

Economic Trade and Atmospheric Transport in Shaping China's Nitrogen Deposition Patterns

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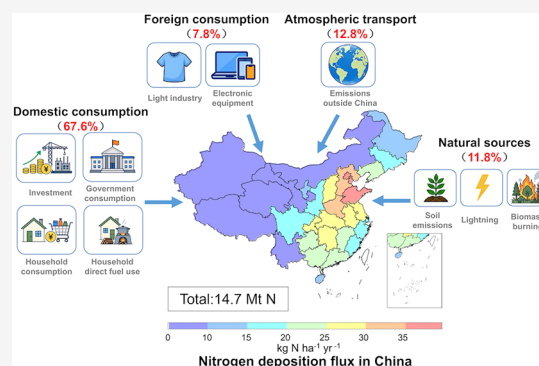
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ABSTRACT: Atmospheric nitrogen deposition in China is driven not only by local emissions but also by global economic demand and transboundary atmospheric transport. Unraveling these dual influences is critical for effective environmental governance. Here, we integrate an economic-emission analysis with a high-resolution atmospheric chemical transport model to quantify, for the first time, the distinct roles of domestic consumption, international trade, and atmospheric transport in shaping China's nitrogen deposition patterns. We find that domestic consumption is the dominant contributor, responsible for 67.6% of the total deposition, involving a substantial interprovincial transfer of emissions from affluent coastal provinces to less developed inland regions. International trade attributes 7.8% of China's deposition to foreign consumption, primarily driven by demand from the USA and Western Europe. In contrast, transnational atmospheric transport directly accounts for 12.8%, with a disproportionately high impact on ecologically sensitive western China. Natural sources contribute the remaining 11.8%. Our results reveal a complex web of drivers extending beyond China's borders. Mitigating nitrogen deposition, therefore, requires moving beyond local emission controls to embrace consumption-based accountability and enhanced international cooperation on both trade and atmospheric pollution to protect vulnerable ecosystems.

KEYWORDS: Input-output analysis, economic trade, atmospheric transport, nitrogen deposition



1. INTRODUCTION

China is confronting one of the world's most severe atmospheric nitrogen deposition challenges, with deposition levels exceeding the ecological critical loads across ecologically sensitive territories.^{1,2} Satellite and ground-based observations reveal that the national average nitrogen deposition flux in China has changed from a rapid increase toward stability since 1980³, significantly surpassing the levels recorded in the USA and Western Europe.⁴ The high deposition level stems largely from a rise in China's reactive nitrogen (N_r) emissions (e.g., NO_x and NH_3), which are primarily caused by rapid industrialization, agricultural intensification and increased fossil fuel combustion.⁵ N_r emissions in the atmosphere can be deposited through both dry and wet pathways, encompassing reduced nitrogen species (NH_x = ammonia [NH_3] + ammonium [NH_4^+]) and oxidized nitrogen compounds (NO_y , the sum of all oxidized N_r species).⁶ Although nitrogen serves as an essential nutrient element for natural ecosystems, widespread exceedance of critical loads threatens to induce soil acidification and reduce biodiversity.^{7,8} Effective environmental management for reducing nitrogen deposition requires understanding its drivers and fairly allocating responsibilities, so as to inform targeted and equitable mitigation strategies.

China's current environmental policies for mitigating nitrogen deposition mainly follow a production-based framework, assigning responsibility to the producers where the N_r emissions are emitted.^{9,10} However, the expansion of economic trade—both domestic and international—has increasingly enabled production activities and their related N_r emissions to occur far from where the goods or services are ultimately consumed.¹¹ The production-based measures fail to address emission leakage,¹² the phenomenon of domestic production reducing their local emissions by shifting pollution-intensive production to other regions. This not only undermines ongoing efforts to reduce N_r emissions, but also overlooks the benefit conveyed to consumers through economic trade.^{14,15} Furthermore, through atmospheric transport, nitrogen deposition from emissions in one region can be transported to more distant areas.^{16,17} Given the variations in geographical location, consumption patterns and economic

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structure among Chinese provinces, the impacts of economic trade and atmospheric transport on nitrogen deposition could exhibit strong regional heterogeneity.

Previous studies have made great efforts on understanding either the economic drivers or the atmospheric transport in shaping nitrogen deposition in China, yet these two factors have largely been addressed in isolation. On one hand, a growing body of literature has employed Multi-Regional Input-Output (MRIO) analysis to trace consumption-based emissions of air pollutants, revealing how domestic and international trade reshape the spatial distribution of emission responsibilities across regions.^{18–21} On the other hand, atmospheric chemical transport models (CTMs) such as GEOS-Chem, CMAQ, and WRF-Chem have been widely applied to simulate the transport, chemical transformation, and deposition of nitrogen species, providing critical insights into the spatial patterns of nitrogen deposition and the source contributions to specific receptor regions;^{22–24} yet the consumption drivers of emissions were not addressed in these atmospheric modeling studies. Although some studies have combined consumption-based accounting with atmospheric transport modeling and recognized the importance of economic trade and atmospheric transport in shaping regional air quality and related health impacts in China,^{13,25–27} the effect on nitrogen deposition and its spatial disparities has never been assessed. In particular, the contribution of each foreign region to nitrogen deposition across Chinese provinces through international trade remains entirely unexplored. This gap is largely hindered by data and methodological barriers in integrating China's interprovincial trade with global international trade into a unified analytical framework, and coupling consumption-based accounting with atmospheric transport modeling for nitrogen deposition assessment. Bridging this gap is essential not only for identifying drivers of nitrogen deposition in China, particularly in ecologically sensitive regions, but also for aligning environmental policy with national targets toward a sustainable nitrogen management and green supply chains.

Here, we investigate the roles of economic trade and atmospheric transport in shaping the nitrogen deposition patterns in China for 2017, which is the most recent year for which all necessary data are available. Through an interdisciplinary framework (SI Figure S1), we employed sector-, region- and pollutant-specific anthropogenic emission data from a customized Chinese provincial emission inventory, created a foreign countries-Chinese provinces linked MRIO table to estimate consumption-based N_r emissions, and ran the GEOS-Chem global chemical transport model to simulate nitrogen deposition impacts of such emissions. Our results offer insight into the important transboundary contributions from domestic and foreign players in the amount and spatial distribution of nitrogen deposition across China, calling for improved mitigation strategy that accounts for both local and nonlocal sources. Although our study is based on China due to its severe nitrogen deposition and large economic trade volume, the implications extend to other economies confronting similar challenges of transboundary environmental problems.

2. MATERIALS AND METHODS

2.1. Customized Provincial Emission Inventory for China

We developed a customized Chinese provincial emission inventory based on Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS, <http://www.iiasa.ac.at/web/home/research/researchPrograms/air/Asia.html>)²⁸ and Multiresolution Emission Inventory for Climate and air pollution research (MEIC, <http://www.meicmodel.org/>).^{29,30} The pollutants analyzed include pollutants that directly contribute to nitrogen deposition (NO_x and NH_3) and those influencing the formation of nitrogen deposition (SO_2 , CO, BC, OC and NMVOC). While MEIC is widely employed in studies on China's atmospheric environment, it provides only 22 integrated sectors (SI Table S1). Thus, we incorporated the emission inventory GAINS, which includes 56 disaggregated sectors to better match with the 65 sectors in the MRIO table used here (SI Tables S2 and S3). We mapped the 56 sectors of GAINS with the 22 sectors of MEIC based on SI Table S3. For each province, sector-specific proportions from GAINS were applied to the corresponding aggregated emission sector in MEIC, resulting in a customized inventory with 56 sectors. To match with the MRIO table used in this study, we further converted this inventory into 65 sectors and the sectoral mapping details can be found in SI Table S3. In addition, we divided the agricultural sector into 14 detailed subsectors, and we updated the emissions of NH_3 for detailed agricultural subsectors with the inventory developed by Chen et al.³¹ (see SI Table S4 for details).

