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Environmental burden and health inequity in China's road-based express delivery

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Urban e-commerce growth has driven unprecedented expansion in express delivery services, yet their cross-regional environmental and health consequences remain poorly understood. Here we present a novel spatially explicit assessment of emissions and their environmental burden in China's express delivery sector by integrating large-scale shipping records, geospatial modeling and atmospheric chemical transport models. In 2021, express delivery transportation emitted 23.9-Mt CO_2-equivalent and 166.4-kt atmospheric pollutant equivalents, creating substantial environmental inequality. These emissions and associated health impacts disproportionately affect key transit regions connecting major urban agglomerations, which handled only 12.7% of parcels but accounted for 37.3% of the total emissions, with 75.2% of their air-pollution-related premature deaths from other regions' delivery activities. Express-delivery-related pollution caused 5,100 premature deaths in 2021, yet implementing synergistic mitigation strategies could prevent over 256,000 cumulative premature deaths by 2050, underscoring the need for sustainable logistics that balance urban convenience with environmental externalities.

The rapid urbanization and digital transformation of cities have propelled e-commerce platforms (for example, Amazon, eBay and Taobao) to unprecedented prosperity, fundamentally reshaping logistics systems through explosive growth in express delivery services, especially in emerging economies[1,2]. Global parcel volume exceeded 160 billion parcels in 2022, with China accounting for a remarkable 69% of global deliveries. China's express delivery volume has undergone a 12-fold expansion over the past decade[3], with over 75% of these deliveries occurring in urban areas[4], fundamentally transforming how urban residents consume goods and services. This logistics revolution, although enhancing convenience and accessibility for city dwellers, has introduced notable environmental challenges to sustainability and inter-city environmental justice[2,5]. The transport sector stands as a major contributor to global greenhouse gas (GHG) and air pollutant emissions worldwide[6,7]. Express delivery transportation, as its rapidly expanding subset, is experiencing substantial emission increases that contribute to climate change and threaten air quality and public health across both urban and rural environments.

Despite the expanding environmental footprint of the express delivery industry, current research on its carbon and pollutant emissions remains limited. Existing research has primarily focused on the environmental impact of packaging materials[2,8], with insufficient

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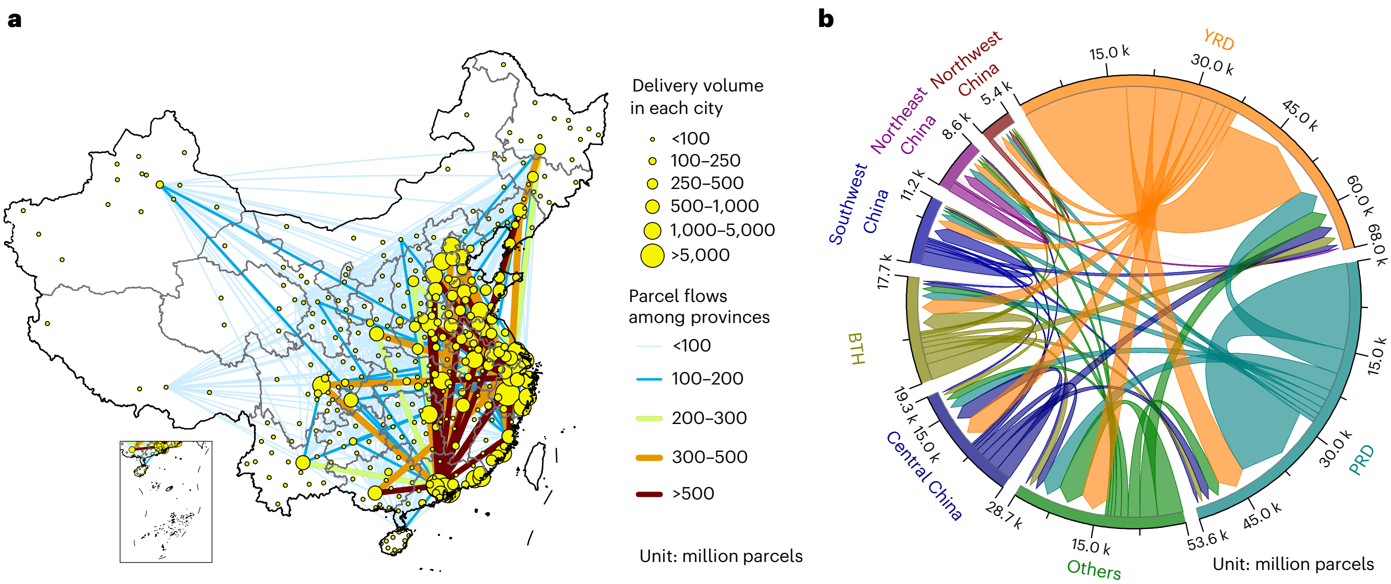

Fig. 1 | Spatial distribution and flow patterns of express delivery in China for 2021. a, Express delivery volume by city and parcel flows at the provincial level. **b**, Parcel flows among major regions, with arrows indicating the delivery directions. The YRD and PRD regions dominate the intra-regional flows (18.0 and 14.9 billion parcels, respectively), whereas the largest inter-regional flow occurs from YRD to PRD (5.0 billion parcels). Detailed regional boundaries are shown in Supplementary Fig. 2. Map in **a** created with ArcGIS Pro (v. 3.1.6, Esri), with administrative boundaries from the Standard Map Service System, Ministry of Natural Resources of China (http://bzdt.ch.mnr.gov.cn/index.html).

attention given to the environmental effects of express delivery transportation. Although limited studies have explored carbon emissions from express delivery transportation[5,9], their analyses fail to capture detailed spatial patterns of emissions along specific transportation routes. In particular, no previous studies have addressed the industry's air pollutant emissions, particularly carbon monoxide (CO), nitrogen oxides (NO_x), volatile organic compounds (VOCs) and particulate matter (PM), as well as their associated health implications for urban populations and transit regions along delivery corridors.

The methodological challenges in quantifying spatially explicit carbon and pollutant emissions of express delivery transportation arise from the industry's inherently complex logistics network. The multitiered delivery system encompasses various stages, including inter-city long-haul transport, intra-city short-distance transport and last-mile delivery[10]. Conventional approaches based on aggregated statistics or origin–destination analysis remain insufficient to characterize these intricate cross-regional transportation patterns[11,12], particularly failing to capture emissions and associated health risks transferred to regions along delivery routes. This methodological gap obscures a critical environmental justice issue, as consumption patterns in major economic centers create environmental burdens for transit regions with potentially fewer economic benefits. However, recent advances in data availability, particularly detailed shipping records (or waybills; an example of waybill records listed in Supplementary Table 1), present new opportunities for addressing these challenges[5]. The integration of such data with advanced geospatial modeling techniques offers promising potential for decoding the complex spatial patterns of emission distribution and their environmental effects.

In this study, we develop a novel integrated approach combining large-scale waybill data (>800,000 real-world records), geospatial modeling and atmospheric chemical transport models to address the growing environmental challenges of the express delivery industry. We characterize the spatial patterns of express delivery transportation and establish a high-resolution inventory of carbon and air pollutant emissions along express routes. Using the GEOS-Chem atmospheric chemistry model and epidemiological models, we assess the industry's atmospheric environmental impacts, associated health effects and resulting environmental inequalities across regions. This multistep methodology enables the tracking of emissions from urban consumption centers to transit regions and the assessment of their cross-regional health implications. We further construct multiple future scenarios projecting the emission trends and their health impacts to 2050. Our findings provide crucial insights into the emission–health nexus of express delivery systems, offering evidence-based pathways toward sustainable logistics that advance multiple UN Sustainable Development Goals.

