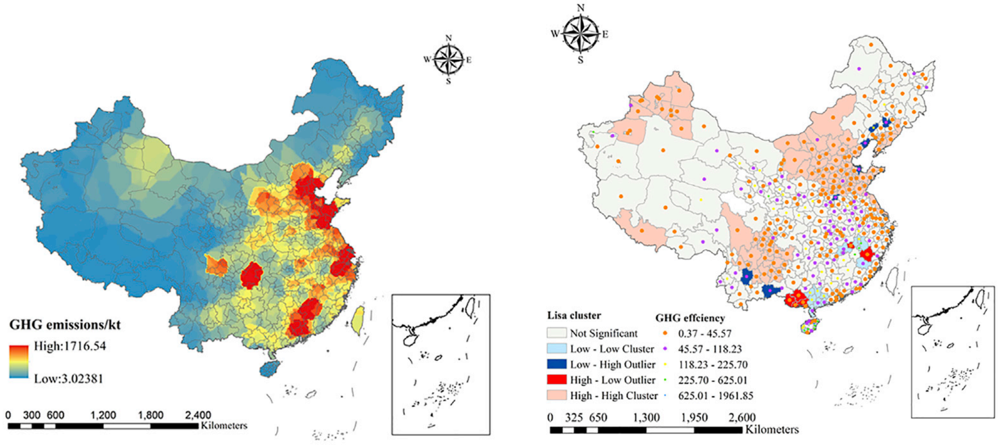
iScience

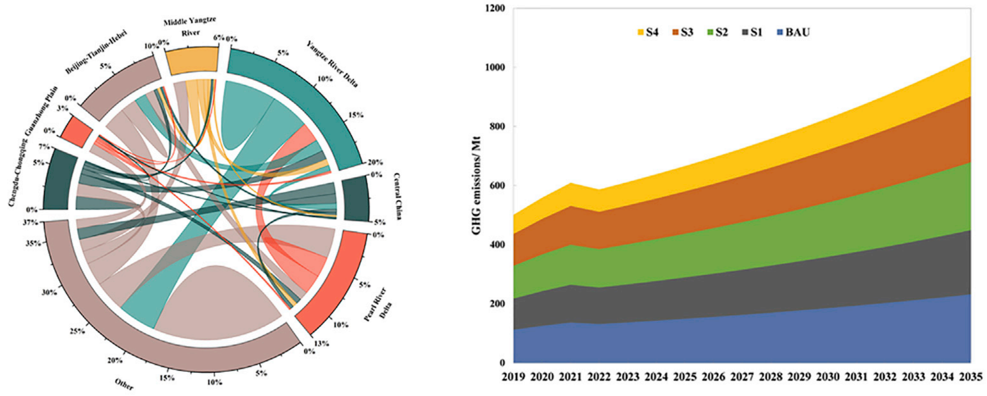
CellPress
OPEN ACCESS

Article

Carbon flow through continental-scale ground logistics transportation



Regions wiht high logistics GHG emissions also have relatively high emission efficiency.



GHG emission flow patterns and several emission mitigation scenarios in China.

Haotian Cui,
Yonglong Lu,
Yunqiao Zhou, ...,
Dag O. Hessen,
Deliang Chen,
Yinyi Cheng

yllu@rcees.ac.cn,
yllu@xmu.edu.cn

Highlights

Propose multisource big data method for ground logistics transportation GHG emissions

Transport distances and road infrastructure are vital to logistic emission efficiency

Commodities underlying value flow is accompanied by GHG flow along the supply chain

Changes in energy combination and freight mode are main determinants of GHG mitigation

Cui et al., iScience *26*, 105792
January 20, 2023
https://doi.org/10.1016/j.isci.2022.105792

iScience

CellPress
OPEN ACCESS

Article

Carbon flow through continental-scale ground logistics transportation

Haotian Cui,[1,2,3,11] Yonglong Lu,[1,2,11,12,*] Yunqiao Zhou,[4] Guizhen He,[2,3] Shuai Song,[2,3] Shengjie Yang,[2,5] Rui Wang,[2,3] Siyu Wang,[3,6] Guoxiang Han,[2,3] Xiaojie Yi,[2,3] Di Du,[2,3] Nils Chr. Stenseth,[7,9] Dag O. Hessen,[8] Deliang Chen,[10] and Yinyi Cheng[3,11]

SUMMARY

The flourishing logistics in both developed and emerging economies leads to huge greenhouse gas (GHG) emissions; however, the emission fluxes are poorly constrained. Here, we constructed a spatial network of logistic GHG emissions based on multisource big data at continental scale. GHG emissions related to logistics transportation reached 112.14 Mt CO_2-equivalents (CO_2e), with seven major urban agglomerations contributing 63% of the total emissions. Regions with short transport distances and well-developed road infrastructure had relatively high emission efficiency. Underlying value flow of the commodities is accompanied by logistics carbon flow along the supply chain. The main driving factors affecting GHG emissions are driving speed and gross domestic product. It may mitigate GHG emissions by 27.50–1162.75 Mt CO_2e in 15 years if a variety of energy combinations or the appropriate driving speed (65–70 km/h) is adopted. The estimations are of great significance to make integrated management policies for the global logistics sector.

INTRODUCTION

Decarbonization of the transport sector is challenging but the key to climate mitigation plans.[1] Globally, the transport sector accounted for approximately 16%–24% of the total CO_2 emissions from fossil fuels.[2] The International Energy Agency (IEA) predicted that global transportation energy use and CO_2 emissions will increase by approximately 80% by 2050.[3] Conventional logistics modes include road, air, rail, and marine transport, but road transport plays an important role in global GHG emissions in over half of the world's countries (Figure S1), accounting for more than 60% of total carbon emissions from the transport sector (see Data S1). Therefore, road transport is identified as the second-largest contributor to long-term climate forcing.[4]

Logistics (freight transport), which relies heavily on road transport, is an important part of the transport sector, accounting for 13% of global anthropogenic carbon emissions.[5,6] Demand for logistics services continues to grow in both developed and emerging economies. Freight shipments in the United States have more than doubled over the past three decades, and ground logistics now accounts for about 25% of total transportation energy consumption.[7] Previous studies have shown that trucks are the second-largest source of GHG emissions from road transport in the European Union (EU), accounting for about 20%–30% of road transport emissions.[8,9] China's total carbon emissions from ground transportation ranked the second in the world in 2019, but its domestic emissions accounted for only about 8% (see Data S1), the lowest compared with other major economies and developed countries (Figures S2 and S3). With rapid development of digital technology, e-commerce has driven increasing ground logistic transport in China. Online sales in China have grown by 250% over the past decade,[10] and the business volume of express deliveries accounts for about 60% of the global total,[11] which is more than that of the United States and the United Kingdom combined. The rapid increase in express delivery volume and e-commerce sales has made the highway freight turnover nearly triple since 2007 (Figures S4 and S5), and GHG emissions from ground logistics will most likely grow in the future, posing a serious challenge to China's ambitious carbon neutrality targets (see Data S1).[12] The carbon flow of ground logistic transport deserves further study.

The international community is increasingly concerned about logistics emission. The European Commission aimed to reduce GHG emissions from transport by 20% from 2008 levels by 2030.[8,9] Then, the CO_2 emission standard was introduced for truck manufacturers in 2018, aiming at reducing emissions.[13] The

[1]State Key Laboratory of Marine Environmental Science and Key Laboratory of the Ministry of Education for Coastal Wetland Ecosystems, College of the Environment and Ecology, Xiamen University, Fujian 361102, China

[2]State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China

[3]University of Chinese Academy of Sciences, Beijing 100049, China

[4]State Key Laboratory of Tibetan Plateau Earth System, Resources and Environment (TPESRE), Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China

[5]Key Laboratory for Geographical Process Analysis, and Simulation of Hubei Province/College of Urban and Environmental Sciences, Central China Normal University, Wuhan 430079, China

[6]Key Laboratory of Land Surface Pattern and Simulation, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

[7]Centre for Ecological and Evolutionary Synthesis, University of Oslo, 031603 Oslo, Norway

[8]Section for Aquatic Biology and Toxicology, Centre for Biogeochemistry in the Anthropocene, University of Oslo, 031603 Oslo, Norway

[9]Ministry of Education Key Laboratory for Earth System Modeling, Department of Earth System Science,

Continued

national low-carbon strategy in France declared that direct emissions from the transport of goods should fall by 97% over the next 30 years.[14] However, this strategy did not accurately describe how it would be achieved. Studies and estimates on freight emission reduction have been underway for more than a decade, but progress has been slow. Extensive evidence from G20 and Southeast Asian countries showed that economic growth and urbanization were important factors influencing logistics carbon emissions.[15,16] Therefore, relying on vehicle technology upgrades alone is not enough to achieve targeted emission reduction. Currently, it is generally agreed that switching modes of transportation and making trucks more efficient are the most effective and sustainable ways to reduce emissions.[17,18] Evidence from the US suggested that network design and vehicle routing optimization could also influence GHG emissions by affecting travel speed and transport efficiency.[19] Nevertheless, an integrated policy mechanism for addressing the ground logistics GHG is lacking at present.[20,21]

The feature of logistics is the integration with supply chains, which leads to the transfer of GHG along the supply chain of regional trade. Some studies have adopted top-down accounting methods to calculate transport emissions based on transport practices reported by thousands of samples, which were small in sample size without considering the complete supply chain.[22–24] The separation between emission and final consumption could undermine local mitigation efforts.[25] This dilemma can be solved by improving the accuracy of emission estimation, establishing a fine link between emission and regional trade, and clarifying the specific driving factors behind the behavior of logistics fleets and emissions. Together, this would promote a long-term effective decarbonization of the transport sector. Owing to the difficulty in obtaining trade information, there are no studies about spatial patterns of logistics emissions from regional trade. Failure to track emission drivers along the supply chain could further hamper climate mitigation efforts. Many accounting energy consumption and GHG emission models for the logistics sector have been developed previously (Table S1), while the main limitation was the inability to obtain real-world data, where vehicle kilometers traveled and fuel economy data were based on the hypothesis of small samples, resulting in huge uncertainty. With the advent of big data era, a "TrackATruck" model based on vehicle-mounted navigation systems has improved accuracy and resolution, but these assessments could not consider the transfer of regional carbon emissions through ground logistics.[26] Only a few studies attempted to calculate GHG emission flow of the express delivery in China through bottom-up assessment.[11] However, express delivery is only a branch of the logistics industry, and the data volume is small, which cannot reflect the whole logistics trade situation.