2.2. Emissions Related to Household Direct Fuel Use

Household direct fuel use refers to their fuel use for energy in activities such as heating, cooking and private vehicle use, which do not participate in economic activities. These activities only contribute to local emissions. We obtained these emissions from the sectors related with household direct fuel use in MEIC (sectors S13–S16 in SI Table S1). These emissions were further traced back to the source from urban or rural households in each province based on the ratio of their fuel consumption, obtained from the China Emission Accounts and Datasets (CEADS, <http://www.ceads.net>). Here, the consumption amounts of different fuel types were unified into raw coal equivalents based on the ratio of their respective emission factors to that of raw coal. The fuel types considered in this study include raw coal, cleaned coal, other washed coal and briquettes, and their emission factors were derived from Peng et al.³²

2.3. Consumption-Based Emissions Related to Economic Trade

In this study, we used MRIO analysis to calculate China's provincial air pollutant emissions triggered by various consumption demands. MRIO analysis has been widely applied in environmental footprint accounting.^{33,34} We first developed a foreign countries-Chinese provinces linked MRIO table to analyze the economic interactions between foreign countries and Chinese provinces. This linked MRIO table was established by integrating a Chinese provincial MRIO table with the global MRIO table. The Chinese table was obtained from Zheng et al.,³⁵ covering trade flows among 42 economic sectors of 31 mainland provinces (data for Hong Kong, Macao and Taiwan are not available). The global MRIO table was obtained from the Global Trade Analysis Project (GTAP) version 11,³⁶ covering trade flows among 65 economic sectors of 160 regions. China's province-level international trade flows were estimated by using product-, province-, and county-specific customs data, which provide detailed trade flows among Chinese provinces and over 200 foreign economies across nearly ten thousand product categories. To facilitate the table linkage, we mapped the foreign countries and sectors in the customs data with those in GTAP MRIO table. Finally, the linked MRIO model covers 65 economic sectors of 157 foreign countries/regions, excluding mainland China, Hong Kong and Macao from the 160 regions in GTAP, and 31 Chinese mainland provinces. Details for the establishment of the foreign countries-Chinese provinces linked MRIO model and customized emission inventory could be found in our previous study.³⁷ The consumption-based emission accounting is

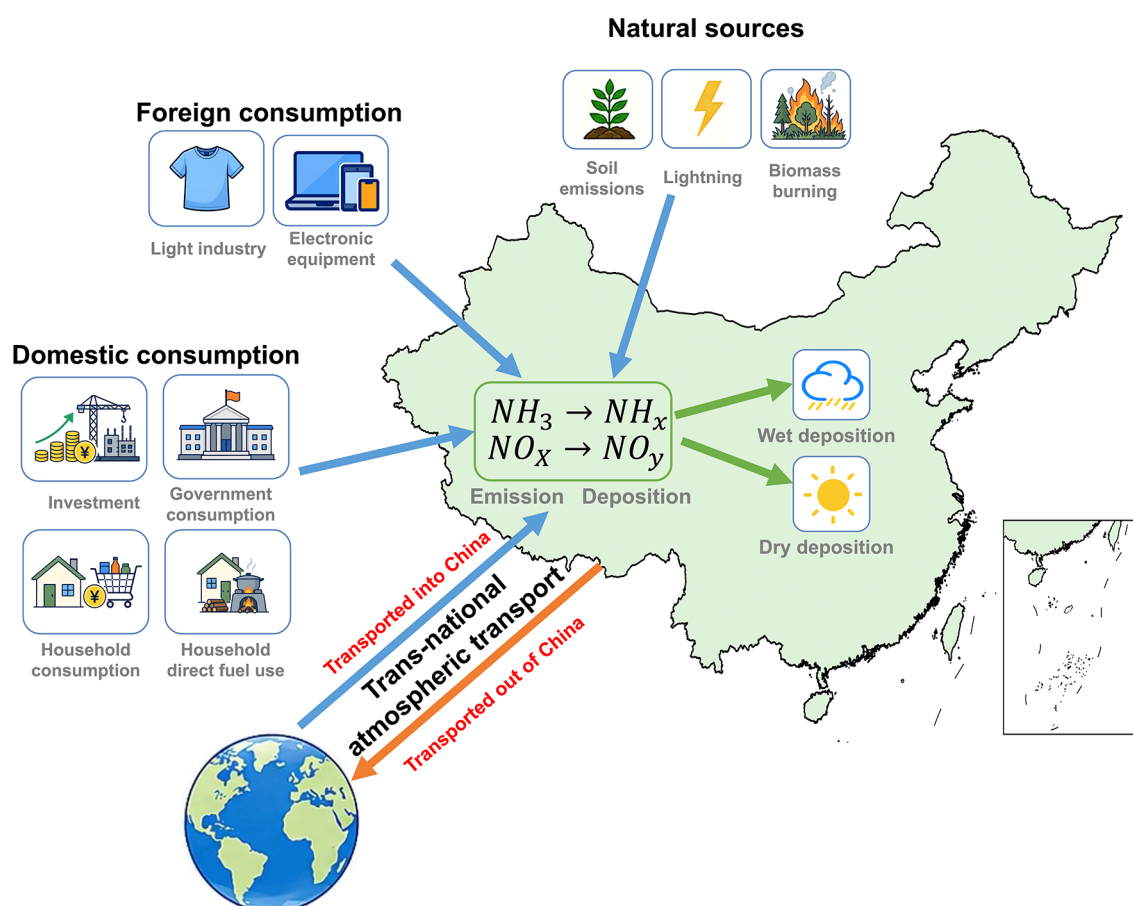


Figure 1. Conceptual framework of this study.

elaborated in [SI Section 1](#). After the calculation of consumption-based emissions, the global countries/regions are further aggregated into 13 regions (China and 12 foreign regions) to facilitate subsequent analysis, and the world region aggregation can be found in [SI Figure S2](#).