Results

Spatial patterns and transportation characteristics of express delivery network

In 2021, China's parcel volume reached 108.3 billion parcels, accounting for 68% of global deliveries, establishing China as the first country to exceed 100 billion annual parcels[1]. The per-capita parcel generation reached 77 parcels annually. The delivery network consists of inter-city deliveries (85%), supplemented by intra-city (13%) and international (2%) services. Among inter-city deliveries, only 5.9% involve air transportation. The spatial distribution of the express delivery business exhibits substantial regional heterogeneity across China (Fig. 1a). Three major urban agglomerations—the Yangtze River Delta (YRD), Pearl River Delta (PRD) and Beijing–Tianjin–Hebei (BTH) regions—collectively account for 70.4% of the total delivery volume (Supplementary Fig. 1), with the top ten cities by express delivery volume (Jinhua, Guangzhou, Shenzhen, Shanghai, Hangzhou, Jieyang, Dongguan, Suzhou, Beijing and Quanzhou) all located within these clusters, except for Quanzhou (Supplementary Table 2).

Analysis of waybill data reveals distinct spatial patterns of parcel flows across regions (Fig. 1b; detailed regional boundaries are shown in Supplementary Fig. 2). The largest parcel flows occur between major urban agglomerations, with the YRD and PRD regions emerging as primary sources of outbound deliveries, generating 19.6 and 13.5 billion parcels, respectively. Specifically, the five largest inter-regional flows are from YRD to PRD (5.0 billion), YRD to other regions (4.6 billion), PRD to YRD (4.2 billion), YRD to Central China (3.5 billion), and PRD to other regions (3.2 billion), collectively constituting 34.8% of the

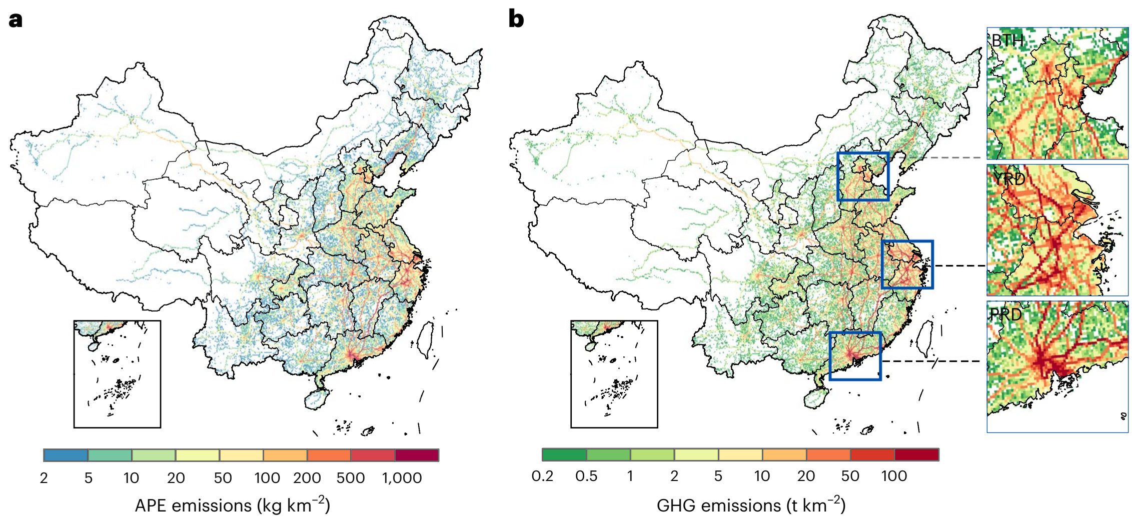

Fig. 2 | Spatial distribution of GHG and APE emissions from express delivery transportation in China. a,**b**, The APE (**a**) and GHG (**b**) emissions from express delivery transportation in China. APE was calculated according to China's environmental protection tax law that takes into account the harm of pollutants and the public cost of dealing with them[14]. Specifically, 1 kg of APE is equivalent to 16.7 kg, 0.95 kg, 0.95 kg and 2.18 kg of CO, NO_x, VOCs and PM, respectively. Maps in **a** and **b** created with ArcGIS (v. 10.8, Esri), with administrative boundaries from the Standard Map Service System, Ministry of Natural Resources of China (http://bzdt.ch.mnr.gov.cn/index.html).

total inter-regional deliveries. Moreover, intra-regional parcel flows account for 44.6% of national deliveries, comparable to inter-regional transportation (55.4%), indicating robust internal connectivity within regions. The PRD and YRD regions particularly exemplify this strong internal circulation, with intra-regional deliveries accounting for 52.5% and 47.9% of their total delivery volumes, respectively. This pattern demonstrates the close economic connections and regional integration within urban agglomerations[13], especially in China's two largest metropolitan clusters.

Inter-city express delivery is operated by heavy-duty logistics trucks connecting various logistics hubs (for example, collection centers and distribution centers), whereas intra-city delivery typically uses light-duty trucks based on our vehicle survey. Using large-scale real-world waybill data and geospatial modeling techniques, we identified transportation routes (Supplementary Fig. 3 and Methods) and calculated an average one-way inter-city distance of 572.4 km. The distribution of distances shows that 16.3%, 47.4%, 13.6% and 22.7% of the total deliveries fall into ranges of <100 km, 100–500 km, 500–1,000 km and >1,000 km, respectively.

For intra-city deliveries, we estimated an average distance of 40 km nationwide using a population-density-based sampling approach across all 333 prefecture-level cities in mainland China (validated with Shanghai's waybill records showing <0.1% deviation; Methods). Cities with higher intra-city delivery volumes tend to have shorter delivery distances, attributed to their well-developed express delivery systems with denser networks of delivery outlets and more extensive routes (Supplementary Fig. 4). For instance, Guangzhou and Shanghai show average intra-city distances of 27.4 km and 27.8 km, respectively, consistent with previous findings (28.9 km for Guangzhou[5]). In particular, over 96% of intra-city delivery routes have average distances below 100 km.

Mapping spatial distribution of express delivery emissions

On the basis of the spatial flow patterns of parcels, transportation distances and differentiated emission factors for various truck types, we quantified emissions from road-based express delivery transportation (Fig. 2 and Methods). GHG emissions, including CO_2, CH_4 and N_2O (expressed as CO_2-equivalent (CO_2e) using 100-year global warming potentials), were estimated at 23.9 Mt (14.8–35.1 Mt, interquartile range from Monte Carlo simulation). Air pollutant emissions, mainly comprising NO_x, VOCs, PM and CO (expressed as atmospheric pollutant equivalents (APE)), reached 166.4 kt (103.2–245.6 kt, interquartile range). APE is a weighted measurement system established by China's environmental protection tax law[14] (Methods). The emission uncertainty was mainly driven by the uncertainty in parcel weight, rated truck payload capacity and truck loading ratio (Supplementary Section 1).

The emissions are equivalent to Croatia's national emissions, a medium-sized European country ranking 118th and 131st globally for GHG and APE, respectively[15]. These emissions constitute 0.31% of China's total APE and 0.18% of the total GHG emissions. Compared with on-road transportation specifically, express delivery contributes 2.07% of APE (4.66% for NO_x and 3.01% for PM) and 2.23% of GHG emissions. Though currently accounting for a small fraction of the total emissions, rapid industry growth suggests potentially substantial environmental impacts in the future[5,16]. In particular, this study presents an estimation of air pollutant emissions from this sector, with specific emissions of NO_x, VOCs, PM and CO estimated at 89.0 kt, 6.6 kt, 3.1 kt and 52.6 kt, respectively.