Accounting logistics transport carbon flow at a finer spatial scale to reduce the uncertainty of logistics GHG emissions is crucial to identify the regional characteristics and determinants of GHG emissions and to achieve low-carbon transition, especially at the city scale.[27,28] To solve the problem, this study aims to examine the new role of logistics in carbon transfer from inter-regional carbon emission flows, by providing a new perspective on the low-carbon transformation of the international logistics industry.

Based on field investigations and multi-source big data mining of logistics, a bottom-up model was constructed, and all data are processed using a parallel computing framework. The advantage of big data method is that basic information on trajectory and fuel consumption is recorded completely and accurately, which improves the accuracy of emission estimation of logistics transportation at different scales. It tracks GHG emission flow along the supply chain and enhances the dynamic interaction between logistics emissions and environmental and socio-economic factors. Taking 2019 as the target year, we studied the precise quantification of GHG (including CO_2, CH_4, and N_2O) emissions of logistics transportation for 334 prefectural cities in China systematically. We accurately quantified the inter-city logistics GHG emission flow network through origin-direction analysis at continental (ground logistics transport) scale, and the emission efficiency between cities and regions was quantified, as well as the emission carrying capacity of different freight types. In addition, the main drivers of emissions were identified, and effective mitigation policies were proposed. In the future, if more time series big data can be combined with GHG emission model, it can be used to accurately measure global logistics emission performance and strengthen the comprehensive management of logistics emission reduction. Clearly, reductions of China's emissions will have a major impact per se, but we also believe that insights from our study can be applied to the logistics sector globally.

Tsinghua University, Beijing 100084, China

[10]Regional Climate Group, Department of Earth Sciences, University of Gothenburg, 40530 Gothenburg, Sweden

[11]Xiamen University and Chinese Academy of Sciences contributed equally to this study

[12]Lead contact

*Correspondence:
yllu@rcees.ac.cn,
yllu@xmu.edu.cn

https://doi.org/10.1016/j.isci.2022.105792

RESULTS

Spatial and temporal variation of ground logistics GHG emissions

In 2019, we estimated that 112.14 Mt of CO_2-equivalents (CO_2e) were emitted by the ground logistics transportation sector in China based on our dataset, being substantially higher than the estimates in a previous

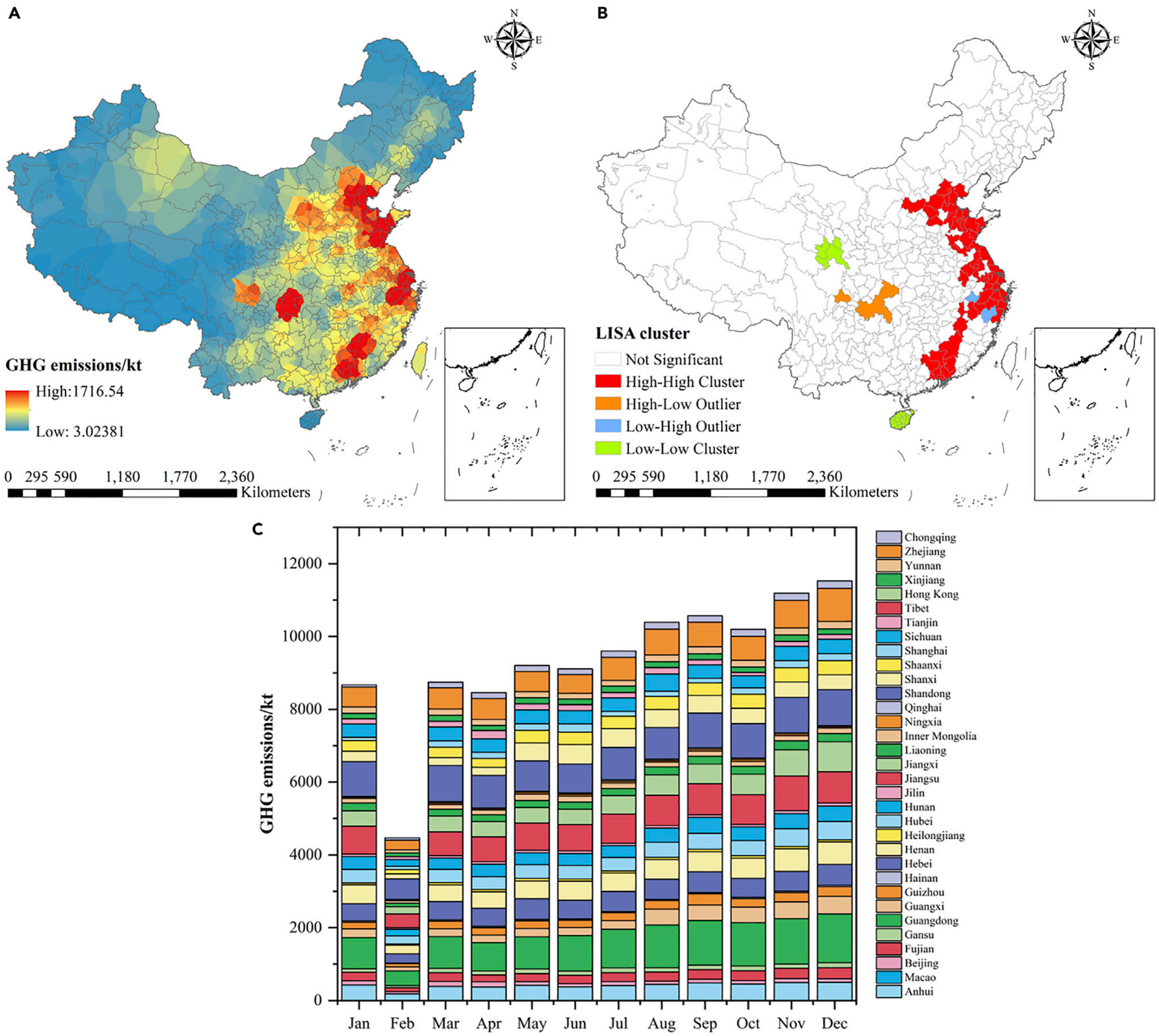


Figure 1. GHG emission characteristics of logistics transport in China

(A) Spatial emission characteristics at an urban scale. The emissions in the eastern regions were significantly higher than those in the western regions. YRD, BTH, PRD, and CC have 30% of the national population and account for 16%, 8%, 7%, and 3%, respectively, of the total emissions in mainland China.

(B) Spatial autocorrelation analysis. Moran's I shows that the Yangtze River Delta (YRD), Beijing-Tianjin-Hebei (BTH), Pearl River Delta (PRD), and Chengdu-Chongqing (CC) were typical high-emission clusters. The northeastern and northwestern regions were typical low-emission clusters.

(C) Monthly allocation proxy in mainland China.

study focusing on the express delivery (13.7 Mt CO_2e).[11] CO_2, CH_4, and N_2O emissions contributed about 98.29%, 0.56%, and 1.15% of the equivalent CO_2 emissions from the logistics transport, respectively. Total GHG emissions varied significantly between regions in China, ranging from 0.10 to 2,875.18 kt CO_2e, and the per capita emission varied from 22.1 to 133.8 t CO_2e (Figure 1), with the majority originating from economically developed and densely populated regions.

Overall, emissions associated with the four key urban agglomerations and high-population centers ranked first, such as the Yangtze River Delta (YRD), Beijing-Tianjin-Hebei (BTH), Pearl River Delta (PRD), and Chengdu-Chongqing (CC) (accounting for 30% of the national population), which accounted for 34% of national emissions (Figure 1A). Local Moran's index (I) showed that GHG emissions had significant spatial autocorrelation Figure 1B). Specifically, the logistics transportation GHG emissions in Guangzhou in South China; Shanghai, Hangzhou, and Suzhou in East China; Beijing, Tianjin, and Linyi in North China; and Chongqing and Chengdu in Southwest China all exceeded 1,200 kt CO_2e, which accounted for approximately 16.1% of the national GHG emissions. In comparison, the total GHG emissions in western regions (Xinjiang, Tibet, Ningxia, and Yunnan) were only 4,457 kt CO_2e.

The higher GHG emissions at a regional scale occurred in well-developed provinces, such as Shandong and Jiangsu, and in provinces that depend on mineral resources, such as Xinjiang and Inner Mongolia. In contrast, the provinces with lower regional GHG emissions were mainly the least developed provinces in western China, such as Qinghai, Ningxia, and Gansu. Guangzhou, Chongqing, Shanghai, and Hangzhou were the top four cities in terms of emission, accounting for 7.6% of the national emissions. It is worth noting that the emissions from the top 10 cities accounted for 16.1% of the total emissions; these cities are at the forefront of economic development in China.