2.4. Nitrogen Deposition Simulation

Nr emissions emitted from anthropogenic and natural sources undergo atmospheric chemical transformations and transport processes, and are ultimately removed by dry deposition and wet deposition. The spatial patterns of deposition are the combined effect of emission magnitudes, chemical conversion efficiency, transport efficiency, and meteorological conditions.^{38,39} We used the three-dimensional global chemical transport model GEOS-Chem (version 14.0.1) to simulate nitrogen deposition in this study. GEOS-Chem incorporates detailed atmospheric chemical mechanisms, encompassing processes in both the stratosphere and troposphere, interactions between aerosols and gases, as well as aqueous-phase chemistry. GEOS-Chem has been widely used in exploring the concentration of nitrogen deposition.^{24,40} In this study, we focus on oxidized nitrogen (NO_y) and reduced nitrogen (NH_x) species, which are the major contributors to atmospheric nitrogen inputs to ecosystems. Although nitrous oxide (N_2O) is an important nitrogen-containing greenhouse gas closely associated with agricultural activities and fertilizer use, it is not considered here because it is chemically stable in the troposphere and has a limited contribution to atmospheric nitrogen deposition. In addition, N_2O is primarily removed through stratospheric photochemical processes rather than through tropospheric oxidation and deposition.⁴¹

Our nested simulations were conducted at a horizontal resolution of $0.3125^\circ \times 0.25^\circ$ (longitude $\times$ latitude), driven by the assimilated meteorological field GEOS-FP. Each nested simulation was run for January, April, July, and October, and the average result of the four

months was taken as the annual average. A 10-day spin-up period was systematically implemented prior to each monthly simulation to ensure proper model calculations. Boundary conditions for the nested simulations were derived from corresponding global simulations at a resolution of $2.5^\circ \times 2^\circ$ (longitude $\times$ latitude), driven by the assimilated meteorological field MERRA-2. The global simulations spanned from July 2016 to December 2017, including a 6-month spin-up phase.

[SI Table S5](#) describes the suite of model simulations in this study. We conducted a control simulation (i.e., CTRL) and 5 groups of sensitivity experiments (i.e., Xdomestic_con, Xforeign_con, Xch_pro, Xch_ex and Xforeign_pro), with a total of 33 sets of GEOS-Chem model experiments. The nitrogen deposition triggered by a certain factor was obtained by subtracting the result of corresponding simulation from CTRL. For example, we derive the deposition triggered by domestic consumption by subtracting Xdomestic_con from CTRL. Among the four drivers contributing to nitrogen deposition in China, deposition attributed to domestic consumption and foreign consumption represents the deposition generated by the anthropogenic emissions physically released within China. Here, the part attributed to foreign consumption does not include the portion of Nr emissions generated outside China by foreign consumption that undergoes atmospheric chemical transport processes and is eventually deposited in China. In contrast, deposition attributed to trans-national atmospheric transport exclusively accounts for the contribution from anthropogenic emissions originating outside China. The deposition contribution from natural sources was derived by subtracting the total contributions of domestic consumption, foreign consumption and trans-national atmospheric transport from CTRL. Thus, the nitrogen deposition in China attributed to each contributor is mutually exclusive.

The global anthropogenic emissions were obtained from the Community Emissions Data System (CEDS) database. For nested

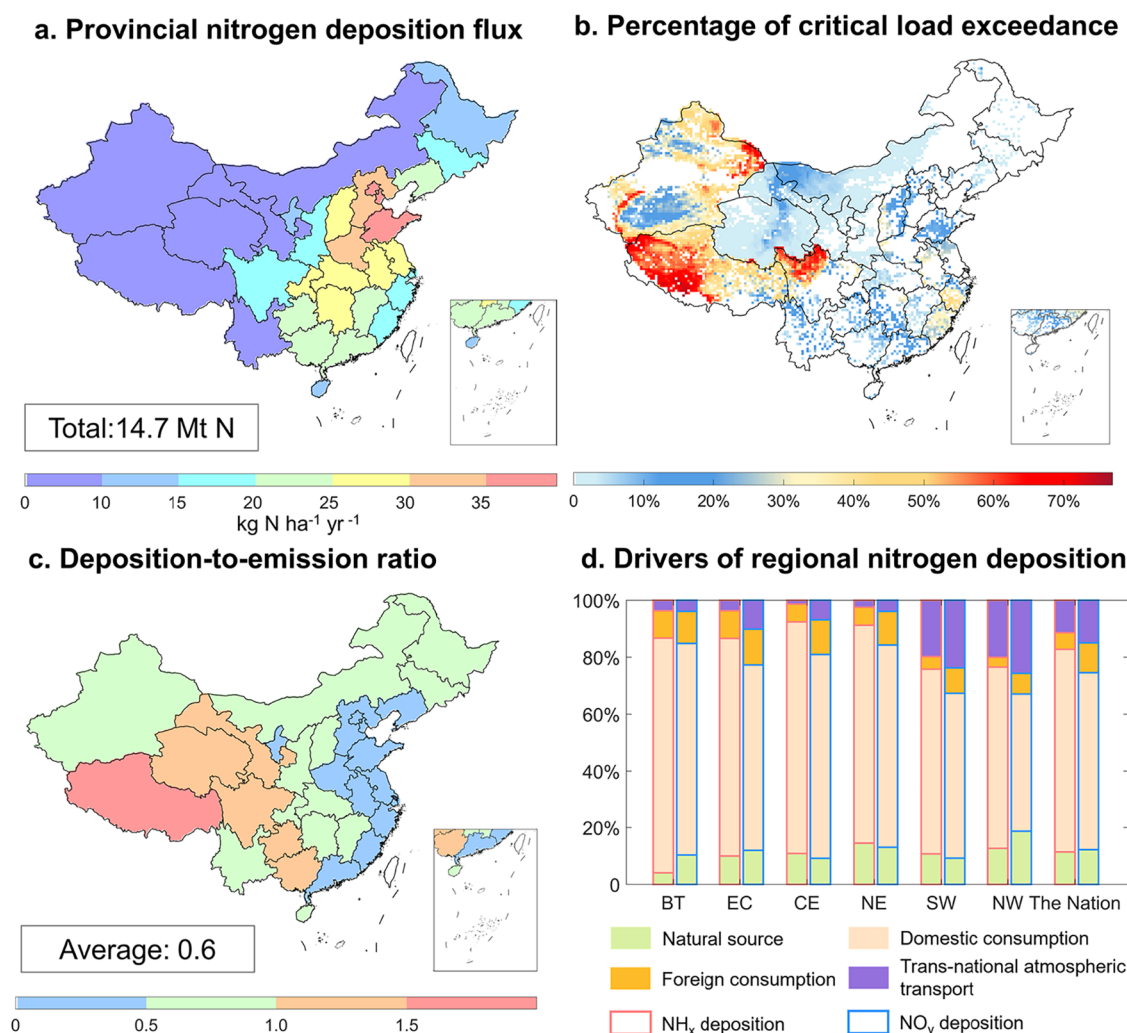


Figure 2. China's nitrogen deposition and the drivers. (a) Chinese provincial nitrogen deposition flux in 2017. The number at the lower left corner represents the national total nitrogen deposition. (b) Percentage of China's critical load exceedance, which is calculated as the percentage by which nitrogen deposition exceeds the critical load. Areas with no exceedance in China are shown in white. Spatial distribution of critical loads for soil nitrogen in China can be found in SI Figure S5. (c) The ratio of nitrogen deposition to emission. Values larger than one indicate net import (import > export) of nitrogen in the atmosphere, while values smaller than one indicate net export. (d) Sources of Chinese regional nitrogen deposition. Here, the regional abbreviations are as BT = Beijing-Tianjin, EC = the East Coast, CE = the Central, NE = the Northeast, NW = the Northwest, SW = the Southwest.

simulations, China's anthropogenic emissions were replaced with the emissions from MEIC with a horizontal resolution of $0.1^\circ \times 0.1^\circ$. The air pollutant emissions from household direct fuel use and various consumption demands were incorporated into the GEOS-Chem model by being gridded into a resolution of $0.1^\circ \times 0.1^\circ$ based on the spatial distribution of emission inventory from MEIC. The model also incorporates various natural sources of N_t emissions. Lightning NO_x emissions are calculated using cloud top height parametrization⁴² and distributed vertically,⁴³ with spatial constraints from satellite observations.^{44,45} Soil NO_x emissions are estimated using the Berkeley-Dalhousie Soil NO_x emission Parameterization.⁴⁶ Biomass burning emissions are from the Global Fire Emissions Database (GFED) inventory.⁴⁷ Natural NH_3 emissions are from the Global Emissions Initiative (GEIA) inventory.⁴⁸

