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Title Page

Cropland Displacement Contributed 60% of the Increase in Carbon Emissions of Grain Transport in China over 1990-2015

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Abstract

Rapid urbanisation and population growth have increased the need for grain transportation in China, as more grain is being consumed and croplands have been moved away from cities. Increased grain transportation has, in turn, led to higher energy consumption and carbon emissions. Here, we undertook a model-based approach to estimate the carbon emissions associated with grain transportation in the country between 1990 and 2015. We found that emissions more than tripled, from 5.68 million tons of CO_2e in 1990 to 17.69 million tons in 2015. Grain production displacement contributed more than 60% of the increase in carbon emissions associated with grain transport over the study period, whereas changes in grain consumption and population growth contributed 31.7% and 16.6%, respectively. Infrastructure development, such as newly built highways and railways in western China, helped offset 0.54 million tons of CO_2e from grain transport. These findings shed light on the life cycle environmental impact within food supply chains.

Main

Rapid urbanisation around the world has driven a greater need for grain transport. This could largely be attributed to two reasons. First, the fast-growing urban population simply requires more grain to be transported from rural to urban areas. Second, to feed the growing urban populations, food production is being increased in areas further away from urban consumers as expanding cities swallow up former agricultural land close to them. In many countries, croplands have been displaced from land close to city regions to much more remote, marginal areas due to urbanisation[1,2]. The increasing distance between grain production areas and consumption areas is expected to continue alongside urbanisation throughout the world[3], leading to rising energy consumption and carbon emissions of grain transport.

Carbon emissions involved in food production and transport, which contributes one-third of the total greenhouse gases emissions of human society[3-9], present a serious challenge to achieving carbon reduction targets set out in the Kyoto and Paris Agreements[4]. Transport-related emission accounts for 11% - 20% of carbon emissions of food supply chains[3,7,13-16]. Despite the merit of embedding transport-related carbon emission with the Life Cycle Analysis (LCA) of the food supply chain[17-19], previous studies usually oversimplified the transport process by applying emission factors to food-miles data from existing databases (i.e. multi-regional input-output table) without explicitly investigating the relationship between the spatial flows of food, the transport infrastructure development and the changing distribution of food production and consumptions. As a result, these studies have rather limited capacity to adequately measure the impact of land-use changes on transport-related carbon emissions and provide evidence-based mitigation suggestions.

This research focuses on grain production displacement and the rising carbon emission of grain transport in China during 1990 – 2015. China has experienced rapid urbanisation in the last four decades. Its urban population more than quadrupled from 184.95 million in 1979 to 793.02 million in 2015 (National Bureau of Statistics of China, NBSC[20]); meanwhile, massive former cropland (3.31×10^4 km^2) has been occupied by urban expansion[21,22]. Since 2000, China has implemented a series of cropland protection policies to ensure that the loss of cropland to urban development can be replenished with newly cultivated cropland in areas with lower population density (i.e. cropland displacement). Such policies have generally stabilised the amount of cropland in China; however, they have increased grain production displacement from the core areas of consumption[23]. Given the speed and intensity of urbanisation and grain production displacement in China, carbon emissions associated with grain transport are believed to be growing fast. Although the issues of cropland displacement and transport-related carbon emissions in China have been studied separately[23-30], few studies have focused on the carbon emission associated with grain transport and the emission impact of grain production displacement. Thus the paper explores the nature and magnitude of the increase in carbon emission associated with grain transport in China.

This paper develops a model-based system first introduced by Zuo et al.[31,32] to estimate the carbon emissions associated with the changing transport of grain in China between 1990 and 2015. First, we developed a spatial interaction model (SIM) to estimate the spatial flows of grain (including cereal, tubers and soybeans according to NBSC), disaggregated by transport modal choice, from the changing grain production areas to grain consumption areas at the fine-scale level. Second, based on these estimated spatial flows of grain transport (including the amounts of transported grain, the choices of transport modes and routes), the total carbon emissions produced by the grain transport system during 1990-2015 were estimated and measured by CO_2 emission equivalent ($kgCO_2e$). Lastly, we examined a series of what-if scenarios to reveal the emission impact of grain production displacement, population growth, dietary change, and transport infrastructure development.

Results

Extended Distances between Grain Production and Consumption

Between 1990 and 2015, the population of China grew from 1.13 billion to 1.37 billion[20], while the cropland area grew from 177.15 million hm^2 to 178.51 million hm^2 (ref.[33]). Although neither the population nor the cropland area has increased much (in relative size), their spatial distribution has varied considerably (Extended Data Fig 3a and b). We adopted the Local Indicators for Spatial Association (LISA[34]) analysis to explore the spatial patterns of the changing distribution of population and cropland during the 25 years (Fig 1a and b). Fig 1a indicates significant population growth in the southeast coastal areas and significant population decreases in the northeast and central regions. Fig 2b indicates significant cropland expansion occurred in Northeast and Northwest China, and significant cropland shrinkages occurred in Central and Eastern China during the same period. The spatial shift of population and cropland extended the distance between grain production and consumption. We measured the distance between the mean centres (Methods Equation [2]) of the cropland and the population at both national and prefecture levels. At the national level, the mean centre of cropland moved 62.53 km north, while the mean centre of population moved 17.91 km south. As a result, the distance between the national mean centres of cropland and of population extended from 260.41 km to 320.66 km between 1990 and 2015 (Extended Data Fig. 1). At the prefectural level, the average distance between the mean centres of population and cropland increased from 10.89 km to 12.59 km during the 25 years; and 251 out of 347 (approx. 72%) prefectures, which cover 80% of the population in China experienced a trend of separation between population and cropland (Fig.1 c and d).