In 2021, the average transportation-related emissions per parcel were 220.6 g of CO_2e and 1.5 g of APE. Although few studies have estimated GHG emissions from express delivery transportation, reporting values of 6.5 Mt (ref. 10) in 2018 and 13.7 Mt (ref. 5) in 2019 (averaging 270 g and 100 g per parcel, respectively), our estimation falls between these values. Inter-city transportation dominates both GHG and APE emissions, accounting for 98.5% and 98.2%, respectively (Supplementary Table 3), attributed to longer transportation distances and higher emission factors compared with intra-city delivery (for example, NO_x and PM emission factors under China V emission standards are 2.1 and 3.0 times higher). Despite urban areas dominating parcel generation[4], non-urban regions bore 78.3% of GHG emissions and 78.0% of APE emissions from express delivery transportation, underscoring cross-regional environmental inequity. Temporally, emissions peak in November (10.3% APE, 10.5% GHG) and reach their lowest in February (4.2% APE, 4.3% GHG; Supplementary Fig. 5), reflecting the influences of Double Eleven e-shopping festival (China's largest annual online shopping event held on November 11) and Spring Festival, respectively[17].

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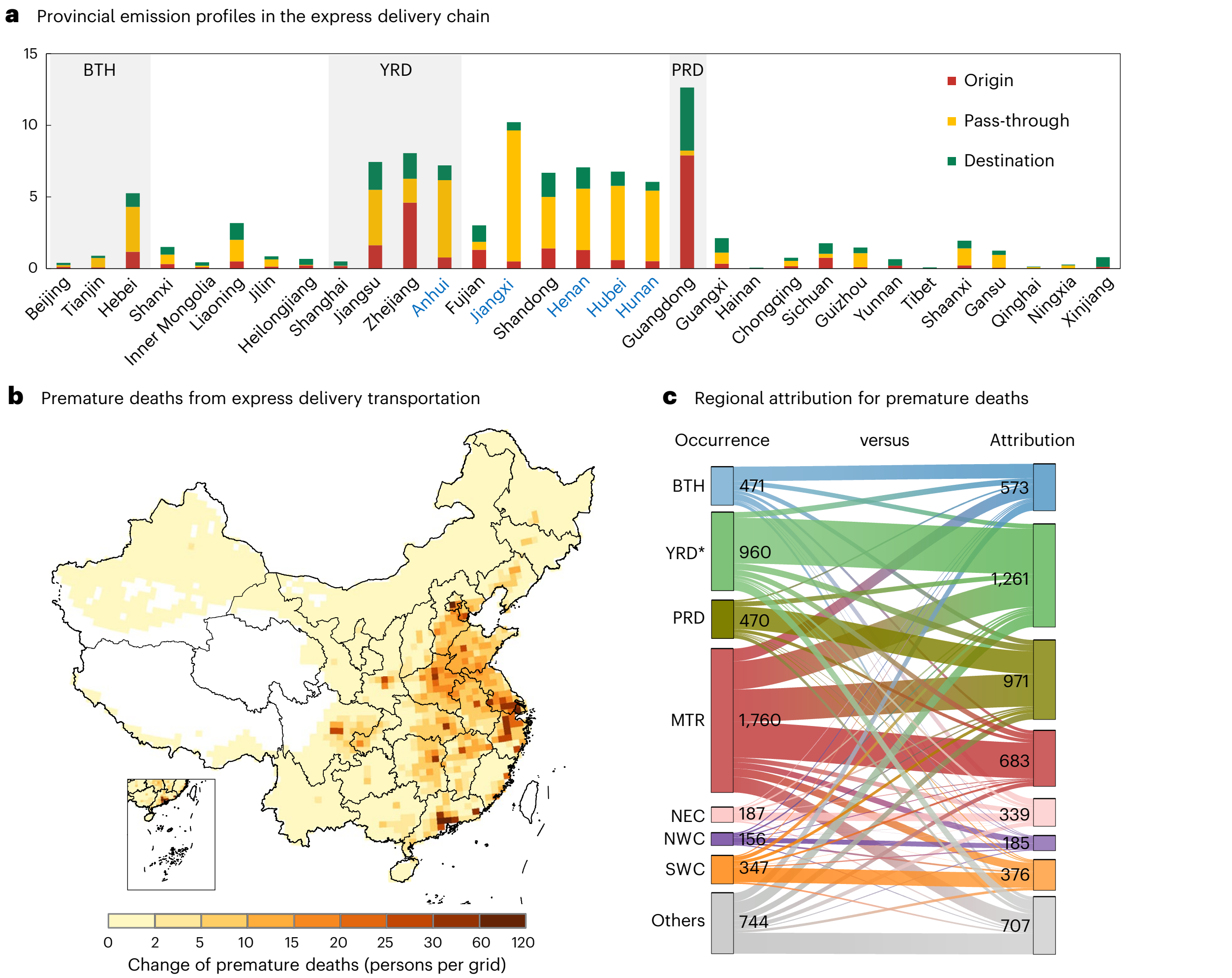

Fig. 3 | Emission and health burden inequalities in express delivery sector. **a**, Provincial emission proportions (%) to national inter-city express delivery transportation emissions as origin, pass-through and destination regions (provinces labeled in blue represent major transit regions for express delivery). **b**, Total premature deaths attributable to $PM_{2.5}$ and NO_2 from express delivery emissions. **c**, Regional allocation between mortality occurrence and attributable regions. YRD*, MTR, NEC, NWC and SWC represent Yangtze River Delta excluding Anhui province, major transit regions, Northeast China, Northwest China and Southwest China, respectively (Supplementary Fig. 2). Map in **b** created with ArcGIS (v. 10.8, Esri), with administrative boundaries from the Standard Map Service System, Ministry of Natural Resources of China (http://bzdt.ch.mnr.gov.cn/index.html).

The GHG and air pollution emissions from express delivery exhibit marked spatial heterogeneity (Fig. 2). Emissions are predominantly concentrated in Eastern China, characterized by developed express delivery networks. Although the three major urban agglomerations (YRD, PRD and BTH) account for 70% of the total delivery volume, they contribute only 45.7% and 44.7% of the total GHG and APE, respectively (detailed provincial emissions are shown in Supplementary Fig. 6). This spatial mismatch between delivery volume and emissions reflects the nature of inter-regional transportation, where emissions occur along delivery routes connecting major economic centers.

Given the similar spatial patterns between GHG and air pollutant emissions, we take GHG emissions as an example. Guangdong, Zhejiang and Jiangxi provinces exhibit the highest contributions, accounting for 14.0%, 9.8% and 8.2% of the total national express delivery emissions, respectively. In particular, the high emissions in pass-through provinces such as Jiangxi highlight the considerable environmental impact of cross-regional transportation (see the 'Cross-regional environmental and health inequalities by express delivery emissions' section). Further analysis reveals that transportation distances substantially influence the emission patterns, with routes between 1,000 km and 2,000 km contributing the largest share (47.1%), followed by 100 km and 500 km (19.7%) and 500 km and 1,000 km (17.6%).

Cross-regional environmental and health inequalities by express delivery emissions

The spatial distribution of express delivery transportation emissions varies considerably by province, creating potential environmental inequalities. Given that inter-city transportation accounts for over 98% of the total APE emissions, we quantified the contribution of each province to national inter-city delivery emissions based on their roles as origin, pass-through or destination regions (Fig. 3a).

As the major freight corridors connecting the three urban agglomerations (BTH, YRD and PRD), the pass-through regions (Supplementary Fig. 2), including Central China (Henan, Hubei and Hunan provinces) and Jiangxi and Anhui provinces, collectively handle only 12.7% of the national delivery volume, yet contribute 37.3% of the total emissions. In particular, pass-through emissions account for 90.0% of Jiangxi's total express delivery emissions, the highest among all provinces, followed by Hunan (81.3%) and Hubei (76.6%; Fig. 3a). The GHG footprint of parcels originating from the PRD region (Extended Data Fig. 1) also confirms this pattern, with substantial impacts concentrated in Jiangxi and Central China. By contrast, emissions from parcels originating from or destined for the PRD region account for 97.4% of its total regional express delivery emissions.