Among these cities, the gap in the economic level between Linyi and other cities was obvious, but Linyi is known as the logistics capital of China, which is located at the junction point of the YRD and Beijing-Tianjin-Tangshan economic circle, with an average daily freight volume of 407.87 million tons and freight turnover of 143.89 billion tons kilometers in 2019.[29] Most areas in northeastern China are classified as emission cold spots, but Harbin and Changchun are emission hotspots compared to surrounding cities. Furthermore, the western and northeastern cities in China are mostly low-emission areas (Figure 1A). Considering the importance of time variation in carbon emission studies,[30] the temporal distribution proxies for different provinces in China were calculated (Figure 1C). The monthly variation in the GHG emissions across the country was significant, ranging from 8.67 to 11.53 Mt CO_2e. The fourth quarter had the greatest total travel distance and the highest GHG emissions, and the first quarter had the lowest total emissions. Owing to the sharp decline in logistics during the Chinese Lunar New Year festival, emissions in February were nearly 50% lower than those in other months. For each quarter, GHG emissions in the first month were relatively low, except for the first quarter, which is related to the scheduling of the freight orders.

Inter-regional GHG flows through ground logistics transportation

The GHG emission flows of ground logistics transportation in China exhibited significant regional characteristics. After more than 40 years of reform and opening-up, China has gradually formed a logistic network with seven urban agglomerations as the core: BTH region, the PRD, the YRD, CC, the Middle Yangtze River, Central China, and the Guan Zhong Plain (Table S2). The GHG emission outflows from these regions were 28.90 Mt CO_2e in 2019, accounting for more than 63% of the total domestic logistics-related emissions. The logistics routes between the YRD and other regions are the most prosperous, accounting for 30% of GHG emissions in the seven areas (Figure 2). In addition, the eastern coastal provinces are not only the richest regions in China but also the busiest regions for logistics and freight transportation in China. The eastern and southern coastal areas were responsible for about 40% of all logistics GHG emissions.

The GHG emission network axis was formed from seven key cities. The total emission network was characterized by a ''double triangle'' framework, which stretched across the southeast coast and southwestern China with a cross-strip shape (Figure S6). There was a significant difference in the development of the network between the east and west, especially in the process of refining and expanding branch lines outside the main emission framework, and the eastern region exhibited strong dispersion effects. Guangzhou, Shenzhen, Shanghai, Beijing, and Tianjin were the key hubs in the eastern region, while Chengdu, Chongqing, and Kunming played a leading role in the southwestern region.

The major contribution sources of GHG emissions in different regions varied greatly, with inter-regional logistics activities as the main source (Table S3). The logistic flow from the YRD mainly went to Jiangsu (15.9%), Zhejiang (14.6%), and Guangdong (13.6%), that from the PRD mainly went to Guangdong (28.9%) and Jiangsu (8.8%), and that from BTH mainly went to Hebei (14.8%), Guangdong (12.4%), and Shandong (9.2%). CC mainly served southwestern China (34.9%) and coastal areas (36.9%), while the Guan Zhong Plain mainly served northwestern China (42.0%) (Figure S7).

GHG flow efficiency is an important indicator of the sustainable development of regional logistics. There is spatial consistency between the total GHG emissions and their efficiency. The geographic center of the high emission efficiency of the logistics routes was situated to the middle and lower reaches of the Yangtze

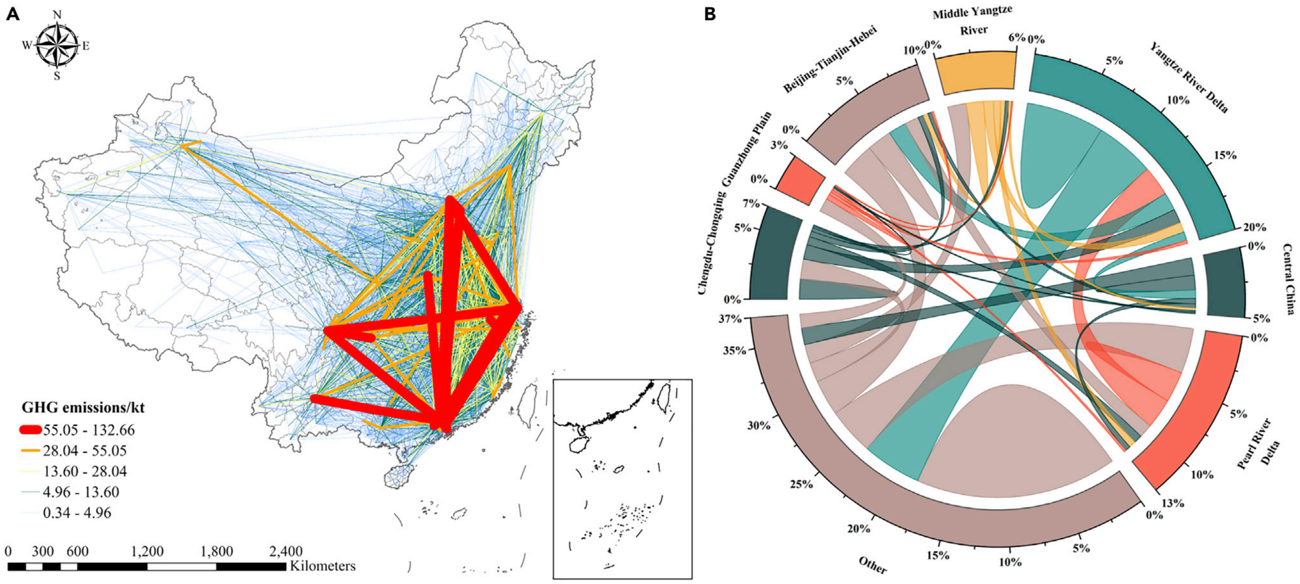


Figure 2. GHG emission flow patterns within China

(A) The top 20% GHG emission flows. Each line represents the total GHG emissions of logistics transport between two cities in 2019 (from origin to destination). The largest GHG transfer through domestic logistics is Shanghai-Chengdu (round trip), with 263.88 kt CO_2 in 2019. This route is one of the most important logistics transportation route in China, with the largest annual total volume of freight cars, the most trips, and relatively high average fuel consumption.

(B) Flows of GHG emissions from the inter-regional logistics transportation in China. The direction of logistics from the origin (sender) region to the destination (receiver) region is shown together.

River. The specific gravity center position and movement trajectory showed that the efficiency decreased from east to west. The regions with the highest emission efficiency mainly included "YRD-BTH", "BTH-Shandong Peninsula", "PRD-YRD", "CC-PRD", and "CC-Yunnan", as well as the intracity logistics in the three provinces (Heilongjiang, Jilin, and Liaoning) in northeastern China (Figure 3). These regions had emission efficiencies as high as 0.13–51.50/t CO_2e per vehicle. Among them, the line with the highest emission efficiency was Qujing-Nanjing. Logistics in these areas is mainly through intracity transportation and regional short-distance connections, while these routes achieved full expressways coverage with less traffic congestion, resulting in more efficient engine combustion and fewer GHG emissions per truck.

The lowest emission efficiency was concentrated in the regions with long-haul transportation. Several lines ran across the whole of the east and west of China or the whole of the north and south of China, with an average travel mileage of 107.43 million km. The "Kashi-Wuxi" line had the lowest efficiency; the annual GHG emission of each vehicle was 49.95 kt CO_2e. Moreover, the logistics and highway infrastructure in some western regions was not optimized; each truck had high GHG emissions, and thus the emission efficiency was lower than that of other areas.

GHG emissions from supply chain

In 2019, about 26.1% of GHGs from logistics transport in China were emitted from commodities that end up for deep processing or direct consumption in different provinces in China or abroad. Through the logistics supply chain analysis, most of the GHG emissions associated with commodities consumed in the eastern coastal provinces were imported from poorer provinces in western China. As one of the least developed regions in China, northwestern China supports the economic development of the developed provinces by providing carbon-intensive but low-value-added products. A large proportion of GHG emissions in the Northwest were caused by the supply of goods and services consumed in the developed regions of China.[31]

China was divided into seven geographical regions to analyze the freight types. The regional freight types varied greatly in different regions (Figure S8). The proportion of total freight types is as follows: Northwest, North, and Southwest China were dominated by commodities with 57.1%, 80.8%, and 26.1%, respectively.

