriculture. Household consumption is the second largest contributor, accounting for 20.7% of NH_x deposition and 25.1% of

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NO_y deposition. The contribution from household consumption is distinct in provinces Shandong, Hebei, Henan and Sichuan (Fig. S2). This is mainly contributed from household demand for food, daily goods, services, and residential energy use. Government consumption is responsible for the rest, i.e., 12.6% of NH_x deposition and 17.0% of NO_y deposition. The higher government share in NO_y than in NH_x indicates government consumption demand is more reliant on fossil fuel combustion and energy-intensive industrial processes.

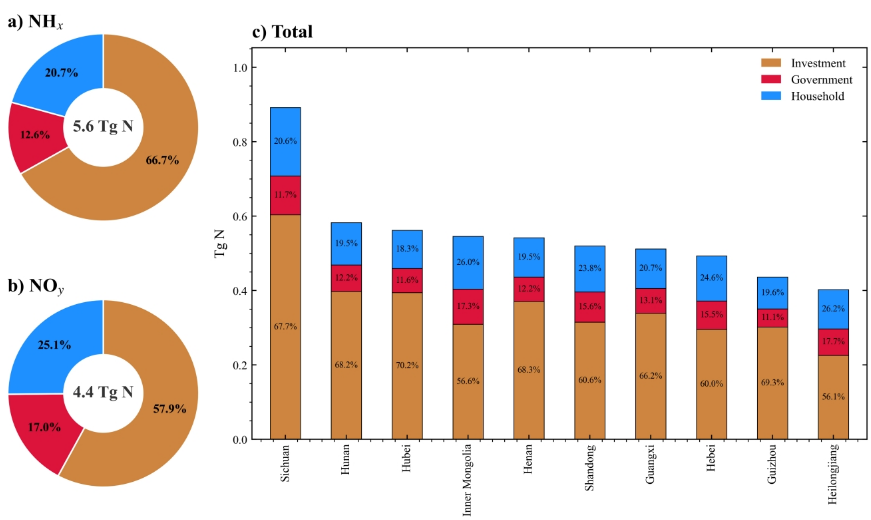

Fig. 2. The contribution of different types of domestic consumption to nitrogen deposition in China in 2017. (a–b) Relative contributions of investment, government consumption, and household consumption to domestic consumption-driven NH_x deposition (a) and NO_y deposition (b) in China. The central values in the donut charts denote the corresponding national total deposition amounts. (c) The contributions of the three consumption categories to total domestic consumption-driven nitrogen deposition in the top ten provinces exhibiting the largest nitrogen deposition amounts.

Fig. 2c further shows the top ten provinces exhibiting the largest nitrogen deposition amounts and the contribution from different domestic consumption types. Sichuan has the highest deposition with 67.7% contributed from investment, 20.6% contributed from household consumption and the rest 11.7% from government consumption. Household consumption's contribution reaches 26% in the total domestic consumption-driven nitrogen deposition in Inner Mongolia and Heilongjiang and is also relatively high in Hebei and Shandong, suggesting that household consumption

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demand is also an important driver of nitrogen deposition in northern and northeastern provinces.

3.3 Role of provinces and sectors in domestic consumption-related N_r emissions

We further evaluate the role of each province in domestic consumption-driven nitrogen deposition by calculating their net N_r emissions. Here, a province is defined as a net importer when emissions attributed to its final demand are greater than those released within its territory. In contrast, a province is taken as a net exporter when emissions released within its territory exceed those attributed to its final demand. Fig. 3 shows that economically developed provinces with high consumption affordabilities generally act as net importers in both NO_x and NH_3 emissions, such as Guangdong, Zhejiang and Beijing, mainly because their strong final demand induces upstream emissions beyond their own provincial boundaries. The provinces in the west are also recognized as net importers in NO_x emissions, such as Xinjiang, Qinghai, Sichuan, Yunnan and Tibet, reflecting that their underdeveloped local production forces them to rely on imports from other provinces. In contrast, provinces developed in industrial production tend to be net exporters in NO_x emissions, such as Shandong, Hebei, Inner Mongolia, Shanxi, and Liaoning. And provinces developed in agricultural production tend to be net exporters in NH_3 emissions, such as Guangxi, Inner Mongolia, Heilongjiang, Xinjiang and Henan. Fig. S3 further shows that large part of the emissions in Southwest and Central China are driven by consumption in Eastern China. This pattern indicates that domestic final demand does not only induce emissions within the consuming province. Instead, consumption in one province can trigger upstream emissions in other provinces through interprovincial supply chains, leading to a mismatch between where goods and services are consumed and where nitrogen precursor emissions are physically released.