3. RESULTS

3.1. Interdisciplinary Framework for Nitrogen Deposition Drivers

The conceptual framework of this interdisciplinary study linking economic trade, atmospheric transport, and natural

sources to nitrogen deposition in China is shown in Figure 1. The economic trade-related drivers include domestic consumption and foreign consumption. For domestic consumption, we account not only for the factors related to economic activities (investment, government consumption and household consumption), but also for household direct fuel use for energy in daily activities such as cooking and heating. For foreign consumption, we include the final demands from 157 countries and regions. Both domestic and foreign consumption-driven emissions refer to emissions physically generated within China. Beyond domestic emissions, long-range atmospheric transport of foreign anthropogenic nitrogen species also contributes to China's deposition. For a complete source attribution, we additionally account for contributions from natural sources such as soil emissions, lightning and biomass burning.

3.2. Spatial Pattern of Nitrogen Deposition across China

As illustrated in Figure 2a, the total annual nitrogen deposition in China for 2017 is estimated at 14.7 Mt N, with NH_x

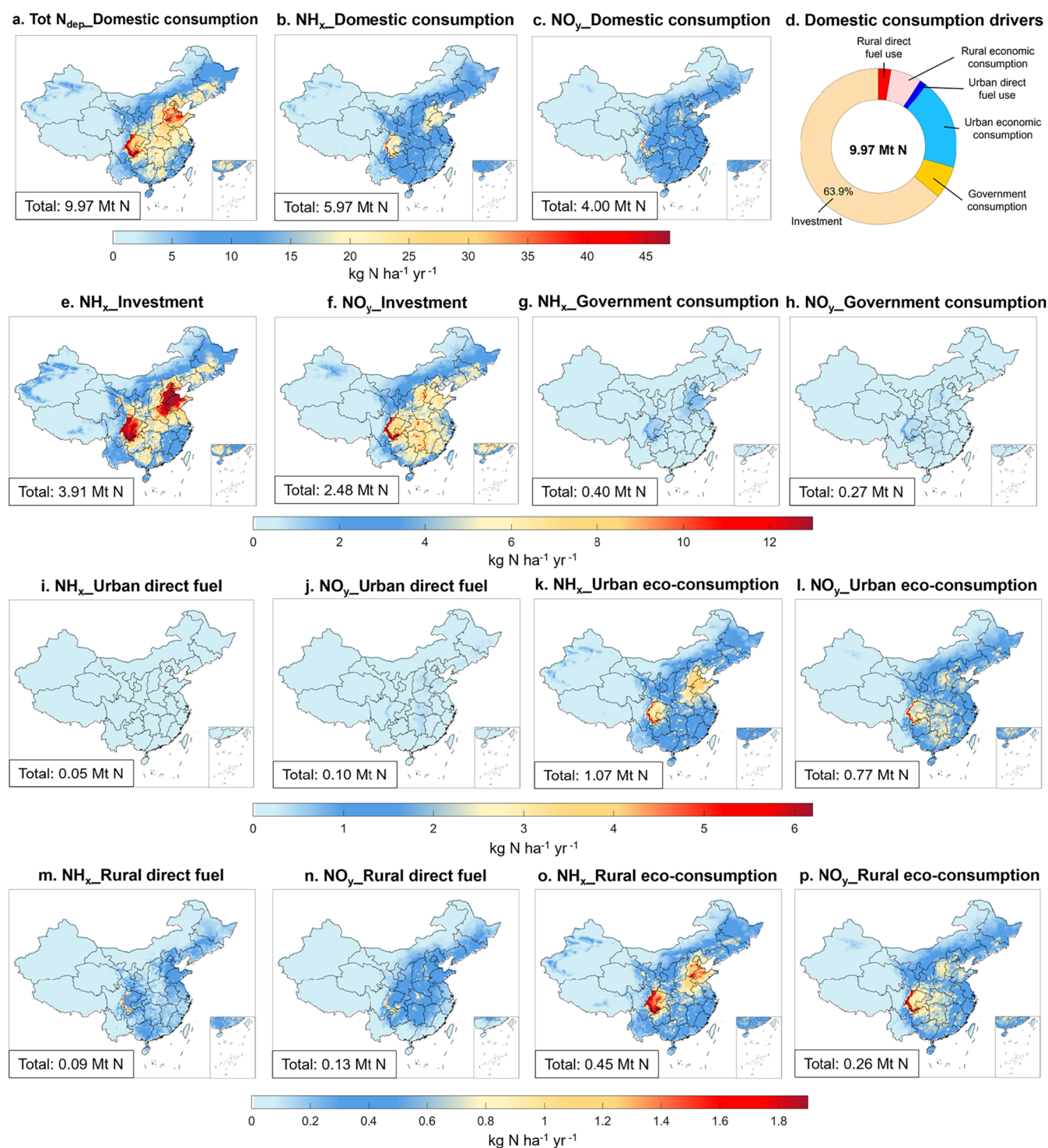


Figure 3. Nitrogen deposition contribution from domestic consumption. (a–c) The spatial pattern of nitrogen deposition contributed by domestic consumption. (d) The contribution proportion of different domestic consumption types. (e–p) The spatial pattern of nitrogen deposition contributed by different domestic consumption types. The numbers at the lower left corner of each spatial distribution figure represent the national total nitrogen deposition driven by different domestic consumption types.

contributing 56.7% and NO_y accounting for the remaining 43.3%. The average nitrogen deposition flux in China is as high as $15.6 \text{ kg N ha}^{-1} \text{ yr}^{-1}$, substantially higher than in the USA ($6.7 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ based on our estimation) and Western Europe ($12.1 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ based on our estimation). The nitrogen deposition flux level has increased by approximately 60% compared with that in 1980¹. Nitrogen deposition shows

a highly uneven spatial distribution across China (Figure 2a). High-deposition areas are mainly concentrated in the East Coast and the Central (the detailed regional classification is shown in SI Figure S3). The East high and West low spatial pattern is in line with previous studies.^{2,3} Shandong, a province characterized by its large population and developed agricultural and industrial production, has the most severe deposition with