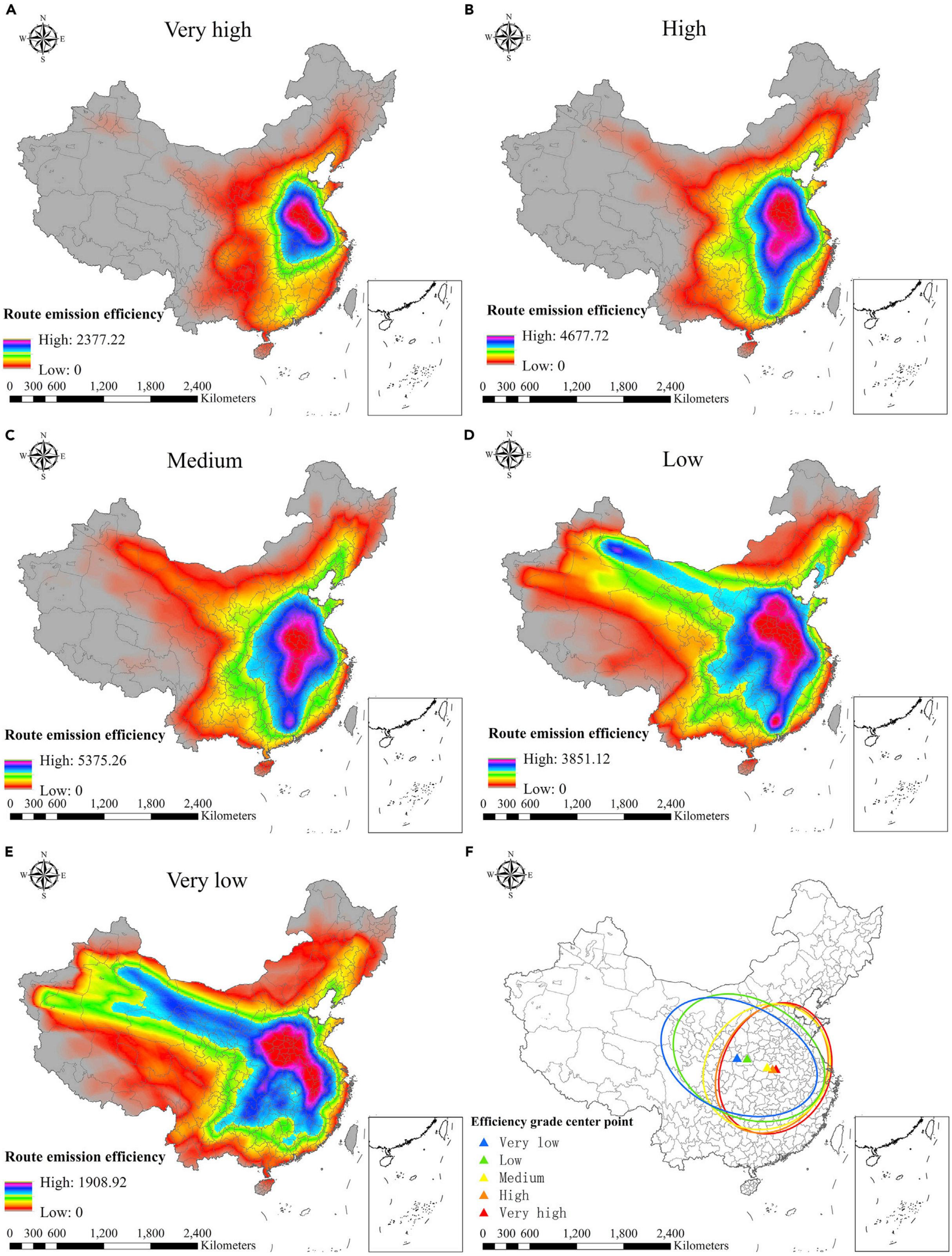


Figure 3. GHG emission flow efficiency within China in 2019

(A–E) show the line density of single route emission efficiency.

(F) Gravity movements and the SD ellipses (SDEs) of the GHG emission flow efficiency.

In Northeast China, the main freight types were commodities (35.5%) and food and beverages (20.9%), compared with mechanical equipment (14.2%) in Central China. The main freight types in Eastern and Southern China were relatively dispersed, where delivery and food and beverages ranked first (29.4%) (see Data S1 for the freight supply).

The routes with high domestic GHG emission flows were mainly distributed in the poor western regions, while routes with high domestic net emission flows were mainly distributed in wealthier eastern China (Figure S9). In terms of product type, western provinces mainly exported high-carbon-intensive products and imported low-carbon-intensive products. In western China (Shaanxi, Gansu, Ningxia, Qinghai, and Xinjiang), more than 60% of GHGs (80%, 90%, and 92% in Qinghai, Xinjiang, and Inner Mongolia, respectively) were emitted during the transportation of commodities, which are eventually consumed in other regions. Xinjiang was the net emission center in western China because it is one of the main suppliers of energy, agricultural, and sideline products in China. The total emissions in Guizhou and Tibet were relatively low, mostly consisting of the transport of building materials (43% and 74%, respectively). In contrast, eastern provinces normally imported high-carbon-intensive products while producing and exporting low-carbon-intensive products. Guangdong, Jiangsu, and Zhejiang had the highest domestic net emissions, mainly from the external transport of machinery equipment and digital products (40%, 30%, and 35%, respectively).

There were also some cases in eastern provinces, such as Shandong, the grain and vegetable base of North China and home to the country's largest fluorine chemical industry park, so the commodities (mainly agricultural and chemical products) transport contributed 48% of GHG emissions. As the largest express transportation distribution center in southern China, Fujian has promoted the development of the express delivery industry,[32] and thus GHG emissions were mainly contributed by express transportation (42%). Guangxi accounted for 41% of emissions from construction materials, which was a pillar industry, contributing about 8.6% of gross regional product.[33] Compared with other regions, the GHG emissions attributed to different freights in Beijing, Tianjin, and Shanghai were relatively balanced, but the freight demand was driven by the service and high-tech industries. Unlike the above three cities, Chongqing mainly discharged less-than-carload lots (Table S4).

Owing to the low proportion of energy and carbon-intensive products in the overall logistics chain, the emission intensity (consumption-based GHG emissions per unit of gross domestic product [GDP]) was generally lower in the technology-based and economically developed provinces than in western provinces (Figure S10). For example, in Beijing and Jiangsu, the logistics GHG emission intensity was 0.36 and 0.5 g/RMB Yuan, respectively, while Tianjin and Shandong had the highest GHG emission intensity, which was about 2.4 times and 2.2 times that of Beijing, respectively, in 2019. The proportion of output value of the three major industries in different regions of China provided evidence for this result from another perspective (Figure S11).

The GHG emission efficiency of logistics transportation (the carbon emission of transporting single goods) was also significantly different (0.37–1961.84 t CO_2e). The results of spatial autocorrelation analysis showed that the four emission hotspots, namely, BTH, YRD, PRD, and CC, had high emission efficiency (Figure 4). This was because these regions had developed economies, highly aligned logistics and transportation infrastructure, and well-connected highway networks. Although the annual waybills in these regions ranked at the top in China, their freight turnover efficiency was high, storage and transportation were highly intelligent, highway network connectivity was high, traffic congestion incidence was low, and the waiting time for freight connections was short. As a result, the additional fuel consumption of single freight was reduced.

Northern Xinjiang (Urumqi, Shihezi, Changji, and Hami), southern Tibet (Shigatse and Naqu), and most cities in Liaoning Province also had high emission efficiency, although these areas are still developing and have a backward logistical infrastructure. In comparison, Hainan is an island, and its logistics transportation is mainly circular within the island. As the terrain is mainly mountainous, road transportation is inconvenient and the logistics connection capacity is poor with low emission efficiency. Jiangxi, Guangxi, and Shaanxi are also affected by the Lushan Mountain range, Shiwan Mountain, and Taihang Mountain range, respectively, so their energy consumption related to road transportation was much higher than that of other plain areas. However, the Hexi Corridor in the Ningxia and Gansu mountainous region led to an increase in road transport mileage and a poor transport capacity; the highway freight turnover in this region accounted for

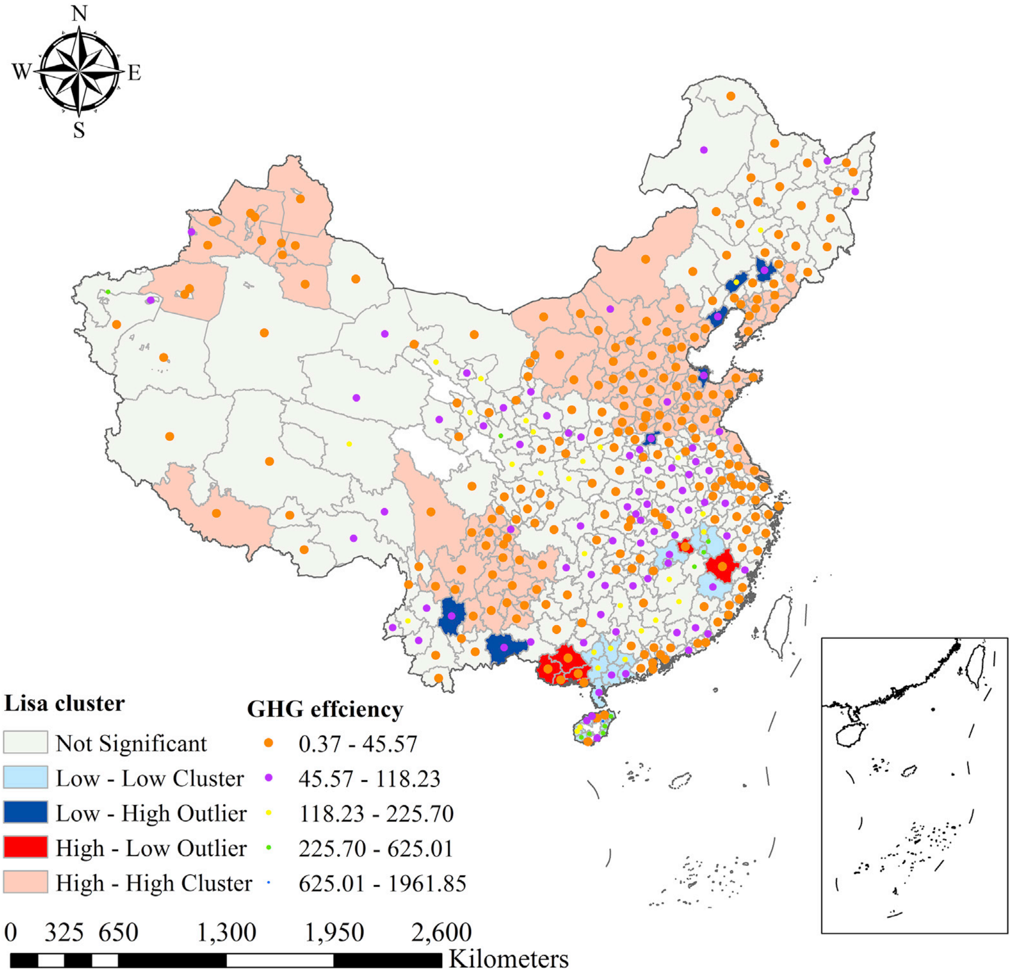


Figure 4. Regional logistics GHG emission efficiency and its spatial autocorrelation

Note: (1) Owing to the lack of freight transportation data in the databases of some cities, their GHG emission efficiencies are zero. (2) The unit of transportation efficiency in this figure is t per goods. (3) The color of the polygons represents the result of Moran's index, representing the spatial aggregation situation. The dot represents the emission efficiency.

32.8% of the whole country, and the railway double-track rate in this region is only 33.8%.[34] The single logistics transportation structure leads to low carbon emission efficiency of highway logistics.