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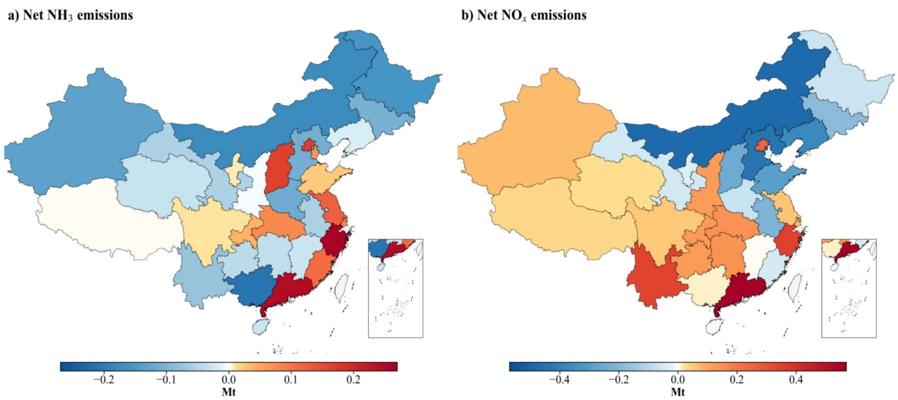

Fig. 3. The provincial net domestic consumption-driven emissions of nitrogen precursors in China in 2017. (a) Net NH_3 emissions. (b) Net NO_x emissions. Net emissions are calculated as consumption-based emissions minus production-based emissions. Positive values indicate net embodied emission imports, whereas negative values indicate net embodied emission exports.

Fig. 4 further dig out each sector's role in domestic consumption-driven nitrogen deposition. From the production-based perspective, NH_3 emissions are highly concentrated in agricultural and livestock-related sectors, including cattle, vegetables and fruits, other grains, rice, wheat, other crops, and raw milk. In contrast, production-based NO_x emissions are dominated by land transport and transport via pipelines, electricity and steam supply, manufacture of non-metallic mineral products, iron and steel, chemicals, and other heavy industrial sectors. From the consumption-based perspective, the consuming sectors leading NH_3 emissions are not limited to agricultural sectors, but also include food, textile, and light manufacturing-related sectors. This is because that these consuming sectors rely on products in agricultural and chemical sectors as inputs. NO_x emissions are primarily driven by consumption in manufacturing and equipment-related sectors owing to their high energy use, material inputs, electricity consumption, and transport requirements.