To further validate these spatial inequalities, we quantified the spatial variations in $PM_{2.5}$ and NO_2 concentrations attributable to China's express delivery system using the GEOS-Chem model. In 2021, express delivery emissions contributed 81.8 ng m^{-3} and 142.7 ng m^{-3} to population-weighted $PM_{2.5}$ and NO_2 concentrations nationally, respectively, with disproportionate impacts in pass-through provinces (Supplementary Fig. 7). Additionally, we implemented high-resolution WRF-Chem simulations (9 km) covering Eastern China to validate the consistency of our conclusions across different model resolutions (Methods). The analysis demonstrated that despite GEOS-Chem's coarser resolution, it remains appropriate for analyzing cross-regional impacts, with both models confirming the robustness of our findings regarding the disproportionate pollution burden on major transit regions (Supplementary Table 4, Supplementary Fig. 8 and Supplementary Section 2).

Premature deaths associated with both long-term $PM_{2.5}$ and NO_2 exposures from express delivery operations were assessed using epidemiological models (Methods). Express-delivery-related air pollution resulted in 5,095 premature deaths (95% confidence interval: 4,242–5,975) across China during 2021, with $PM_{2.5}$ and NO_2 contributing 56.7% and 43.3% of mortality, respectively (Fig. 3b). Express-delivery-related mortality corresponds to approximately 0.20% of the total $PM_{2.5}$-attributed deaths and 1.05% of NO_2-attributed deaths nationally. Although these proportions appear modest in the national context, they reveal a substantial and previously unquantified environmental health burden from a single, rapidly expanding industry sector, comparable with mercury-related mortality from all sectors in China (~5,600 deaths)[18].

The highest mortality burden was observed in the major transit region (1,760 deaths; detailed provincial-level mortality is shown in Supplementary Fig. 9). However, the regional attribution of air-pollution-related mortality differs markedly from its geographical distribution (Fig. 3c). Express delivery activities from origin and destination provinces are attributed to premature deaths in pass-through provinces. In Central China, only 23.8% of premature deaths are attributable to its own express delivery activities, whereas 47.6% are associated with express delivery activities from the three major urban agglomerations (YRD, PRD and BTH). Jiangxi province experiences an even more pronounced disparity, with 94.5% of mortality attributed to other regions' delivery activities and 76.0% specifically linked to the three urban agglomerations. By contrast, the PRD and YRD regions show high local attribution of air-pollution-related mortality (59.2% and 56.3%, respectively). Northeast and Southwest China exhibit similar patterns of high local attribution (52.9% and 51.8%, respectively), reflecting their limited express delivery interactions with other regions due to less developed economies. Detailed provincial allocation of air pollution-related premature mortality attribution is presented in Extended Data Fig. 2.

Future projections of environmental impacts and mitigation pathways

We projected express delivery volume through 2050 using a logistic growth model[5] (R^2 = 0.99; Supplementary Fig. 10), which characterizes the typical development pattern in service sectors in which rapid expansion driven by technological adoption and market penetration is followed by eventual saturation as the market matures. The projected GHG and air pollutant emissions were analyzed under six scenarios: business as usual (BAU), electric vehicle substitution (ES), fuel and powertrain upgrade (FU), increased rail transport share (RT), express route optimization (RO) and synergistic mitigation (SM; Table 1 and Methods).

Express delivery volume is projected to reach 169.5 billion parcels by 2030, followed by modest growth to 173.1 billion by 2050 (Supplementary Fig. 10). Under the BAU scenario, GHG and air pollutant emissions would increase by 59.8% by 2050, with 56.6% of this growth occurring during 2021–2030 (Fig. 4a,b). For GHG emissions, although FU, RT and RO scenarios show declining trends after 2030, their 2050 emission levels remain above current levels (RT, 33.5 Mt; FU and RO, 26.7 Mt each). The SM scenario demonstrates the highest effectiveness with a reduction rate of 0.6 Mt per year, followed by the ES scenario, which peaks at 31.2 Mt in 2027 before declining markedly. For APE emissions, only RT and RO scenarios show higher emissions than current levels by 2050 (227.5 kt and 181.4 kt, respectively). The FU scenario exhibits distinctly different trends from GHG emissions, achieving a 92.7% reduction in air pollutants during 2021–2050, primarily driven by China's increasingly stringent vehicle emission standards. Detailed projections of individual pollutant emissions are provided in Supplementary Fig. 11.

Table 1 | Scenarios for future projection of express delivery emissions in China

Scenario	Description
BAU	Express delivery volume grows according to logistic growth model projections, with other parameters maintained at 2021 levels
ES	Gradual replacement of conventional vehicles with electric vehicles, reaching 30% by 2035 and 65% by 2050[a] (ref. 49)
FU	Full implementation of China VI emission standards and 15% reduction in fuel consumption by 2035; complete adoption of more strict emission standards and achieving 30% fuel consumption reduction by 2050 (ref. 50)
RT	Rail transport substitution for deliveries over 500 km, with rail freight volume share increasing to 25% by 2035 (ref. 51) and 35% by 2050
RO	Average transportation distance reduction of 15% by 2035 and 30% by 2050[b]
SM	Integration of ES, FU, RT and RO scenarios

[a]The rates (30% by 2035 and 65% by 2050) approximate the average values across multiple scenarios for future freight vehicle electrification replacement rates[49]. [b]Route optimization projections are derived from data of three major Chinese courier companies[5].

Projections of air-pollution-related premature mortality (Methods) reveal substantial differences among scenarios. Although pollutant emissions stabilize after 2030 in the BAU scenario, accelerating population aging in China[19] leads to a 167% increase in annual premature deaths by 2050, reaching 13,600 deaths per year (nearly 1% of current annual air-pollution-related mortality in China; Fig. 4c). Among the mitigation scenarios (excluding the SM scenario), the FU scenario proves the most effective in mortality reduction, achieving 2021-level mortality rates by 2027, whereas the ES scenario reaches this benchmark by 2049. The cumulative mortality during 2021–2050 ranges from 56,800 under the SM scenario to 313,400 under the BAU scenario (Fig. 4d), indicating that the implementation of ES, FU or SM scenarios would reduce cumulative premature deaths by over 256,000 relative to BAU.

Discussion

By integrating large-scale waybill data, geospatial modeling and atmospheric chemical transport models, this study reveals the substantial yet previously overlooked environmental externality of urban convenience in the digital economy era. Our finding that this single industry generated emissions of 23.9 Mt of CO_2e and 166.4 kt of APE in 2021, approximating the national emissions of a medium-sized country (ranking 118th and 131st among all countries globally)[15], highlights an emerging challenge for urban sustainability and global climate governance. This integrated framework enables urban planners to trace how city-based consumption creates environmental burdens beyond administrative boundaries.