Driving mechanism for GHG emissions and scenario-based mitigation measures

Taking inter-city logistics transport as an example, we studied the correlation between GHG emissions during transport and various socio-economic factors. According to our field survey with logistics suppliers and G7 internet of things (iot) Company, the main driving factors affecting logistics transportation are social economy, industrial structure, transportation structure, and fuel consumption.[9,11,23] The specific parameter values for each factor were detailed in Table S5. There was a significant positive correlation between total logistics GHG emissions and GDP, express volume, freight turnover, and fuel consumption. Because GHG emissions had strong relationship with population, we also paid attention to the impact of per capita data. Per capita GHG emissions were significantly positively correlated with urbanization rate, household consumption level, per capita express delivery volume, and freight turnover, and the impact of population on emissions is mainly reflected through urbanization, which may be due to more efficient logistics and transport systems in wealthier and more urbanized areas (Figure S12). Overall, several important driving factors were identified that affected the logistics GHG emissions, including the volume of express delivery business, urbanization rate, and freight turnover.

For the mobile source GHG emissions, the factors affecting emissions were mainly fuel consumption and the emission factor. The emission factor of diesel vehicles has a relatively narrow range, so the key factor is fuel consumption. According to previous studies, vehicle fuel consumption is related to the average driving speed and may be higher in the case of parking and idling. With million-level big data mining, the function between vehicle speed and fuel consumption was constructed by machine learning, which revealed a quadratic functional relationship (Figure S13). Therefore, on the premise of timeliness, a reasonable driving speed (65–70 km/h) and route should be chosen to avoid traffic congestion, which can effectively reduce carbon emissions in the transportation process.

Different scenarios were set up to simulate future emissions of logistics transport GHG emissions in the background of truck growth. Based on the motor vehicle growth model, the total number of freight heavy trucks will increase to about 19.05 million by 2035 under the business as usual (BAU) scenario. As a result, GHG emissions from logistics transportation will continue to grow steadily from 2020 to 2035, with emissions expected to reach 231 Mt CO_2e by 2035, which is equal to the total emissions from fuel combustion in emerging economies like Thailand in 2018.[35]

In addition to the BAU scenario, based on the logistics driving factors described above, a series of strategies were also proposed to reduce GHG emissions from the logistics industry through other scenarios, which are in accord with the future direction of green transportation in most countries worldwide (Table S6). These scenarios specifically include the following: selecting the suitable travel speed to ensure the reduction of fuel consumption (scenario1); using electric trucks in short trip distance lines with dense freight, the GHG emissions intensity during transportation can be reduced (scenario2); according to the single freight distance and vehicle range, a variety of energy combination is adopted in medium- and short-distance transportation to improve fuel economy (scenario3); and replacing energy of all freight trucks with liquefied natural gas to reduce total GHG emissions (scenario4). According to the simulation results, scenario1 and scenario3 can achieve moderate emission reductions compared with the BAU, reducing emissions by 167.95 Mt and 103.55 Mt CO_2e between 2020 and 2035, respectively, while scenario2 can achieve 27.50 Mt CO_2e emission reductions slightly. Among all of the scenario strategies, scenario4 can achieve greater emission reductions, about 1,162 Mt CO_2e in next 15 years, which, nevertheless, depends more on advanced technology to ensure complete replacement of fuel in heavy trucks (Figure 5).

DISCUSSION

Logistics carbon flow analysis can help present inter-regional trade and emissions transfer with supply chains. Big data-based emission network maps are more operational than proportional emission maps with small samples, allowing collaborative mitigation efforts for emission hotspots. But there is a lack of a system that collects data on the position of vehicles per second based on big databases, even if this is the most suitable data source for emissions simulation.[36–38] A comparison with the existing literature and results related to logistics carbon emissions in China was analyzed in detail (Table S7). Through comparative analysis, we found that previous studies investigated into key themes and challenges in several aspects, including logistics carbon strategy, carbon risk assessment, carbon target setting, emission reduction initiatives, carbon performance, and influencing factors. The results showed that although an increase in carbon management practices in logistics and transportation can be observed, the accounting methods and comprehensive measures of carbon reduction are not well studied. Therefore, based on multisource big data, this study constructs the logistics GHG emission flow map at continental scale, estimates the different transportation structures and the emission efficiency in different regions, and identifies the key driving factors affecting emissions. Results in this study can guide the government to take more targeted measures to achieve low carbon goal of logistics.

Overall, China's GHG emissions from logistics transportation accounted for about 15.3% of global emissions in 2019.[39] The emission hotspots mainly appear in large urban agglomerations such as the YRD and PRD, while the western provinces and northeast regions become the emission cold points. Logistics GHG emission is usually accompanied by underlying value flow of the commodities.

The large differences in economic and trade structure between cities are attributable to the imbalance of GHG emissions embodied in urban logistics. In general, the goods and services consumed by the highly developed eastern regions produce a major share of GHG emissions. Wealthy eastern coastal regions mainly import low-value-added and high-carbon-intensive products from the less developed western regions, while exporting

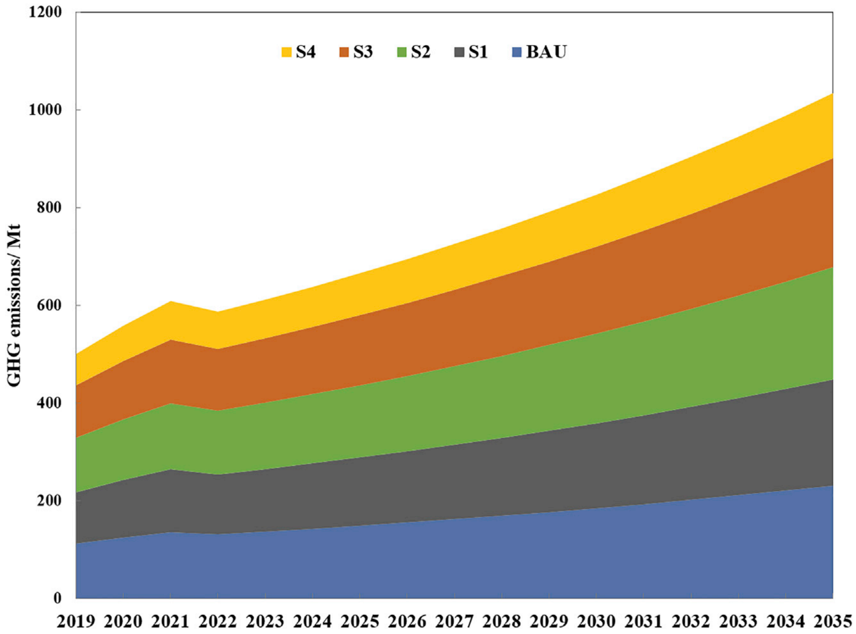


Figure 5. GHG emissions from logistics transportation under various scenarios in China

high-value-added and low-carbon-intensive products.[31] In other words, household consumption and international exports from the richer east are supported by emissions of primary products in less developed regions of China.[40] In fact, more than 50% of the emissions of industrial raw materials and commodities in the cities with good economic development such as Beijing, Shanghai, and Tianjin, as well as in provinces such as Guangdong and Zhejiang, are outsourced to less technologically efficient underdeveloped regions. In the future, the logistics volume from the east to the west may increase further.[41] To some extent this also reflects the role of China for the global market, as only 8% of emissions is related to the domestic market.

The next decade will be critical for the carbon peak in China, and the logistics industry will also grow rapidly.[12] The online retail transaction volume in China ranked first in the global e-commerce industry, accounting for more than half (52.1%) of all e-commerce globally in 2020.[42] In 2021, the Chinese government established China Logistics Group Limited to achieve an 8% average annual increase in the logistics added value.[43] Not only China, but also major economies around the world are increasingly concerned about the impact of freight on climate change.[44] For example, in 2018, many European freight companies committed to reducing 290 Mt carbon emissions over the next decade.[45] Therefore, it is necessary to formulate supporting policies around green logistics. Green logistics focuses on improving the efficiency of logistics services, reducing corresponding costs and reducing externalities while achieving a sustainable balance between economic, environmental, and social objectives. The multi-objective (e.g., distance, time, and speed) optimization may play a key role in green transport.

At present, the globalization and centralization in logistics are obvious, and the environmental benefits brought by the advancement of vehicle technology are being sacrificed.[46] The key to achieving green logistics is the reduction of externalities per kilometer of travel. Therefore, comprehensive policies should be proposed including route optimization, infrastructure planning, and operational measures.

First and foremost, the regions with developed economies and sound logistics infrastructure have higher emission efficiency. Therefore, less developed regions should strengthen the construction of integrated logistics system. The dominant freight type in less developed regions is bulk commodity, so it is possible to use multimodal transport, which is a systematic movement of goods in one unit state from the consignor to the consignee. Large-scale transfer through railways and waterways can cut the total road transport trips, shorten transport time, and reduce driving mileage and carbon emissions. Economic measures (subsidies and taxes) can give full play to economic leverage and strengthen the regulation of logistics trucks. The local governments can provide fiscal incentives for multimodal transportation of bulk commodities. For example, Jiangsu Province subsidized about 200 yuan per standard container or 500 yuan per carload for freights that use intermodal combinations such as rail and water or truck and rail,[47] which helps carriers choose multimodal transportation. China has a cap of 49,500 yuan per vehicle for heavy electric trucks after 2020, but these subsidies are minimal.[48] Therefore, the use of incentive and penalty mechanisms can help ensure the financial sustainability of long-term subsidy programs while curbing the demand for fuel vehicles and reducing GHG emissions.