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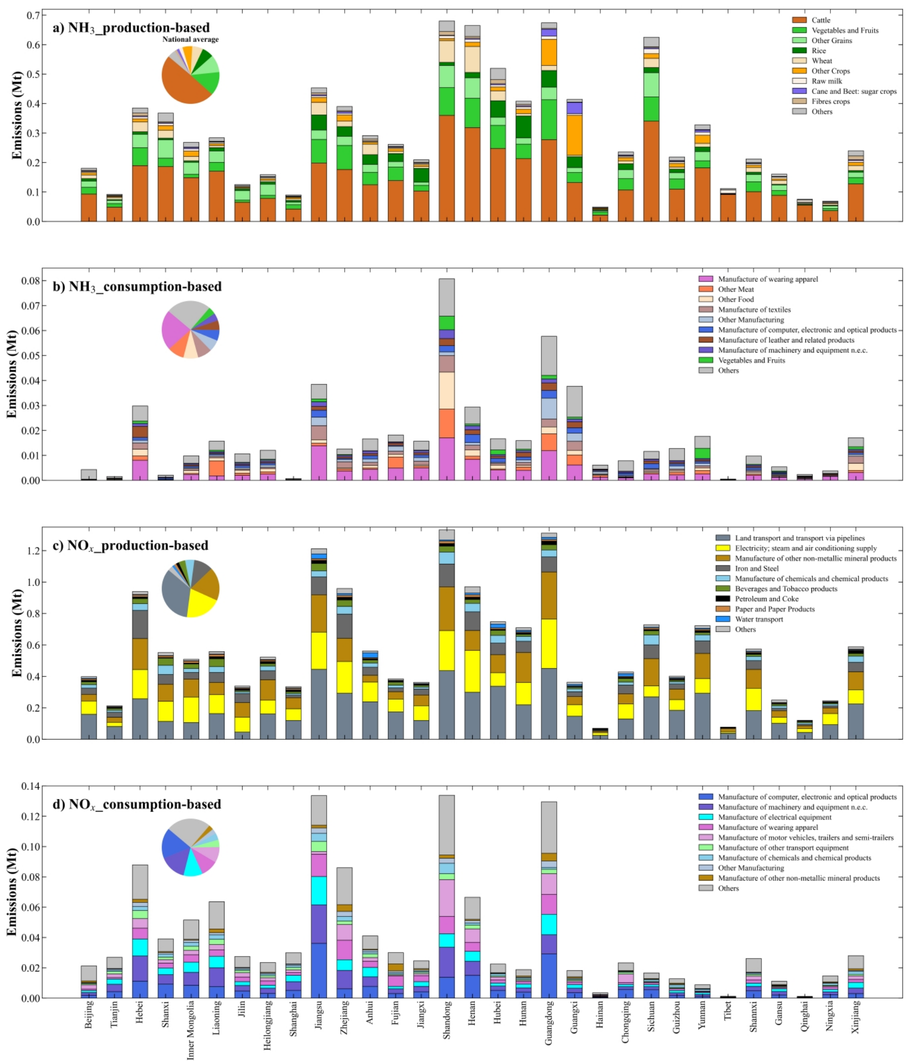

Fig. 4. Sectoral attribution of nitrogen-precursor emissions under production- and consumption-based accounting across Chinese provinces in 2017. Panels (a) and (b) show the sectoral contributions to NH_3 emissions from the production- and consumption-based perspectives, respectively. Panels (c) and (d) present the corresponding contributions to NO_x emissions. Stacked bars represent provincial emission amounts and the sectoral contributions, while the pie charts show the national average sectoral emission contribution. The production-based panels identify the sectors as producers where emissions are physically released, and the consumption-based panels identify the sectors as consumers and drive emissions through supply chains. Here, only the top nine sectoral contributors are displayed separately in each panel, with all remaining sectors grouped as “Others”.

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4 Conclusions

This study quantifies the role of domestic consumption in driving provincial nitrogen deposition across China. Our findings reveal that domestic consumption accounts for approximately 10.5 kg N ha^{-1} yr^{-1} of nitrogen deposition, representing 67% of the national total deposition budget in 2017. The dominance of NH_x (5.9 kg N ha^{-1} yr^{-1}) over NO_y (4.6 kg N ha^{-1} yr^{-1}) and wet over dry deposition pathways reflects the strong influence of agricultural NH_3 emissions and precipitation-driven removal processes in shaping the national deposition pattern. Spatially, a pronounced east-to-west decreasing gradient is evident, with hotspots concentrated in densely populated and agriculturally or industrially intensive provinces.