Our analysis uncovers substantial cross-regional environmental inequities in the express delivery system. The disproportionate burden on major transit regions, which bear 37.3% of emissions while handling only 12.7% of parcels, exemplifies this spatial inequality. This mismatch between economic benefits and environmental burdens manifests

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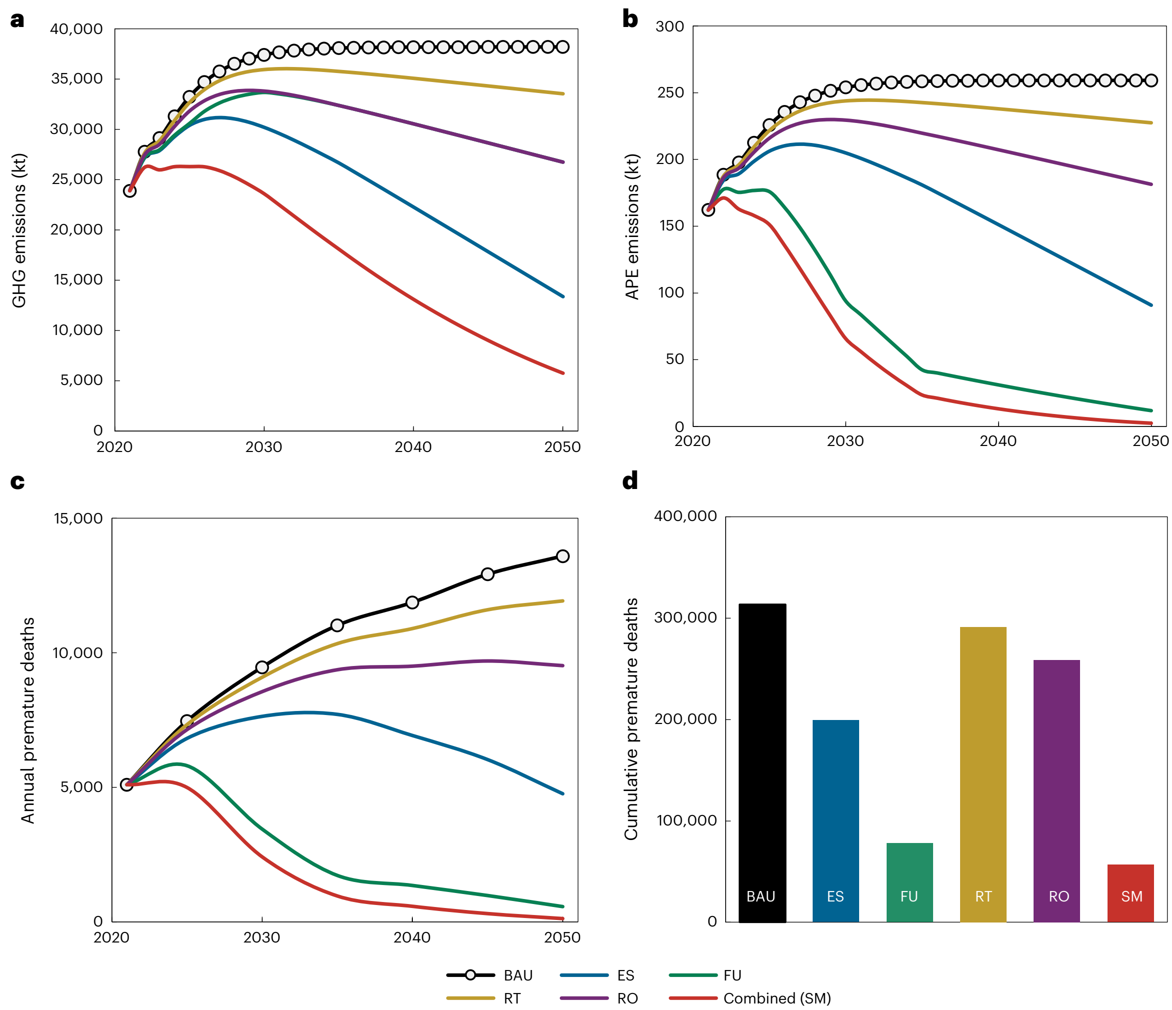

Fig. 4 | Projections of express delivery transportation emissions and health impacts through 2050 under various scenarios. a, GHG emissions. **b**, APE emissions. **c**, Annual air-pollution-related premature deaths attributable to express delivery emissions. **d**, Cumulative air-pollution-related premature deaths by 2050 under different mitigation scenarios.

more severely in health impacts, with 75.2% of air-pollution-related mortality in these transit regions attributable to other regions' delivery activities. These findings indicate that the digital economy creates novel forms of environmental injustice, requiring innovative governance approaches that address cross-regional externalities.

Although express delivery currently represents a modest fraction of China's total emissions, its importance stems from its accelerating growth trajectory against the backdrop of declining emissions in other transportation sectors[20], making it a notable exception within China's progressing transportation decarbonization. These characteristics identify express delivery as a strategic priority for early environmental intervention and emissions control. This insight has broad international applications, as the global parcel market is projected to reach US$648.8 billion by 2030 (ref. 16), whereas emerging markets, particularly India, are expected to maintain growth rates exceeding 10% (ref. 21). This rapid global expansion adds to the urgency of transforming logistics systems internationally.

The health inequality would probably intensify under current practices, with express-delivery-related air pollution projected to cause 13,600 annual deaths by 2050. However, strategic mitigation measures, particularly electric vehicle substitution and upgrades to fuel standards, could prevent over 256,000 cumulative premature deaths by 2050. China's substantial new energy vehicle market penetration (25.6% versus global average of 14% in 2022 (ref. 22)) and the implementation of stringent emission standards[23] demonstrate the feasibility of rapid technological transformation. Concerns about emissions displacement to power plants are addressed by China's renewable energy expansion, which currently accounts for 34% of electricity generation[24] and is projected to meet all new electricity demand with clean energy by 2030 (ref. 25). This ensures that vehicle electrification delivers genuine environmental benefits rather than merely relocating emissions.

Although this study quantifies the environmental impacts and spatial inequalities of China's express delivery sector, understanding the complete environmental implications requires investigating how e-commerce interacts with traditional retail patterns[26]. China's urban shopping commonly relies on public transportation and non-motorized modes, suggesting potentially different environmental tradeoffs between online and offline retail channels than in car-dependent regions[27]. Future research should integrate consumer behavior data with transportation models to evaluate how express delivery complements or substitutes traditional shopping trips across diverse urban contexts, providing a more comprehensive understanding of net environmental effects as digital retail transforms consumption patterns worldwide.

Despite these valuable insights, methodological challenges constrained certain aspects of our analysis. Although we conducted uncertainty analyses at each stage of our modeling chain to confirm the robustness of our findings, full uncertainty propagation analysis would require hundreds of air quality simulations, presenting substantial computational challenges[28]. Additionally, although this study focuses on road-based transportation, our estimation indicates that air transport in express delivery contributes an additional 3.02 Mt of CO_2e (Supplementary Section 3). Given the high uncertainties in parcel weights and flight routing data[29], we excluded air freight transport emissions from our main cross-regional analysis. Future advances in air transport tracking and data transparency could enable more comprehensive environmental assessments that integrate all transport modes within the express delivery sector.

Our findings ultimately demonstrate that achieving sustainable cities requires looking beyond urban boundaries to address the full environmental implications of urban convenience. By integrating considerations of environmental justice into urban logistics planning, cities can develop more equitable and sustainable systems that advance multiple dimensions of urban sustainability and protect vulnerable populations in surrounding regions. This integrated assessment approach provides policymakers with a scientific framework to balance economic benefits with environmental sustainability, particularly valuable for metropolitan regions expanding their express delivery infrastructure worldwide.

Methods

Scope of express delivery

Express delivery refers to a delivery activity that is finished promptly within a specified time frame, including online shopping delivery service and customer-to-customer and business-to-business deliveries[5]. The logistics and transportation for both large freight and industrial or business freight are not considered express delivery. Conventional postal mail services are also not included in this study.