In the EU, for example, road tolls for zero-emission heavy trucks are reduced by up to 75%, and conventional gas-powered semi-tractors are charged a carbon fee of up to 0.16 Euros per kilometer.[49] Lower tolls for zero-emission heavy-duty trucks would yield greater profit margins, strengthening the electrification of trucks. In 2020, the carbon tax was 43 yuan per ton CO_2e in China, while the Europe's tax was 26.87 euros (~210 yuan) per ton CO_2e.[50] If the tax rate was increased three to five times, zero-emission trucks would benefit immediately. From a strict economic point of view, the best strategy for reducing emissions is to make marginal emission reduction costs equal. The United States will allocate $5 billion to build a nationwide charging network.[51] So logistic carbon reduction policies should be applied to address regional differences within China. The higher emission reduction targets were suggested to be set in major logistics hubs such as the YRD and PRD, while the emission reduction targets of the northeastern, central, northwestern, and southwestern provinces should be more moderate. Therefore, we suggested that the charging facilities should continue to be developed vigorously in the eastern region. While the road density in the central and western regions is only about 1/10 of that in the eastern region, the construction of roads, storage, and other logistics infrastructure and the introduction of advanced technologies should be achieved in central and western provinces to achieve the corresponding reduction targets. Emissions trading can help achieve the lowest cost reductions in the western region through technology transfer and capital investment from the coastal to interior.[52] Therefore, accounting based on logistics emission networks and freight-carrying capacity can provide a detailed assessment of effective and fair policies, facilitating collaborative decision-making on localized mitigation strategies.

Secondly, choosing the new energy trucks from the available fleet is promising to reduce GHG emissions.[9,14] As mentioned in our scenario analysis, switching energy from heavy trucks is a key initiative to mitigate GHG emissions. However, the electrification of heavy trucks is difficult, and the battery range is short, so the conditions for replacing all of them with natural gas fuel are extremely rigorous. Therefore, considering the costs and benefits, we suggest choosing an energy-alternative approach in combination with the vehicle's single-pass mileage in the future. This requires logistics enterprises to upgrade management systems, improve the efficient coordination of departure and destination, and rationally arrange trucks according to the driving distance of each transportation to maximize comprehensive benefits. For those regions with a developed express transportation industry, the government should pay more attention to improving the transport capacity of the railway freight and the new energy trucks, avoiding excessive dependence on heavy diesel trucks.

Thirdly, an efficient and convenient comprehensive transportation system should be established, as Germany connected electric trucks to overhead power lines on so-called electric highways which is the most energy-efficient route to zero-emission road freight.[53] Furthermore, driving routes and distribution times should be rationally planed, for example, dispatching in cities at the night when traffic is relatively smooth. Only in this way we can ensure that the driver chooses the most reasonable driving speed and improves fuel efficiency. Our scenario simulations show that reasonable speed choice is as effective as energy substitution.

Finally, the conventional hub-satellite distribution model is overconcentrated, resulting in more transport mileages on indirect routes through hubs than direct inter-warehouse trunks. Therefore, we suggest a combination of centralized and decentralized freight modes, with a "cooperative freight system" to reduce unnecessary mileage and fuel consumption (Figure S14). According to our field survey on underlying demand patterns and supply strategies of carriers, we suggested that manufacturers and the distributors can share the warehouse resources of the logistics enterprise, reducing the distribution link between the manufacturer and the distributor, reducing the frequency and distance of freight transportation, thereby reducing GHG emissions. In addition, it can also be a purposeful and intensive distribution mode carried out by carriers to meet the needs in a certain area of the city through joint distribution (shared user services). Unified gathering and distribution of freights by the same logistics service provider can significantly reduce redundant routes, alleviate traffic congestion, and take low-carbon pathway.

A multisource big data model proposed here is significantly improved than the previous surveys on the spatial heterogeneity of logistics carbon emissions, which provide a key contribution to the measurement of GHG emissions in logistics transportation. Spatial hotspots and environmental impacts for international transport can also be identified with the same method, providing a new perspective on the low-carbon path for logistics.

Limitations of the study

This study focuses mainly on the heavy truck transportation phase, while emissions from private cars, international delivery, packaging, last-mile services, and consumer behavior can undoubtedly affect GHG emissions, which need to be included in future studies. In addition, the truck age distribution, maintenance conditions, and engine combustion efficiency will also have impact on GHG emission, resulting in the uncertainty of total emissions. The methodology is applicable to countries with advanced information technology and vehicle-monitoring systems. If companies are more socially responsible, logistics-related big data will be continuously available. More dynamic emissions information can be obtained by combining these data with GHG emission models, which can be used to measure the precise performance of global logistics carbon emissions.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

- KEY RESOURCES TABLE
- RESOURCE AVAILABILITY
  - Lead contact
  - Materials availability
  - Data and code availability
- METHOD DETAILS
  - Data sources, collection, and analysis
  - Logistics transportation GHG emissions
  - Uncertainty analysis

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2022.105792.

ACKNOWLEDGMENTS

Funding: This study was supported by the National Natural Science Foundation of China (Grant No. 71761147001, No. 42030707), the National Key R&D Program of China (2019YFC0507505), International Partnership Program by the Chinese Academy of Sciences (121311KYSB20190029), and the Fundamental Research Fund for the Central Universities (No.20720210083). We are grateful to G7 Company for generous provision of basic logistics data.

AUTHOR CONTRIBUTIONS

Y.L. conceived the idea and study design. H.C., Y.L., Y.Z., S.S., S.Y., S.W., R.W., G.H., X.Y., and D.D. performed research. H.C., Y.Z., G.H., S.Y., S.W., X.Y., R.W., G.H., and D.D. collected and analyzed the data, and all authors contributed to the interpretation. H.C., Y.L., and Y.C. contributed analytical tools. H.C. and Y.L. drafted the paper. Y.L., H.C., D.C., D.H., and N.S. revised the paper.

DECLARATION OF INTERESTS

The authors declare no competing interests.

Received: September 12, 2022
Revised: November 1, 2022
Accepted: December 7, 2022
Published: January 20, 2023