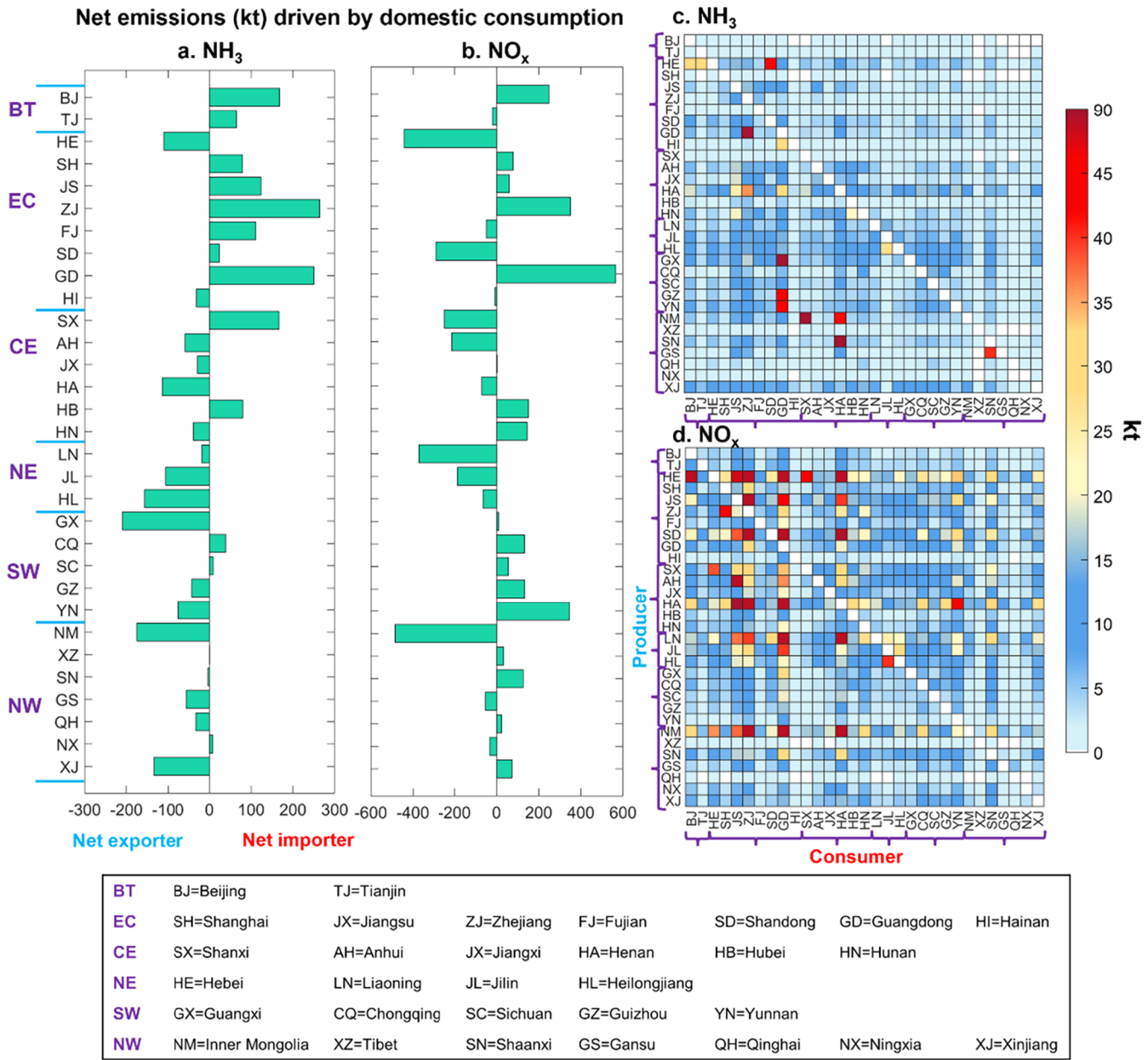


Figure 4. Interprovincial emission transfers driven by domestic consumption. (a, b) show provincial net emissions driven by domestic consumption. A positive value means that emissions in a province due to its production for other regions' consumption are smaller than the respective emissions. (c, d) show detailed emission flows between each pair of provinces. Each cell represents the emissions in the province on the y-axis driven by consumption in the province on the x-axis. Results for production to support self-consumption are excluded. Here, the regional abbreviations are as BT = Beijing-Tianjin, EC = the East Coast, CE = the Central, NE = the Northeast, NW = the Northwest, SW = the Southwest.

a flux of 45.0 kg N ha⁻¹ yr⁻¹, nearly 2.9 times the national average. We further find that NH_x deposition dominates in major agricultural zones such as Shandong, Southern Hebei and the Sichuan Basin, while NO_y deposition is more widely distributed across industrialized and urbanized areas along the East Coast and the Central (SI Figure S4).

Figure 2b indicates that in most regions, nitrogen deposition exceeds its critical load, defined as the maximum amount of nitrogen deposition that does not cause long-term adverse chemical changes in sensitive ecosystems.⁴⁹ In most areas of the Southwest and the Northwest, nitrogen deposition has exceeded the critical load by more than 50.0%, despite their relatively low absolute deposition levels. This is because in these ecologically sensitive regions, the dominant vegetation

types are alpine meadows, steppes, and desert shrubs, which have very low critical loads for nitrogen (SI Figure S5). So they are highly vulnerable to even minor increases in the absolute amount of deposition. These findings reveal extreme spatial heterogeneity, distinct source signatures, and widespread critical load exceedances of nitrogen deposition in China, advancing beyond previous estimates to inform targeted policy interventions at both regional and sectoral levels.

To further investigate the relationship between nitrogen emissions and deposition, we calculated the deposition-to-emission ratio at the provincial scale following Liu et al.,⁴ and the characteristics of Nr emissions in China are analyzed in SI Section 2. As shown in Figure 2c, the national average ratio is approximately 0.6, indicating that a considerable fraction of