Identification of express delivery transportation routes

We collected 824,508 express delivery waybills from 2021 (see Supplementary Table 1 for an example), which documented the specific locations along delivery routes. To validate the representativeness of our sample for nationwide analysis, we compared with data from Kuaidi100 (China's leading express delivery tracking platform) based on their 12.97 million delivery records, showing strong agreement in inter-city delivery flow patterns ($R^2 = 0.90$; Supplementary Fig. 12 and Supplementary Section 4). The waybill records were transformed into city-to-city transportation records. Origin–destination matrix estimation serves as a crucial method for analyzing population/freight movement[30]. Using the network analyst model in ArcGIS v. 10.8 with the 2021 road network data from OpenStreetMap (https://www.openstreetmap.org/), we mapped the transportation routes and calculated the parcel volumes and actual distances for each route segment. We then scaled up our sample data to match China's total express delivery volume and maintained the spatial distribution characteristics of parcel flows.

To validate our route identification accuracy, we randomly selected 50 routes and compared them with actual routes from Baidu Maps (a widely used navigation platform in China). The comparison demonstrated high precision (Supplementary Fig. 13; $R^2 = 0.99$, normalized mean bias (NMB) = 2.8%). The high R^2 value reflects the consistent distance calculations on fixed road networks, whereas the small NMB indicates minor systematic differences in route selection algorithms.

Construction of GHG and air pollutant emission inventory for express delivery transportation

Total emissions of GHGs (including CO_2, CH_4 and N_2O) and major air pollutants (PM, CO, NO_x and VOCs) from express delivery transportation comprise both inter-city and intra-city components. Inter-city transportation involves delivery portions within the origin and destination cities, as well as express transport crossing different city administrative regions. The total emissions calculation is expressed as

$$E_{\text{total}} = \text{EF}_{\text{inter,cross}} \times \text{Length}_{\text{inter,cross}} + \text{EF}_{\text{inter,city}} \times \text{Length}_{\text{inter,city}} + \text{EF}_{\text{intra}} \times \text{Length}_{\text{intra}}, \quad (1)$$

where E_{total} represents the total emissions of each pollutant or GHG. Emission factors for the cross-regional transportation portion between cities ($\text{EF}_{\text{inter,cross}}$) are based on heavy-duty truck emission factors, whereas emission factors for both within-city portions of inter-city deliveries ($\text{EF}_{\text{inter,city}}$) and intra-city deliveries (EF_{intra}) use light-duty truck emission factors. Emission factors were obtained from the national handbook of vehicle emissions[23,31] and adjusted for speed and environmental factors[23,32,33] (Supplementary Table 5). Last-mile delivery emissions were not included in this study as these deliveries are typically completed by couriers/customers on foot or using electric motorcycles[9].

For speed correction, we collected extensive vehicle trajectory data from AutoNavi (Amap), China's leading ride-hailing platform (https://dache.amap.com/amap_mini#/). This dataset comprised 236 million vehicle trajectory records across six representative days (two weekdays, two weekend days and two days of holiday), with each vehicle transmitting data at 3-s intervals. From this high-resolution dataset, we derived gridded daily average speeds that capture traffic conditions, including congestion patterns (Supplementary Fig. 14). The speed–EF relationships of different pollutants were based on correction curves established by previous studies[32,33]. Meteorological data were obtained from the ECMWF Reanalysis v. 5 (https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5), and elevation data were derived from the Shuttle Radar Topography Mission high-resolution digital elevation model[34].

GHG emissions were expressed as CO_2e, using global warming potentials of 1, 34 and 298 for CO_2, CH_4 and N_2O, respectively, over a 100-year time horizon[35]. Air pollutants were expressed as APE based on China's environmental protection tax law, which accounts for the relative harm and public cost of managing different pollutants[14]. Specifically, 1 kg of APE is equivalent to 16.7 kg of CO, 0.95 kg of NO_x, 0.95 kg of VOCs and 2.18 kg of PM.

$\text{Length}_{\text{inter,cross}}$, $\text{Length}_{\text{inter,city}}$ and $\text{Length}_{\text{intra}}$ represent the total transportation distances for the cross-regional portion between cities, within-city portions of inter-city deliveries and intra-city deliveries, respectively:

$$\text{Length}_{\text{inter,cross},g} = \sum_{j=1}^{r} l_{j,g} \times n_{j,g}, \quad (2)$$

where $\text{Length}_{\text{inter,cross},g}$ represents the total distance traveled by all delivery vehicles in grid cell g (with a resolution of 5 arcmin × 5 arcmin), calculated by summing the product of the actual road length (l) and number of delivery vehicles (n) for each road segment j within the grid. The number of delivery vehicles on road j was determined by

$$n_j = C \times P_j \times \frac{w}{W \times \text{Loading}}, \quad (3)$$

where P_j represents the number of parcels on road j, w is the average parcel weight (1.6 ± 0.9 kg) based on literature review[5,36,37], W is the rated truck payload capacity (10.5 ± 1.5 t, derived from surveying 69 inter-city delivery trucks on https://www.autohome.com.cn/), and loading represents the truck loading ratio (0.56, obtained from China's highway toll system)[38]. C is the scaling factor derived from the ratio of national inter-city delivery volume to our sample volume.

The total vehicle distance for intra-city delivery ($\text{Length}_{\text{intra}}$) is calculated as

$$\text{Length}_{\text{intra}} = L_c \times P_c \times \frac{w}{W_l \times \text{Loading}}, \quad (4)$$

where P_c represents the total number of intra-city parcels in city c and W_l is the average rated truck payload capacity of intra-city delivery vehicles (2.0 ± 0.7 t, based on a survey of 34 common urban delivery vehicles). L_c denotes the average distance within cities.

Given the difficulty in obtaining precise address data for intra-city deliveries and the strong correlation between population density and parcel volume[39], we randomly generated 1,000 delivery origins/destinations in each of the 333 prefecture-level cities based on population density distribution and simulated delivery routes between these points. Deliveries with distances less than 2 km were excluded due to their short distances. This method was validated using Shanghai (one of China's largest cities) as a case study, where our estimated average delivery distance (27.8 km) showed high consistency with the actual average distance (27.4 km) calculated from over 1,200 intra-city waybill records, with a deviation of less than 0.1%. For $\text{Length}_{\text{inter,city}}$, we applied a similar calculation method as used for $\text{Length}_{\text{intra}}$. We distinguished between origin and destination cities and determined the transportation distance within each origin and destination city for inter-city parcels.

Seasonal variations in emissions were analyzed considering changes in delivery volume and meteorological conditions. We conducted a comprehensive uncertainty analysis for emission estimation using Monte Carlo simulation implemented in MATLAB 2021b (Supplementary Section 1). Additionally, we calculated the proportion of express delivery transportation emissions in urban areas versus other regions by overlaying the spatially explicit emissions inventory with urban boundaries. Urban boundary data were obtained from the GUB 2018 dataset (https://data-starcloud.pcl.ac.cn/zh/resource/14)[40]. Although express delivery in China includes both road and air modes, our primary analysis focuses on road transportation. Despite air transport representing only 5.9% of express deliveries, we estimated its GHG emissions contribution (Supplementary Section 3), but excluded it from detailed analysis due to huge uncertainties in flight routes and parcel weights[29].

Air quality simulation and health impact assessment

The simulation of $PM_{2.5}$, NO_2 and associated species was conducted using the GEOS-Chem global chemical transport model (v. 13.4.0), which incorporates fully coupled ozone–NO_x–VOC–aerosol chemistry[41]. We used a nested-grid simulation with a horizontal resolution of 0.5° × 0.625° (latitude × longitude) covering East Asia (68–140 °E, 10–55 °N), with 47 vertical layers. The model was driven by assimilated meteorological data from NASA MERRA-2 for 2021, with a six-month spin-up period for each simulation.