REFERENCES

1. Lin, Y., Qin, Y., Wu, J., and Xu, M. (2021). Impact of high-speed rail on road traffic and greenhouse gas emissions. Nat. Clim. Chang. *11*, 952–957. https://doi.org/10.1038/s41558-021-01190-8.
2. International Energy Agency (2016). CO_2 Emissions from Fuel Combustion Highlights 2016.
3. International Energy Agency (2009). Transport, Energy and CO_2: Moving toward Sustainability.
4. Unger, N., Bond, T.C., Wang, J.S., Koch, D.M., Menon, S., Shindell, D.T., and Bauer, S. (2010). Attribution of climate forcing to economic sectors. Proc. Natl. Acad. Sci. USA *107*, 3382–3387. https://doi.org/10.1073/pnas.0906548107.
5. Geneva (2016). Logistics industry. In World Economic Forum White Paper - Digital Transformation of Industries in collaboration with Accenture (World Economic Forum).
6. McKinnon, A.C., and Piecyk, M.I. (2012). Setting targets for reducing carbon emissions from logistics: current practice and guiding principles. Carbon Manag. *3*, 629–639. https://doi.org/10.4155/cmt.12.62.
7. Liu, L., Hwang, T., Lee, S., Ouyang, Y., Lee, B., Smith, S.J., Tessum, C.W., Marshall, J.D., Yan, F., Daenzer, K., and Bond, T.C. (2019). Health and climate impacts of future United States land freight modelled with global-to-urban models. Nat. Sustain. *2*, 105–112. https://doi.org/10.1038/s41893-019-0224-3.
8. Liimatainen, H., Hovi, I.B., Arvidsson, N., and Nykänen, L. (2015). Driving forces of road freight CO_2 in 2030. Int. J. Phys. Distrib. Logist. Manag. *45*, 260–285. https://doi.org/10.1108/IJPDLM-10-2013-0255.
9. Inkinen, T., and Hämäläinen, E. (2020). Reviewing truck logistics: Solutions for achieving low emission road freight transport. Sustainability *12*, 6714. https://doi.org/10.3390/su12176714.
10. Statista (2019). Retail E-Commerce Sales Worldwide from 2014 to 2023 (in billion U.S. dollars). https://www.statista.com/statistics/379046/worldwide-retail-ecommerce-sales/.
11. Kang, P., Song, G., Xu, M., Miller, T.R., Wang, H., Zhang, H., Liu, G., Zhou, Y., Ren, J., Zhong, R., and Duan, H. (2021). Low-carbon pathways for the booming express delivery sector in China. Nat. Commun. *12*, 450. https://doi.org/10.1038/s41467-020-20738-4.
12. Mallapaty, S. (2020). How China could be carbon neutral by mid-century. Nature *586*, 482–483. https://doi.org/10.1038/d41586-020-02927-9.
13. Siskos, P., and Moysoglou, Y. (2019). Assessing the impacts of setting CO_2 emission targets on truck manufacturers: a model implementation and application for the EU. Transport. Res. Pol. Pract. *125*, 123–138. https://doi.org/10.1016/j.tra.2019.05.010.
14. Demir, E., Bektaş, T., and Laporte, G. (2014). A review of recent research on green road freight transportation. Eur. J. Oper. Res. *237*, 775–793. https://doi.org/10.1016/j.ejor.2013.12.033.
15. Nguyen, H.A.T. (2021). The role of logistics industry in the sustainable economic development of Southeast Asian countries. Accounting *7*, 1681–1688. https://doi.org/10.5267/j.ac.2021.5.001.
16. Habib, Y., Xia, E., Hashmi, S.H., and Ahmed, Z. (2021). The nexus between road transport intensity and road-related CO_2 emissions in G20 countries: an advanced panel estimation. Environ. Sci. Pollut. Res. Int. *28*, 58405–58425. https://doi.org/10.1007/s11356-021-14731-7.
17. Kim, N.S., Wiegmans, B., and Bu, L. (2016). Potential CO_2 Savings by increasing truck size: a Korean case study. KSCE J. Civ. Eng. *20*, 997–1005. https://doi.org/10.1007/s12205-016-2560-4.
18. McKinnon, A.C. (2003). Logistics and the environment. In Handbook of Transport and the Environment (Emerald Group Publishing Limited), pp. 665–685.
19. Blanco, E.E., and Sheffi, Y. (2017). Green logistics. In Handbook of Logistics and Supply-Chain Management. Springer Series in Supply Chain Management, *4*, pp. 147–187. https://doi.org/10.1007/978-3-319-29791-0_7.
20. Zając, P. (2011). The idea of the model of evaluation of logistics warehouse systems with taking their energy consumption under consideration. Arch. Civ. Mech. Eng. *11*, 479–492. https://doi.org/10.1016/S1644-9665(12)60157-5.
21. Tang, S., Wang, W., Yan, H., and Hao, G. (2015). Low carbon logistics: reducing shipment frequency to cut carbon emissions. Int. J. Prod. Econ. *164*, 339–350. https://doi.org/10.1016/j.ijpe.2014.12.008.
22. Yang, J., Tang, L., Mi, Z., Liu, S., Li, L., and Zheng, J. (2019). Carbon emissions performance in logistics at the city level. J. Clean. Prod. *231*, 1258–1266. https://doi.org/10.1016/j.jclepro.2019.05.330.
23. Khan, S.A.R. (2019). The nexus between carbon emissions, poverty, economic growth, and logistics operations-empirical evidence from southeast Asian countries. Environ. Sci. Pollut. Res. Int. *26*, 13210–13220. https://doi.org/10.1007/s11356-019-04829-4.
24. Bebkiewicz, K., Chłopek, Z., Lasocki, J., Szczepański, K., and Zimakowska-Laskowska, M. (2020). Analysis of emission of greenhouse gases from road transport in Poland between 1990 and 2017. Atmosphere *11*, 387. https://doi.org/10.3390/atmos11040387.
25. Davis, S.J., Peters, G.P., and Caldeira, K. (2011). The supply chain of CO_2 emissions. Proc. Natl. Acad. Sci. USA *108*, 18554–18559. https://doi.org/10.1073/pnas.1107409108.
26. Deng, F., Lv, Z., Qi, L., Wang, X., Shi, M., and Liu, H. (2020). A big data approach to improving the vehicle emission inventory in China. Nat. Commun. *11*, 2801. https://doi.org/10.1038/s41467-020-16579-w.
27. Gately, C.K., Hutyra, L.R., Wing, I.S., and Brondfield, M.N. (2013). A bottom up approach to on-road CO_2 emissions estimates: improved spatial accuracy and applications for regional planning. Environ. Sci. Technol. *47*, 2423–2430. https://doi.org/10.1021/es304238v.
28. Gately, C.K., Hutyra, L.R., and Sue Wing, I. (2015). Cities, traffic, and CO_2: a multidecadal assessment of trends, drivers, and scaling relationships. Proc. Natl. Acad. Sci. USA *112*, 4999–5004. https://doi.org/10.1073/pnas.1421723112.
29. Linyi Bureau of Statistics (2020). Linyi Statistical Yearbook 2020 (Linyi Bureau of Statistics).
30. Gea, O.J. (1996). Description of EDGAR Version 2.0: A Set of Global Emission Inventories of Greenhouse Gases and Ozone-Depleting Substances for All Anthropogenic and Most Natural Sources on a Per Country Basis and on 1 Degree X 1 Degree Grid.
31. Mi, Z., Meng, J., Guan, D., Shan, Y., Song, M., Wei, Y.M., Liu, Z., and Hubacek, K. (2017). Chinese CO_2 emission flows have reversed since the global financial crisis. Nat. Commun. *8*, 1712. https://doi.org/10.1038/s41467-017-01820-w.
32. People's Government of Fujian (2017). Measures for Promoting the Development of Express Industry in Fujian. http://fj.spb.gov.cn/dtxx_14169/201705/t20170515_1159881.html.
33. Guangxi Department of Housing and Urban-Rural. 14th Five-Year Plan for Guangxi Construction Industry High Quality Development. in Chinese. http://zjt.gxzf.gov.cn/zfxxgk/fdzdgknr/wjtz/t12939034.shtml.
34. People's Government of Ningxia (2021). Ningxia Comprehensive Transportation System "14th Five-Year" Development Plan. http://www.nx.gov.cn/zwgk/qzfwj/202109/t20210923_3044317.html.
35. Guan, D., et al. (2021). Annual Report 2021 for Carbon Dioxide Emission Accounts of Global Emerging Economies (Institute of Carbon Neutrality, Tsinghua University).
36. Peng, T., Ou, X., Yuan, Z., Yan, X., and Zhang, X. (2018). Development and application of China provincial road transport energy demand and GHG emissions analysis model. Appl. Energy *222*, 313–328. https://doi.org/10.1016/j.apenergy.2018.03.139.
37. Knobloch, F., Hanssen, S., Lam, A., Pollitt, H., Salas, P., Chewpreecha, U., Huijbregts, M.A.J., and Mercure, J.F. (2020). Net emission reductions from electric cars and heat pumps in 59 world regions over time. Nat. Sustain. *3*, 437–447. https://doi.org/10.1038/s41893-020-0488-7.

38. Axsen, J., Plötz, P., and Wolinetz, M. (2020). Crafting strong, integrated policy mixes for deep CO_2 mitigation in road transport. Nat. Clim. Chang. *10*, 809–818. https://doi.org/10.1038/s41558-020-0877-y.

39. Zhang, Q., and Tong, D. (2022). Carbon Emissions and Commitments of Global Energy Infrastructure 2021 (In Chinese) (Institute of Carbon Neutrality, Tsinghua University).

40. Minx, J.C., Baiocchi, G., Peters, G.P., Weber, C.L., Guan, D., and Hubacek, K. (2011). A "carbonizing dragon": China's fast growing CO_2 emissions revisited. Environ. Sci. Technol. *45*, 9144–9153. https://doi.org/10.1021/es201497m.

41. Feng, K., Davis, S.J., Sun, L., Li, X., Guan, D., Liu, W., Liu, Z., and Hubacek, K. (2013). Outsourcing CO_2 within China. Proc. Natl. Acad. Sci. USA *110*, 11654–11659. https://doi.org/10.1073/pnas.1219918110.

42. Cramer-Flood, E. (2021). China Ecommerce Forecast 2021. https://www.emarketer.com/content/china-ecommerce-forecast-2021#page-report.

43. State Council of China (2021). China Logistics Group Was Established. http://www.gov.cn/xinwen/2021-12/06/content_5657945.htm.

44. Zhang, J., Zhang, S., Zhang, X., Wang, J., Wu, Y., and Hao, J. (2022). Developing a high-resolution emission inventory of China's aviation sector using real-world flight trajectory data. Environ. Sci. Technol. *56*, 5743–5752. https://doi.org/10.1021/acs.est.1c08741.

45. Editorial (2019). On-road freight complexities. Nat. Sustain. *2*, 77. https://doi.org/10.1038/s41893-019-0241-2.

46. Wang, S., Wang, L., Huan, Y., Wang, R., and Liang, T. (2022). Concentrations, spatial distribution, sources and environmental health risks of potentially toxic elements in urban road dust across China. Sci. Total Environ. *805*, 150266. https://doi.org/10.1016/j.scitotenv.2021.150266.

47. Shao, Z., He, H., Mao, S., et al. (2022). Toward Greener and More Sustainable Freight Systems (Transportation Planning and Research Institute of the Ministry of Transportation). https://theicct.org/publication/china-us-freight-systems-jan22/.

48. Ministry of Finance (2020). Notice on the Demonstration Application of Fuel Cell Vehicles. http://www.gov.cn/zhengce/zhengceku/2020-10/22/content_5553246.htm.

49. European Parliament Think Tank (2021). Revision of the Eurovignette Directive. https://www.europarl.europa.eu/thinktank/en/document.html?reference=EPRS_BRI.

50. Mao, S., Basma, H., Ragon, P.L., et al. (2021). Total Cost of Ownership for Heavy Trucks in China: Battery Electric, Fuel Cell, and Diesel Trucks. https://trid.trb.org/view/1894361.

51. U.S. Department of Transportation (2022). The National Electric Vehicle Infrastructure Formula Program Guidance. https://www.fhwa.dot.gov/environment/alternative_fuel_corridors/nominations/90d_nevi_formula_program_guidance.pdf.

52. Lo, A.Y. (2012). Carbon emissions trading in China. Nature Clim. Change *2*, 765–766.

53. Amelang, S. (2021). Electric Highways Offer the Most Efficient Path to Decarbonise Trucks. https://www.cleanenergywire.org/factsheets/electric-highways-offer-most-efficient-path-decarbonise-trucks.

54. People's Daily (2021). The Country's Total Highway Length Reached 5.198 Million Kilometers. http://www.zjsjw.gov.cn/shizhengzhaibao/202109/t20210910_4719925.shtml.

55. IPCC (2006). IPCC Guidelines for National Greenhouse Gas Inventories. https://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html.

STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
CO_2 emissions from road transportation	OECD, Transportation and Emissions from Transportation	https://knoema.com/ITF_INDICATORS/transportation-and-emissions-from-transportation
Carbon emission in ground transport sector	Carbon Emission Accounts & Datasets	https://www.ceads.net/
Carbon emission in transportation, storage, post and telecommunication services in China	Carbon Emission Accounts & Datasets	https://www.ceads.net/
E-commerce sales and express volume in China	E-commerce sales and express volume in China	http://data.stats.gov.cn/index.htm
Highway freight turnover and proportion in China	National Bureau of Statistics of China	http://data.stats.gov.cn/index.htm
Data generated by this paper (GHG emission f low and GHG emissions by different freight types)	This paper	Tables S3 and S4
Software and algorithms		
ArcGIS	ESRI	https://www.arcgis.com/index.html
MATLAB 2018a	Mathworks	https://www.mathworks.com/products/matlab.html
Origin 2022b	OriginLab	https://www.originlab.com/OriginProLearning.aspx
SPSS 22.0	IBM SPSS	https://www.ibm.com/cn-zh/spss

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources and reagents should be directed to the corresponding author (yllu@rcees.ac.cn).