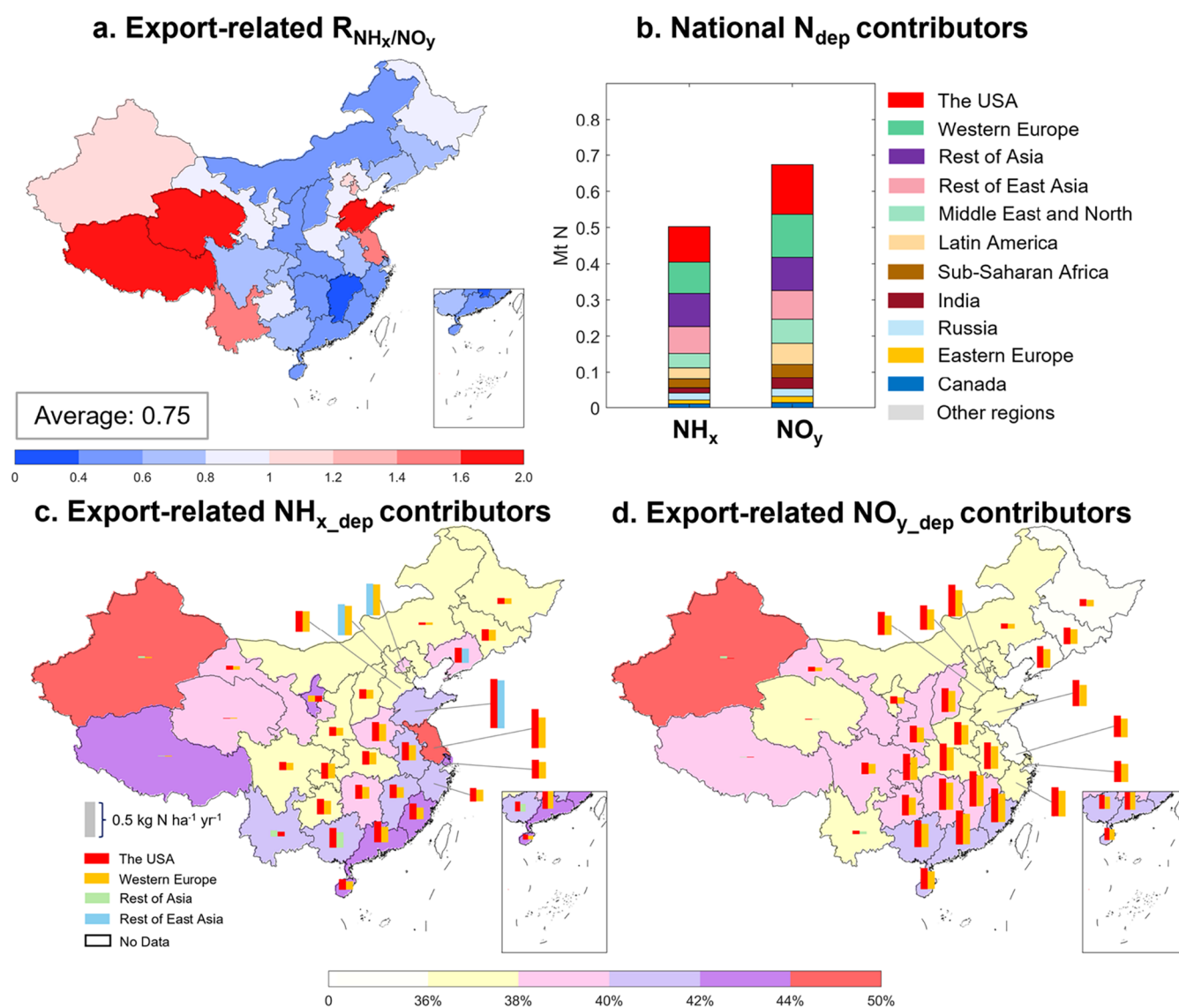


Figure 5. Nitrogen deposition contribution from foreign consumption. (a) The ratio of provincial export-related NH_x deposition to NO_y deposition ($R_{\text{NH}_x/\text{NO}_y}$). The number at the lower left corner represents the national average $R_{\text{NH}_x/\text{NO}_y}$. (b) Each region's contribution to foreign consumption-related nitrogen deposition in China. (c, d) The top two foreign contributors of each province (the bars), and their contribution proportion to this province's export-related nitrogen deposition (the shading). The definition of the world regions can be found in SI Figure S2.

emitted reactive nitrogen is transported away from the emission regions before deposition. This ratio shows strong spatial heterogeneity, reflecting the combined effects of emission, atmospheric transport, and deposition processes. For example, the East Coast generally shows ratios below 0.5, suggesting substantial export of reactive nitrogen from these high-emission regions. In contrast, the deposition-to-emission ratio exceeds 1.5 in Tibet, highlighting the important role of transported nitrogen in shaping regional deposition patterns.

To understand what drives the spatial patterns of nitrogen deposition in China, we decompose the deposition into contributions from four source categories, including domestic consumption, foreign consumption, trans-national atmospheric transport and natural sources. For the first three drivers, we consider only the deposition contributed by anthropogenic activities. The deposition contribution from domestic and foreign consumption activities also includes the effects of cross-regional atmospheric transport on nitrogen deposition formed from emissions within China's territory. Figure 2d shows that

the drivers related with anthropogenic emissions (i.e., domestic consumption, foreign consumption and trans-national atmospheric transport) together account for 88.2% of China's nitrogen deposition. Natural sources, such as soil emissions, lightning-induced fixation, natural wildfires and marine sources, are responsible for the remaining 11.8%. Overall, anthropogenic activities dominate the contribution to nitrogen deposition in China, and the following sections provide detailed analyses for this part.

3.3. Domestic Consumption Predominately Drives Nitrogen Deposition

Domestic consumption is the leading driver, responsible for 67.6% (9.97 Mt N) of national total nitrogen deposition (Figures 2d and 3a). In most regions, its contribution is higher for NH_x than for NO_y , a pattern largely attributable to domestic food demand that sustains the intensive agricultural activities—the dominant source of anthropogenic NH_3 emissions. Specifically, the domestic contribution accounts

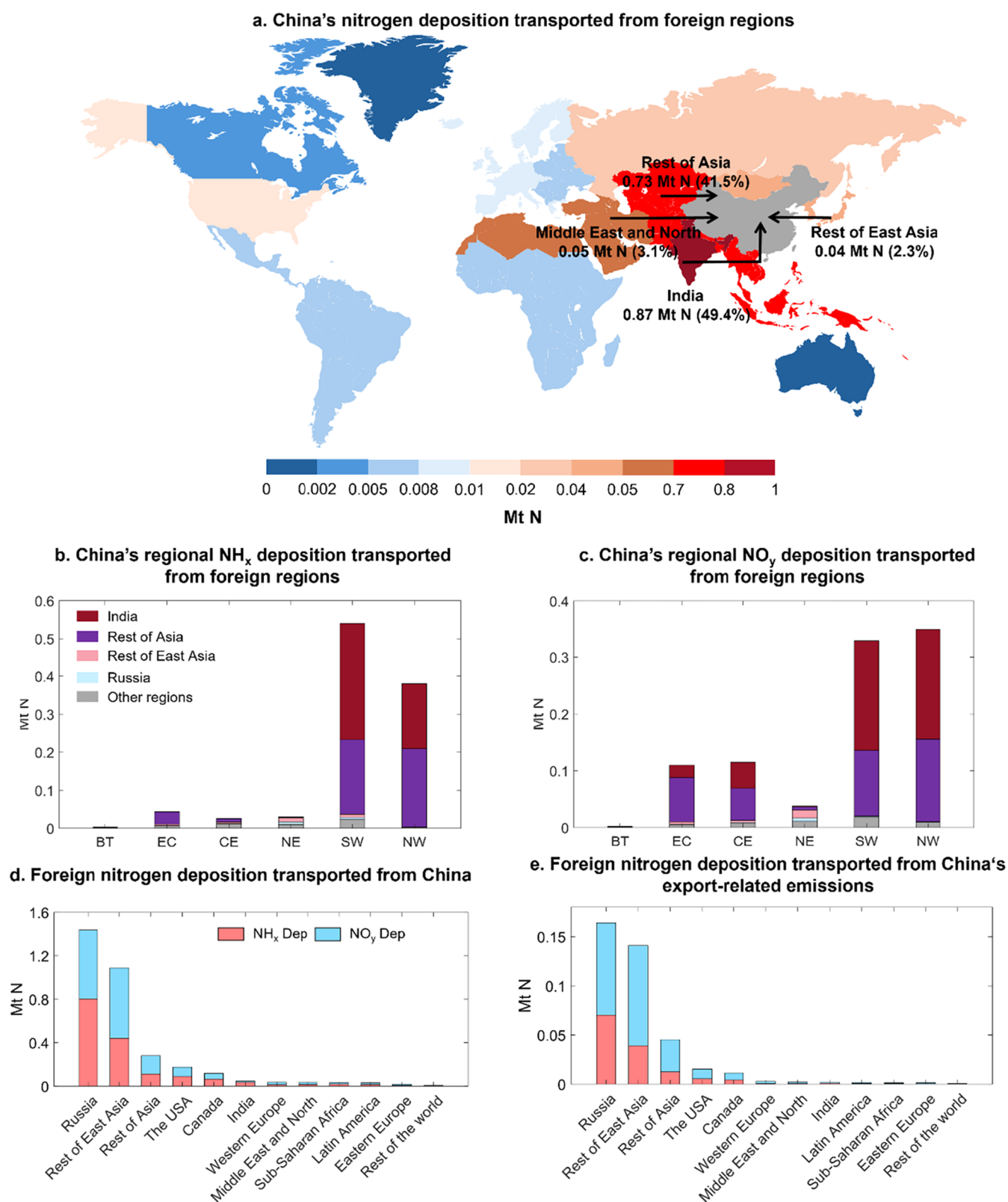


Figure 6. Nitrogen deposition contribution from trans-national atmospheric transport. (a) The foreign sources of trans-national atmospheric transport-related nitrogen deposition in China. The shading of each foreign region shows the amount of nitrogen deposition transported from this region. Note that the color scales are nonlinear. The top four contributors are shown with their respective contribution amount and percentages in trans-national atmospheric transport-related nitrogen deposition. (b, c) China's regional nitrogen deposition transported from foreign regions. (d, e) Foreign nitrogen deposition transported from China's total emissions (d) and export-related emissions (e).

for over 75.0% of the deposition in highly populated regions such as Beijing-Tianjin and the Central. This domestic

consumption-driven impact peaks in the Sichuan Basin (Figure 3b,c). High local Nr emissions driven by domestic con-

sumption, combined with basin-enhanced precipitation, drive wet nitrogen deposition to nearly 80% of the total there.