To quantify the contribution of express delivery to $PM_{2.5}$ and NO_2 pollution, we conducted simulations with and without express delivery emissions. Anthropogenic emissions in China for 2021, including SO_2, NO_x, CO, CO_2, NMVOC, BC, OC, NH_3, $PM_{2.5}$ and PM_{10}, were obtained from the Air Benefit and Cost and Attainment Assessment System—Emission Inventory (ABaCAS-EI v. 2.0)[42]. The spatiotemporal changes in $PM_{2.5}$ and NO_2 concentrations attributable to express delivery emissions were determined by comparing these two scenarios.

Model performance was evaluated against ground-based observational data from China's national monitoring network, showing strong agreement with observations ($PM_{2.5}$: R = 0.86, NMB = −13.2%, Supplementary Fig. 15; NO_2: R = 0.87, NMB = −13.6%, Supplementary Fig. 16). The inclusion of express delivery emissions improved the model performance, particularly in high-emission regions. Detailed model performance after incorporating express delivery emissions is provided in Supplementary Section 5 and Supplementary Fig. 17. Additionally, we complemented GEOS-Chem modeling with high-resolution WRF-Chem (v. 4.6.0) simulations (9 km) for representative months (January, April, July and October 2021) over Eastern China, encompassing major urban agglomerations and transit corridors to verify the impact of different resolutions on our results (Supplementary Section 2).

We assessed premature deaths associated with both long-term $PM_{2.5}$ and NO_2 exposures from express delivery operations using established epidemiological models. For $PM_{2.5}$-related premature mortality, we applied the Global Exposure Mortality Model[19,43]. Health impacts for $PM_{2.5}$ were assessed for four diseases: chronic obstructive pulmonary disease, lung cancer, ischemic heart disease and stroke. The premature mortality for each disease was calculated as

$$M_{\text{PM}_{i,g}} = \text{Pop}_g \times \text{Rate}_a \times \text{Mortbase}_{a,i} \times \left(1 - \frac{1}{\text{RR}_{a,i,g}}\right), \quad (5)$$

where Pop_g represents the total population in each grid cell (g; 0.625° × 0.5°); Rate_a represents the proportion of population in each age group a; $\text{Mortbase}_{a,i}$ indicates the baseline mortality rate for each disease by age group (https://vizhub.healthdata.org/gbd-results/); and RR represents the relative risk evaluated by Global Exposure Mortality Model, with age-specific values for ischemic heart disease and stroke.

For NO_2 exposure, a transport-related pollutant epidemiologically linked to excess mortality[44], we used a different approach. The total attributable deaths were calculated as[45]

$$M_{\text{NO}_2} = \text{Pop}_g \times B_a \times \left(1 - \frac{1}{\text{RR}_g}\right), \quad (6)$$

$$\text{RR}_g = e^{\beta(C_g - \text{TMREL})}, \quad (7)$$

where B_a represents the non-accidental mortality rate for different age groups a, calculated from the China Health Statistics Yearbook 2022 (ref. 46). RR represents the relative risk value. β is the pooled effect estimate of long-term NO_2 exposure on total non-accidental deaths (0.002), derived from a comprehensive meta-analysis of 41 cohort studies[44]. C_g indicates the NO_2 concentration, whereas TMREL represents the annual average theoretical minimum referent exposure level for NO_2 (10 μg m^{-3}) according to the 2021 Air Quality Guidelines. Gridded population data were obtained through the calibration of LandScan data (https://landscan.ornl.gov/) and provincial official statistics. Uncertainties (95% confidence interval) in mortality estimates were calculated by incorporating the uncertainties in dose–response relationships.

Future projections of emissions and environmental impacts

Express delivery volume through 2050 was projected using a logistic growth model based on China's delivery volume data from 2010 to 2021, with the model showing excellent fit (R^2 = 0.99; Supplementary Fig. 10). In the emission projections, we maintained several key parameters constant throughout the study period: parcel weights, vehicle loading ratio, rated truck payload capacity and spatial flow patterns of express delivery. Detailed scenario parameters are listed in Table 1.

We developed six scenarios to evaluate future trends: BAU, ES, FU, RS, RO and SM. Our scenario development excluded waterway transport shifts based on empirical analysis of our comprehensive waybill dataset, which revealed no instances of water transport utilization in the express delivery network. This absence reflects the incompatibility between express delivery timeframes (24–72 h) and the slower speeds of waterway shipping, which is better suited for large container freight with flexible delivery schedules[47].

For each scenario, we projected GHG and air pollutant emissions for 2021–2050, and estimated their impacts on $PM_{2.5}$ and NO_2 concentrations assuming constant pollutant sensitivity to unit APE emissions. This assumption was validated through an additional GEOS-Chem simulation with 1.5-fold express delivery emissions, which showed that $PM_{2.5}$ sensitivity to unit APE emissions remained nearly constant (0.53 μg m^{-3} per kg at current emissions versus 0.58 μg m^{-3} per kg at 1.5-fold emissions). The resulting health impacts were evaluated using both Global Exposure Mortality Model for $PM_{2.5}$ and established NO_2-mortality risk functions for NO_2, incorporating China's projected demographic changes through 2050 (ref. 19). The baseline mortality rates were maintained at current levels. The proportion of population aged over 60 years is projected to increase from 19.0% in 2021 to 30.7% in 2050 (Supplementary Table 6). Age-specific relative risks were applied to better reflect the varying susceptibility across age groups.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The gridded road-based express delivery emissions inventory data we developed are openly available via Zenodo at https://doi.org/10.5281/zenodo.15726553 (ref. 48). Road network data are from OpenStreetMap (https://www.openstreetmap.org/); meteorological data are from ECMWF Reanalysis v. 5 (https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5) and NASA MERRA-2 (https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/); population data are from LandScan (https://landscan.ornl.gov/); anthropogenic emissions are from ABaCAS-EI v. 2.0 (ref. 42); and air quality monitoring data are from the China National Environmental Monitoring Centre (https://quotsoft.net/air/).

Code availability

The analysis was conducted using ArcGIS v. 10.8, Python 3.11 and MATLAB R2021b. Route identification, emission calculations and spatial allocation were performed using existing ArcGIS Network Analyst and Spatial Analysis tools. Custom code for the gridded transportation distance calculations and Monte Carlo uncertainty analysis we developed are deposited via Zenodo at https://doi.org/10.5281/zenodo.15726553 (ref. 48). Air quality simulations used GEOS-Chem v. 13.4.0 and WRF-Chem v. 4.6.0, with source codes freely available at https://geoschem.github.io/ and https://github.com/wrf-model/WRF/releases, respectively.

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Author contributions

B.L., H. Liao and D.J.J. designed the research. B.L., H. Liao, K.L. and J.L. performed the research. C.G., Y.L., L.C., Y.Y., X.J., Y.Z. and T.W. analyzed the data. B.L., H. Liao, K.L., H. Liu and D.J.J. wrote the paper. J.J. and R.D. reviewed the paper.

Competing interests

The authors declare no competing interests.

Additional information

Extended data is available for this paper at https://doi.org/10.1038/s44284-025-00300-3.

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s44284-025-00300-3.