Materials availability

This study did not generate new unique materials.

Data and code availability

- Data: All data needed to evaluate the conclusions in the paper are present in the paper and/or the supplemental information. Additional data related to this paper can be requested from the authors.
- Code: This paper does not report original code.

METHOD DETAILS

Data sources, collection, and analysis

Multiple data sources were used to analyze logistics volumes, logistics transportation features, and GHG emission factors. The data were mainly collected from the three dimensions of vehicles, routes, and freights, including the whole process of ground logistics such as the vehicle locations, driving routes, entry and exit areas, fuel consumption, and freight types. The data collection process in this study was random and did not involve human intervention. We randomly collected data from approximately 1.8 million trucks and 0.4 million electronic waybills showing freight types, logistics origins, and destinations to confirm the shares and delivery volumes. The truck load in this study was more than 12000 kg during normal service, which was well maintained on a daily basis, and all vehicles were equipped with GPS signal receivers. Generally, it was forced to take GPS switch on when the truck drivers start driving, otherwise, the vehicle will alert the drivers. However, there was still GPS damage, causing little data shortage, which was one of the results uncertainties. These data were validated by field surveys on freight types and the number of items at multiple distribution centers in different cities.

We used GPS for real-time positioning, determined the driving distance of the vehicle according to the actual road network information, and obtained real-time fuel consumption data through engine management system (EMS) sensors. The frequency of the signal collection was 10 s. In addition, socio-economic data were sourced from the *China Statistical Yearbook* and the *China City Statistical Yearbook*.

The GPS data, raster data, and text data used in this experiment were stored in the database after the preprocessing to improve the computing performance of the data in the parallelization model. The data with 10 s was too redundant, and road freight traffic in China usually shows clear changes on a quarterly basis, so we set up the temporal resolution on a monthly basis. In terms of spatial resolution, the total length of road in China is 5.198 million kilometers, and the road density is 54.15 km per 100 square kilometers, and the road classification system is too complex.[54] The main objective of this study is to quantify the logistic GHG emission flow along supply chain, therefore, we chose the prefecture-level city as the spatial resolution for this study. The data cleaning module helped to eliminate redundant information from the raw data. In order to achieve big data modeling, the processed data was fed into the Spark 2.4 parallel framework. Supported by the Map-Reduce model, the data block obtained secondary product data such as local GHG emission and truck fuel consumption efficiently by simultaneously calculating streams. Spatial analysis was performed using ArcMap 10.6, SPSS 22.0 was used for correlation and regression analysis, and MATLAB 2018a was used for uncertainty analysis. The framework of this study is shown in Figure S15.

Logistics transportation GHG emissions

The *IPCC Guidelines for National GHG Inventories* were used to quantify GHG emissions, including CO_2, CH_4, and N_2O, in this study.[55] More details on determination methods and data sources are available in the supplemental information.

Specifically, we used the following formula to calculate the GHG emissions: First, the database was called to select the daily trajectory, distance traveled and fuel consumption data of each truck. The timescale in this study was one month, so it was necessary to filter and clean the big data and integrate the track and fuel consumption data for each day to obtain information on the driving distance, several trucks, and the fuel consumption of each line in each month. The equations are as follows:

$$D(t) = \int f(D)dt \qquad \text{(Equation 1)}$$

$$M(t) = \int f(M)dt \qquad \text{(Equation 2)}$$

where D is the distance traveled between the origin and destination; M is the quantity of freight vehicles; and t is the statistical time.

Second, GHG emissions from a single driving route in a one-month period can be calculated using the following equations:

$$G_m = G_{b,m} + \sum_c G_{c,m,} \qquad \text{(Equation 3)}$$

where G_m is the total GHG emission (kt CO_2e); $G_{b,m}$ represents the total CO_2 emission (kt); $G_{c,m}$ represents the total CH_4 and N_2O emission (kt CO_2e).

$$G_{b,m} = \sum \rho \times FC_m \times M_m(t) \times D_m(t) \times EF_b \times NCV \times 10^{-14} \qquad \text{(Equation 4)}$$

where $G_{b,m}$ represents the total CO_2 emission (kt); ρ is the fuel density (g/mL). Here, the fuel used for all the freight trucks was diesel, so, ρ is equal to 0.835 g/mL; FC_m is the fuel consumption (L/100.km); EF_b is an emission factor, which is equal to the carbon content of the fuel multiplied by 44/12. It is worth noticing that, in this study, the default CO_2 emission factor (74,100 kg/TJ) was used to calculate carbon emissions. According to IPCC guidelines, road transport default CO_2 emission factor has an uncertainty of 2–5%, due to uncertainty in the fuel composition. The default emission factors in the IPCC guidelines are based on statistical analysis of available fuel features data. Monte Carlo simulation (5000 iterations) was used to calculate uncertainty range. In this analysis, lognormal distribution, the lower and upper limits of the 95% confidence intervals were applied for the probability distribution functions. For gasoline and diesel, the default probability distribution functions of the default final effective CO_2 emission factors were shown in Figure S16; *NCV* is the net calorific value of diesel (43 TJ/Gg); b indicates the CO_2; *m* indicates the fixed route; and *t* is the time period (month).

$$G_{c,m} = EF_c \times M_m(t) \times D_m(t) \times CF_c \times 10^{-12} \quad \text{(Equation 5)}$$

where, $G_{c,m}$ represents the total CH_4 and N_2O emission (kt CO_2e); EF_c are emission factors of CH_4 (175 mg/km), and N_2O (30 mg/km), respectively; CF_c are conversion factors from CH_4 (25), N_2O (298) to CO_2.

Third, considering the fragmentation and hierarchy of each city, we assumed that the urban form was composed of several satellite patches. The intra-city and inter-city logistics distance consists of three parts (Figure S17). The big data were demarcated in a specific data fence, and filters of a certain resolution for segmentation were used to screen out all types of data such as fuel consumption. Assuming that a single urban patch can be regarded as a circle, GHG emissions from a certain city can be calculated as follows:

$$G_k = G_{b,k} + \sum_c G_{c,k} \quad \text{(Equation 6)}$$

$$G_{b,k} = \sum_{j=1}^{M} \left(\sum_{i=1}^{n} \sqrt{(X_{i+\Delta t} - X_i)^2 + (Y_{i+\Delta t} - Y_i)^2} \right) \times EF_c \times CF_c \times 10^{-14} \quad \text{(Equation 7)}$$

$$G_{c,k} = \sum_{j=1}^{M} \left(\sum_{i=1}^{n} \sqrt{(X_{i+\Delta t} - X_i)^2 + (Y_{i+\Delta t} - Y_i)^2} \right) \times EF_c \times CF_c \times 10^{-14} \quad \text{(Equation 8)}$$

where G_k is the total GHG emissions in a city (kt CO_2e); $G_{b,k}$ represents the total CO_2 emissions (kt); $G_{c,k}$ represents the total CH_4 and N_2O emissions (kt CO_2e); (X_i ,Y_i) is the coordinate points of a truck at a specific moment t; *M* indicates the quantity of trucks; and *n* is the trucks coming from different cities.

Finally, to present policy suggestions for the low-carbon development of the logistics industry, it is necessary to calculate the GHG emission efficiency of a single line and the emission efficiency of a single piece of goods in a region, find the low-efficiency carbon emission areas of logistics transportation systems, and analyze the problems in regional development. The specific formula of the emission efficiency are as follows:

$$E_{m,t} = \frac{G_{m,t}}{M_m(t)} \quad \text{(Equation 9)}$$

$$E_{i,t} = \frac{G_{i,t}}{F_{i,t}} \quad \text{(Equation 10)}$$

where $E_{m,t}$ is the GHG emission efficiency per vehicle on a single route; $E_{i,t}$ is the GHG emission efficiency per freight in a fixed city; and $F_{i,t}$ is the total volume of freights in a fixed city.

The methodology about spatial analysis of the logistics GHG emissions are described in the supplemental information (Table S8).

Uncertainty analysis

Multi-source big data were used to construct a high-resolution inventory of annual logistics GHG emissions for China that differed remarkably from other emission estimates. The data source of the logistics system was the national logistics big data platform at the G7 Company in China. All data with sensors in the platform were collected from 1st January 2019 to 31st December 2019. The overall uncertainties include, first, the uncertainties in emission factors due to fuel composition, fleet age distribution, truck maintenance patterns, combustion conditions, and driving practices. Secondly, the sampling uncertainty. The vehicles registered on the big data platform are all heavy trucks, and data on light and medium trucks is missing. Furthermore, nearly 1.8 million logistics trucks are connected to the platform, covering 25% of the large/medium trucks in the Chinese freight market. In calculating GHG emissions, we backtracked emissions from all freight vehicles in the country at a 25% rate. However, some trucks are not registered due to policy control or the retirement of older trucks. Therefore, scaling up may lead to a partial overestimation of total emissions. Only a very small number of trucks on the platform lack GPS information (less than 0.001%) to determine their route, and tracks associated with these trucks were excluded from the calculation. Thirdly, the incompleteness of fuel consumption data. Vehicle fuel consumption data comes from the engine management system (EMS), and about 1/9 trucks are equipped with EMS sensors. Although the calculation requirements are met statistically, missing data may also lead to uncertainty in the results. Finally, the uncertainty of GPS positioning. All trucks are equipped with GPS system, but a few GPS positioning deviation or equipment damage, or a few GPS systems not turning on during driving, may result in data shortage and inaccuracy. Since a huge amount of data is collected, the overall impact is slight.

Monte Carlo simulations and Bootstrap sampling analysis were performed to identify the uncertainties and probability distributions associated with these parameters such as fuel consumption and distance traveled (Figures S18–S20).