We further separate domestic consumption into four types—investment, government consumption, household consumption, and household direct fuel use for energy—to trace their respective contributions to China's nitrogen deposition (Figure 3d–p). Overall, investment is the dominant driver, responsible for 63.9% of domestic consumption-related nitrogen deposition, while government consumption contributes only 6.8% (Figure 3d). This is in line with previous emission studies.^{50–52} Their contribution to NH_x deposition is largely driven by their demand for services related with accommodation and food, whereas NO_y deposition stems more from their construction and transport-related activities. Household activities account for the remaining 30% (Figure 3d). Urban households contribute more to nitrogen deposition through consumption, especially in the affluent East Coast (Figure 3i–l). In contrast, rural households contribute more nitrogen deposition via direct fuel use (Figure 3m–p). However, in highly urbanized metropolises such as Beijing and Shanghai, where urban residents comprise nearly 90% of the population, urban households lead in both categories (SI Tables S6 and S7).

A region's consumption not only contributes to nitrogen deposition locally, but also drives nitrogen deposition in other regions through the transfer of Nr emissions along supply chains. Figure 4a,b show provincial differences in consumption- and production-based emissions, or the net emissions embodied in trade (emissions embodied in interprovincial imports minus emissions embodied in interprovincial exports). Our results indicate that most provinces in the developed Beijing-Tianjin and the East Coast tend to net outsource pollution to other provinces. This is because they rely on imports of agricultural products and pollution-intensive goods from less developed provinces. In contrast, most provinces in other regions tend to have net export due to their abundant mineral resources and developed manufacturing. Consumption in the East Coast drives a significant share (up to ~35%) of indirect NH_3 and NO_x emissions in inland provinces (Figure 4c,d). Here, indirect emissions refer to the emissions triggered by final demand from other provinces. Notably, net imports are distinct in the affluent Guangdong Province, accounting for over 10.0% of the indirect Nr emissions in inland provinces. As detailed in SI Table S8, the top 10 interprovincial transfer pathways consistently flow from the East Coast to inland provinces, with NH_3 emissions originating primarily from crop and livestock farming, and NO_x from industry, power generation, and transportation.

3.4. Developed Regions Dominate Export-Related Nitrogen Deposition

Foreign consumption also drives considerable nitrogen emissions in China through international trade, and these emissions further result in nitrogen deposition in China. As estimated in Figure 2d, foreign consumption is responsible for 7.8% (1.2 Mt N) of China's total nitrogen deposition, varying from 5.0% in the Southwest to 11.1% in the East Coast. Foreign consumption's contribution share is relatively higher for NO_y than NH_x , especially on the East Coast and the Central, due to their international exports of industrial products. SI Figure S6 indicates that total nitrogen and NH_x deposition from foreign consumption is pronounced in Shandong Province, a consequence of its extensive agricultural

international exports. In contrast, NO_y deposition from foreign consumption primarily impacts southeastern coastal provinces (SI Figure S6).

The ratio of export-related NH_x deposition to NO_y deposition ($R_{\text{NH}_x/\text{NO}_y}$) serves as an indicator, revealing whether industrial or agricultural activities dominate the region's export-related nitrogen deposition. Figure 5a shows that the average export-related $R_{\text{NH}_x/\text{NO}_y}$ in China is 0.75, suggesting that industrial production is the main source of export-related nitrogen deposition across most regions. The key contributors to export-related NO_x emissions are transportation, electricity and ferrous metals, driven by foreign consumption of construction and manufacturing products (SI Figure S7a,b). In contrast, export-related $R_{\text{NH}_x/\text{NO}_y}$ is higher than 1 in several eastern and western provinces. The leading sources of export-related NH_3 emissions are livestock farming and crop cultivation, supplying foreign demand for food, textile and apparel products (SI Figure S7c,d).

The deposition contribution from each foreign region is shown in Figure 5b–d. Among the 12 foreign regions, the USA and Western Europe contribute the majority of China's export-related nitrogen deposition, together accounting for 37.6% of NO_y and 39.2% of NH_x (Figure 5b). Their contribution is particularly pronounced across China's southern provinces, where consumption in these two regions drives more than 40.0% of local export-related NO_y deposition (Figure 5d). China's Asian neighbors also act as considerable contributors to export-related NH_x deposition, especially to China's eastern agricultural hubs. Details for the major foreign contributors to provincial export-related nitrogen deposition are listed in SI Table S9.

3.5. Significant Nitrogen Deposition along China's Borders from Trans-National Atmospheric Transport

Nitrogen deposition in China is also influenced by the nitrogen species emitted from foreign countries and then transported in the atmosphere into China. As illustrated in Figure 2d, trans-national atmospheric transport accounts for 12.8% of nitrogen deposition in China, exhibiting considerable differences among different regions. Trans-national atmospheric transport accounts for only 4.1% and 3.0% of nitrogen deposition in the Central and the Northeast respectively, while the contribution ratio exceeds 20.0% in ecologically sensitive western regions. In the Southwest and the Northwest, the contribution from trans-national atmospheric transport far surpasses that from foreign consumption. As shown in Figures 6a and S8, this part of nitrogen deposition is mainly transported from India and Rest of Asia, collectively accounting for over 90.0% of the total externally transported nitrogen deposition (including both NH_x and NO_y). Southwest and Northwest China receive substantial deposition contributions from India and Rest of Asia, largely because they are situated downwind of these foreign emission sources. The contribution from Rest of East Asia is notably distinct in Chinese regions such as the East Coast, the Central and the Northeast, particularly in terms of NO_y deposition (Figure 6b,c). These findings highlight that although the contribution of China's western neighbors to nitrogen deposition via economic trade is minimal, their influence through atmospheric transport is dominant.

3.6. Trans-National Nitrogen Deposition from China to Surrounding Regions

In addition to being a receptor of trans-national nitrogen deposition, China also serves as a considerable emission source

affecting the deposition abroad, especially in its neighboring regions. Figure 6d shows that deposition of nitrogen transported out of China is estimated to be 3.3 Mt N in 2017 (in detail, 1.6 Mt N NH_x and 1.7 Mt N NO_y). Given the relatively short atmospheric residence time of Nr emissions,^{53,54} the main affected regions are those surrounding China, such as Russia, Rest of East Asia and Rest of Asia.