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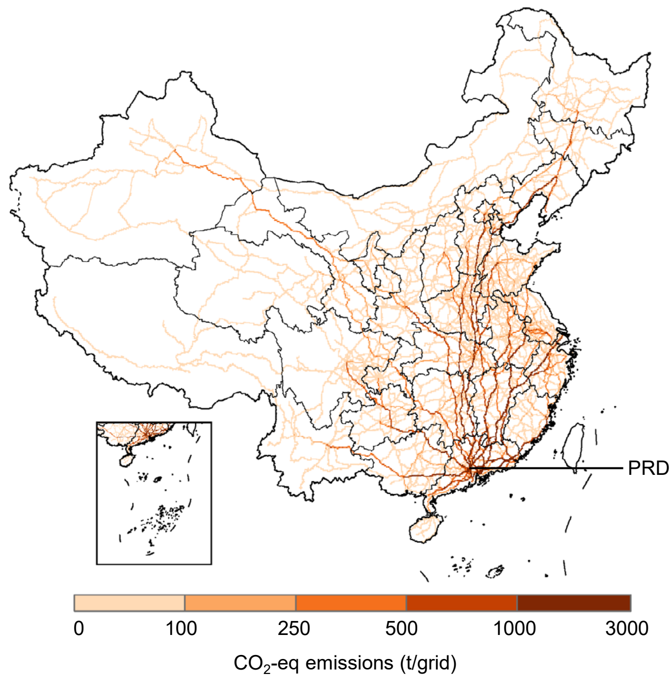
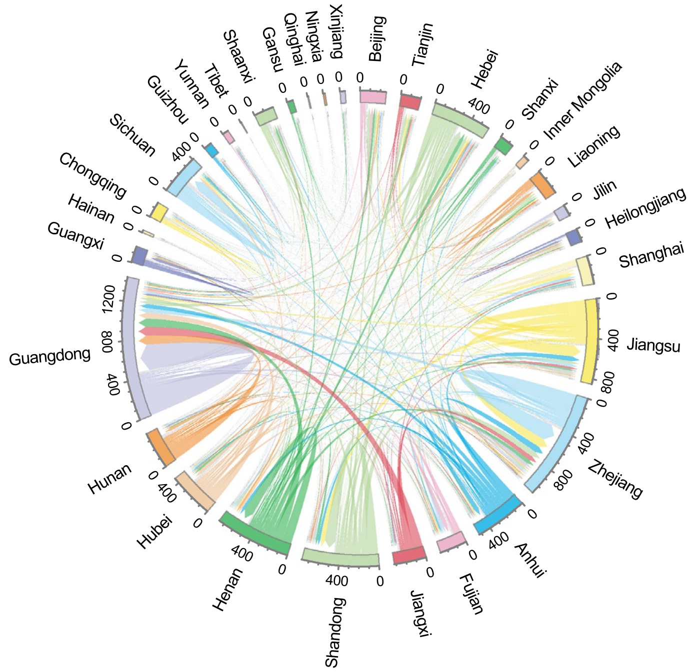


Extended Data Fig. 1 | GHG footprint from parcels originating in the PRD region. Map created using ArcGIS (v. 10.8, Esri), with administrative boundaries from the Standard Map Service System, Ministry of Natural Resources of China (http://bzdt.ch.mnr.gov.cn/index.html).

 https://doi.org/10.1038/s44284-025-00300-3



Extended Data Fig. 2 | Provincial allocation of air pollution-related premature mortality attribution (deaths). Arrows flow from provinces where deaths occur to those responsible for the emissions causing these health impacts. The attribution allocation reveals substantial cross-provincial impacts, as exemplified by Jiangxi, where 94.5% of premature deaths are associated with other regions' express delivery activities.

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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	Waybill data were collected from a public logistics tracking platform (https://www.51tracking.com/) through their API interface in 2021.
Data analysis	Data analysis was performed using: ArcGIS v10.8 and ArcGIS Pro v3.1.6 (Esri) for geospatial mapping and route analysis; Python 3.11 with packages including Pandas, Pyproj and GeoPandas for data processing; GEOS-Chem v13.4.0 and WRF-Chem v4.6.0 for atmospheric chemical transport modeling; MATLAB R2021b for Monte Carlo simulations and uncertainty assessment; Route identification, emission calculations, and spatial allocation were performed using existing ArcGIS Network Analyst and Spatial Analysis tools. Custom Python scripts were developed for gridded transportation distance calculations within each grid cell, and MATLAB scripts for Monte Carlo uncertainty analysis. All custom Python and MATLAB scripts are deposited in Zenodo: : https://doi.org/10.5281/zenodo.15726553 and cited in the reference list.

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- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our policy

The gridded road-based express delivery emissions inventory data we developed are openly available at Zenodo: https://doi.org/10.5281/zenodo.15726553. Road network data are from OpenStreetMap (https://www.openstreetmap.org/); meteorological data are from ECMWF Reanalysis v5 (https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5) and NASA MERRA-2 (https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/); population data are from Landscan (https://landscan.ornl.gov/); anthropogenic emissions are from ABaCAS-EI v2.0; and air quality monitoring data are from China National Environmental Monitoring Centre (https://quotsoft.net/air/).

Research involving human participants, their data, or biological material

Policy information about studies with human participants or human data. See also policy information about sex, gender (identity/presentation), and sexual orientation and race, ethnicity and racism.

Reporting on sex and gender	Not applicable.
Reporting on race, ethnicity, or other socially relevant groupings	Not applicable.
Population characteristics	Not applicable.
Recruitment	Not applicable.
Ethics oversight	Not applicable.

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

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Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	This study quantifies GHG and air pollutant emissions from China's road-based express delivery transportation and their health impacts using waybill data, geospatial modeling, and atmospheric chemical transport models to examine cross-regional emissions distribution and associated health inequalities.
Research sample	The study collected 824,508 express delivery waybills from 2021, processed to 688,415 waybills after quality control. Sample representativeness was validated against Kuaidi100 platform data (12.97 million deliveries) showing strong correlation (R^2=0.90) for inter-city parcel flow patterns.
Sampling strategy	Random sampling of waybills was implemented for each city to align with official municipal delivery volume proportions, addressing potential bias from single-company data. This approach demonstrated high representativeness when validated against Kuaidi100 platform data (12.97 million deliveries, R^2=0.90).
Data collection	The waybill data were collected from a public logistics tracking platform (https://www.51tracking.com/) through their API interface in 2021, and underwent comprehensive anonymization to remove personally identifiable information before analysis. Records were transformed into city-to-city transportation data with origin-transit-destination segments for route analysis. Additional data used in the study came entirely from publicly available sources, including meteorological, geographical and health-related datasets from established databases to support emissions mapping and impact assessment.
Timing and spatial scale	Study focused on road-based express delivery transportation in China during 2021. Emissions mapped at 5 arcmin × 5 arcmin resolution. Air quality simulations conducted at 0.5° × 0.625° resolution for GEOS-Chem and 9 km resolution for WRF-Chem validation.

Data exclusions	For inter-city parcels involving air transportation (5.9%), only their road segments were included in the main analysis. Air transport emissions were estimated separately (Section S3) but excluded from detailed cross-regional analysis due to uncertainties in flight routing data.
Reproducibility	Route accuracy validated by comparing 50 randomly selected routes with Baidu Maps (R^2=0.99, NMB=2.8%). Air quality model evaluated against national monitoring data (PM2.5: R=0.86, NMB=-13.2%; NO2: R=0.87, NMB=-13.6%). Uncertainty assessed using Monte Carlo simulation for key parameters including parcel weight, truck loading ratio, and payload capacity.
Randomization	Random sampling of waybills was implemented to match official municipal delivery volume proportions across all 333 prefecture-level cities in mainland China.
Blinding	Not relevant to this study, which involved objective data analysis and modeling approaches without risk of observer bias.

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

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☒	☐	Animals and other organisms
☒	☐	Clinical data
☒	☐	Dual use research of concern
☒	☐	Plants

Methods

n/a	Involved in the study	
☒	☐	ChIP-seq
☒	☐	Flow cytometry
☒	☐	MRI-based neuroimaging

Plants

Seed stocks	Not applicable.
Novel plant genotypes	Not applicable.
Authentication	Not applicable.