These results advance our understanding of the atmospheric nitrogen cycle and its anthropogenic modulation effects. First, interprovincial supply chains fundamentally reshape the deposition pattern by reallocating emission burdens from developed coastal provinces to inland agricultural and industrial regions. This spatial decoupling between consumption centers and deposition hotspots demonstrates that the atmospheric nitrogen budget in China cannot be fully understood without accounting for the economic linkages that drive emissions. Critically, our deposition-to-emission analysis shows that the provincial deposition-to-emission ratio varies by a factor of approximately 139 across China, indicating that the atmospheric residence time and transport distance of consumption-driven emissions are strongly modulated by regional meteorological conditions and topography. These findings challenge the conventional view and policies taking nitrogen deposition as a predominantly local or regional air quality issue (Ma et al., 2020; Zhao et al., 2015; Zhao et al., 2017; Zhu et al., 2022).

Second, our sectoral decomposition reveals fundamental asymmetries in how different components of the atmospheric N_r cycle are driven by consumption. NH_x deposition, which dominates the total budget, is primarily tied to agricultural supply chains, i.e., production-based emissions are concentrated in livestock and crop sectors, but consumption-based drivers extend into food processing, textiles, and light manufacturing, the sectors not traditionally associated with NH_3 emissions. This means that interventions targeting agricultural production alone may have limited effectiveness if downstream demand continues to incentivize intensive farming practices. Conversely, NO_y deposition, though smaller in magnitude, is driven by a more diffuse set of consumption categories spanning infrastructure investment, manufactured goods, and transport service. This reflects how fossil fuel combustion is

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pervasively driven multiple economic sectors. reveals that the atmospheric N_r composition over China is not an independent function of emission controls but is systematically shaped by the structure of final demand. Because NH_x and NO_y differ fundamentally in their formation pathways, atmospheric lifetimes, and deposition mechanisms, the same total N_r emission from different consumption sources can produce markedly different atmospheric outcomes, affecting not only the magnitude but also the spatial pattern and ecological form of deposition. Effective mitigation of N_r deposition requires a co-ordinated understanding of how different consumption categories influence the coupled NH_3-NO_x chemistry that ultimately governs the atmospheric fate of reactive nitrogen.

Uncertainties arise from several factors in this study. The sectoral mapping among multiple emission and economic datasets bring uncertainties into our estimates. Such misalignments can affect sectoral emission intensities, the consumption-based emission accounting, and consequently, the nitrogen deposition estimates. To minimize such uncertainties, we prioritized preserving emission sector disaggregation at the finest level available and only performed aggregation at the final step of consumption-based emission accounting. The basic emission inventories are subject to uncertainties in basic data such as activity rate and emission factor (Lei et al., 2011; Zhang et al., 2009) and the GEOS-Chem simulations are subject to uncertainties in aerosol chemical and physical processes (Ge et al., 2020; Luo et al., 2020; Pai et al., 2020). To evaluate the overall performance of our modelling framework, we compared the simulated nitrogen deposition with observation estimates at monitoring sites across China (Fig. S4). The model reproduced the observed spatial variability of total nitrogen deposition reasonably well, with a correlation coefficient of $r = 0.79$ and a normalized mean bias (NMB) of 13.7%, indicating a slight overestimation but overall acceptable reliability for our analysis. Overall, the comparison suggests that our simulation captures the magnitude and spatial pattern of nitrogen deposition in China with acceptable reliability, supporting its application for our analysis. Given that the static MRIO framework assumes fixed production structures and does not capture how supply chains may reconfigure in response to consumption interventions or price signals, future studies could further move toward a dynamic modelling, helping with examining whether consumption-based policies are effective in achieving real emission reductions or merely shift the pollution burden elsewhere.

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Code and data availability

The code and data used to support the results and generate the main figures in this study are available on Zenodo at https://doi.org/10.5281/zenodo.21666480.

Author contribution

JW conceived the study, supervised the research, and wrote the manuscript. YC processed and calculated the data, drew the figures, and wrote the original manuscript. JT contributed to the initial data processing and code development. ZL performed the GEOS-Chem simulations and provided methodological guidance. All authors contributed to the analysis of the results and the writing of the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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