It is worth noting that the Nr emissions in China contributed by foreign consumption may undergo further atmospheric transport and contribute to nitrogen deposition beyond China. This phenomenon highlights the coupling of economic trade and atmospheric transport in shaping global nitrogen flows. To better understand this mechanism, we specifically examined the contribution of China's export-related emissions to nitrogen deposition abroad (Figure 6e). Our estimates indicate that 6.4% (0.2 Mt N) of anthropogenic nitrogen deposition in the Rest of East Asia, and 3.2% (0.1 Mt N) in Russia can be attributed to emissions generated by China's export production. These results underscore that foreign demand not only drives nitrogen deposition within China, but also extends its ecological footprint to surrounding regions through atmospheric transport. This aligns with previous findings that the coupling of international trade and atmospheric transport plays a critical role in shaping transboundary environmental impacts.^{13,55}

4. DISCUSSION

Different from previous studies based on a production-based perspective, our study for the first time evaluates the drivers of nitrogen deposition in China from a consumption-based perspective. Our findings reveal that nitrogen deposition in China is not solely a result of local emissions, but is also driven by the interplay of interregional and international economic activities, as well as atmospheric transport processes. However, our emission and atmospheric model results are also subject to uncertainties from a variety of sources, and the detailed analysis can be found in SI Section 3.

The dominant role of domestic consumption in shaping nitrogen deposition, combined with a substantial transfer of Nr emissions from affluent to less developed regions, highlights the urgency for China to move beyond traditional, production-based environmental policies. Current policy frameworks, which allocate responsibility based on production-based emissions, fail to recognize the emissions embodied in economic trade and may even penalize less developed provinces for their production of goods consumed elsewhere.^{56,57} To support national goals in ecological management and coordinated regional development, it is essential to adopt an integrated strategy that addresses both production and consumption sides. For NO_y , whose interprovincial transfer is predominantly driven by coastal regions' demand for industrial and manufactured goods, consumption-based policies such as extending the existing environmental protection tax to include embodied emissions in supply chains^{58,59} could effectively incentivize cleaner production in provinces as producers. For NH_x , where agricultural activities are the primary source, production-side interventions such as promoting enhanced-efficiency fertilizers and improved manure management appear to be particularly relevant. These could be usefully complemented by demand-side measures such as green public procurement that favors low-ammonia farming practices. Furthermore, an interprovincial ecological compensation mechanism, in which final consumers

share the financial and technological burden of emission reduction of producers, would also enhance the equitable distribution of mitigation responsibilities. Such a mechanism might be designed to be sector-specific, i.e., for NH_x , funds could be directed to agricultural services in provinces as agricultural exporters to support the adoption of ammonia-reducing technologies; for NO_y , compensation could support retrofitting industrial facilities whose emissions are largely driven by distant consumption. Such approaches that distinguish different pollution sources would help the nation toward a more sustainable and balanced development pathway.

Foreign consumption via international trade accounts for a substantial portion of nitrogen deposition in China, particularly from developed countries, highlighting China's role as a "world factory" and the environmental costs embodied in its international exports.⁶⁰ This not only drives nitrogen deposition within China's export-oriented coastal provinces but also creates an uneven environmental burden, as regions specializing in pollution-intensive manufacturing bear disproportionate deposition impacts compared with their export volume. Atmospheric trans-national transport especially from neighboring foreign regions also contributes to nitrogen deposition in China, with a disproportionately high impact on ecologically sensitive western regions; in turn, emissions in China associated with both its own and foreign consumption affect nitrogen deposition in neighboring foreign regions. To address these, a multiregional collaborative framework on nitrogen management could offer a useful pathway to track mutual impacts and identify shared responsibilities, for example, by joint monitoring, shared early warning information, and coordinated emission reduction targets. Such international cooperation, similar to the long-range trans-boundary air pollution conventions in Europe and North America,⁶¹ would benefit from covering both trade-embodied and atmospherically transported pollution.

In summary, effective mitigation of nitrogen deposition in China cannot be achieved through local emission controls alone. Domestically, an interprovincial ecological compensation framework could serve as a useful mechanism for distributing mitigation costs more equitably among producers and consumers. Internationally, there may be scope for China to engage in bilateral and multilateral agreements that jointly account for both trade-embodied emissions and trans-national atmospheric transport. By implementing a comprehensive strategy that combines consumption-based responsibility, green trade practices, and international atmospheric cooperation, China might be able to better protect its vulnerable ecosystems while pursuing sustainable development. Although there are substantial changes in the absolute magnitudes of nitrogen deposition and economic volume after our studied year 2017, the core deposition spatial pattern^{40,62,63} and Chinese economic structure (SI Figure S9) remain qualitatively consistent. This temporal consistency ensures that our conclusions and policy implications offer insightful implications for China's present nitrogen deposition management.

■ ASSOCIATED CONTENT

Data Availability Statement

The MEIC emission inventory is available at <http://www.meicmodel.org/>. The GAINS emission inventory is available at <http://www.iiasa.ac.at/web/home/research/researchPrograms/air/Asia.html>. The GTAP global MRIO

table is available at <https://www.gtap.agecon.purdue.edu/>. The Chinese provincial MRIO table is available at <https://www.ceads.net.cn/>. GEOS-Chem used here is an open-source model and available at <https://geoschem.github.io>. The data and code that support the findings of this study are available on Zenodo with the identifier <https://zenodo.org/records/21435228>.

SI Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acs.est.6c07734>.

Interdisciplinary framework (Figure S1); definition of the 13 world regions (Figure S2); regional classification of China (Figure S3); total nitrogen deposition in China (Figure S4); critical loads of nitrogen in China (Figure S5); China's foreign consumption-related nitrogen deposition (Figure S6); sectoral contributions (Figure S7); China's NH_x and NO_y deposition transported from foreign regions (Figure S8); Chinese household consumption and exports during 2017–2024 (Figure S9); provincial production-based emissions (Figure S10); sectoral production-based emissions (Figure S11); share of the emission contribution from domestic and foreign consumption (Figure S12); comparison between the simulated and observed nitrogen deposition (Figure S13); CTRL simulation vs four independent component simulations (Figure S14); MEIC 22 sectors (Table S1); GTAP 65 sectors (Table S2); sectoral mapping between MEIC, GAINS, and GTAP (Table S3); sectoral mapping between agricultural NH_3 inventory and GTAP (Table S4); simulation configurations (Table S5); contributions of domestic demands to NH_x deposition (Table S6); contributions of domestic demands to NO_y deposition (Table S7); top 10 interprovincial emission transfer pathways (Table S8); top contributors of provincial export-related nitrogen deposition (Table S9); consumption-based emission accounting (Section 1); production- and consumption-based Nr emissions (Section 2); and uncertainty analysis (Section 3) (DOCX)

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Author Contributions

J.L. and J.W. conceived the study and designed the research. Z.L. calculated the emissions and conducted GEOS-Chem simulations. Y.L. and H.Z. provided economic data. X.L. and W.X. provided nitrogen deposition observation data. Y.C. provided provincial NH_3 emissions for detailed agricultural sectors. Y.Z. helped with GEOS-Chem model configuration. J.W., J.L., and Z.L. analyzed data and wrote the draft. L.S.,

H.Z., Y.L., Y.Z., K.H., K.F., M.D., H.K., X.L., and F.R. contributed to the discussion and the writing.

Notes

The authors declare no competing financial interest.

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