We estimated the demand for grain by prefectures in 1990, 2000, 2005, 2010 and 2015 based on three types of grain consumption: staples, animal feed, and industrial & other uses (e.g. grain-based snacks and alcoholic drinks; Extended Data Fig. 2a; Methods Equation [1]). Results indicate a transformed grain consumption pattern due to the changing dietary structure during this period. First, grain consumption of staples dropped nearly 30% from 281.44 million-ton in 1990 to 182.42 million-ton in 2015 despite the population growth. Second, grain consumption for feeding animals more than doubled from 110.52 million-ton to 263.89 million-ton, which outranked staples as the second largest type of grain consumption in 2015. Lastly, industrial & other uses of grain also increased from 66.80 million-ton to 315.68 million-ton.

Overall, grain production in China grew from 468.01 million-ton to 484.02 million-ton to 648.06 million-ton from 1990, 2005, to 2015; while grain imports increased from 12.53 million-ton to 32.86 million-ton to 114.39 million-ton (Extended Data Fig. 2b). Spatial distributions of domestic grain production at the prefecture-level show that, as a result of grain production displacement towards "marginal land"[35], the increase in grain production occurred primarily in the north, northeast and northwest of China (Extended Data Fig. 3 b & c). In comparison, the increase in grain demand mainly occurred in the east and southeast of China (Extended Data Fig. 3 e & f). Compared to 1990, the whole country relied more on grain supplies originating in northern China and overseas by 2015 (Fig. 1 e & f). The distance between national mean centres of grain production and consumption extended from 178.54km to 328.93km. Considering the increasing proportion of imported grain (mainly from the Americas) in China's grain market, the average transport distance for the grain consumed in China extended even further.

Spatial Flows of Grain Transport

Harnessing the doubly constrained SIM (Methods Equation [3]-[8]) and integrated transport network data (including road, railway, and waterway), we estimated the spatial flows of grain transport among prefectures of China (including both intra-prefecture and inter-prefecture flows) in 1990, 2000, 2005, 2010 and 2015. Extended Data Fig. 6 shows the provincial-level grain flows in those years which were aggregated from the prefecture-level flows. The modelling results suggest that the scale of inter-provincial grain flows grew from 89.72 million-ton to 265.43 million-ton (including the imported grains); the entire country, especially the East and Central-South provinces which are more reliant on the imported grains. The general pattern of grain transport turned more north-to-south than east-to-west (Fig.2). In 1990, the provinces in Northeast China were the major grain suppliers for the North and Northwest of China, while the Eastern provinces of China were the major suppliers for central and southern China. In 2015, Neimenggu (Inner-Mongolia) outranked Liaoning as the third-largest grain supplier in northern China after Heilongjiang and Jilin. Hunan and Hubei Provinces' role as major grain suppliers in central China declined, while Henan became the biggest supplier in the Central-South region. Provinces in the East of China (i.e. Zhejiang and Jiangsu) turned from net grain exporters to net importers. In Guangdong and Guangxi, two of the most southern provinces in Chinese mainland, the self-sufficiency rate for grain supply dropped from nearly 70% to less than 40%. These changes reflect the fact that grain production in China has been moving northward (and toward overseas), and the transport distances have been extending during this 25-year period.

A breakdown of the inter-provincial flows of grain by the three transport modes (Fig 4) shows that the railway has been the most critical transport mode for supplying grain to Southwest China and that grain from the northeast dominated the market share of grain transported by railway. Due to the railway network development in Northwest China since the early 2000s, grain exported from Xinjiang Province has been one of the most significant changes in grain transport by railway between 1990 and 2015. The waterway mode of transport was mostly responsible for transporting grain from Northeast and East China to East and Central-South China. Guangdong Province was the largest destination for waterway-transported grain in 1990 (accounting for 12% of the total waterway transported grain). However, in 2015, this position was taken by Zhejiang province (accounting for 23%). Road transport was mainly used for short-distance transport within all regions. Inter-regional grain transport by road was relatively small in 1990; however, it became more common in 2015 due to the increasing distances between grain production and consumption.

Carbon Emissions Associated with Grain Transport

Based on the modelled spatial flows of grain transport and the carbon emission conversion factors of different transport modes, we estimate that carbon emissions associated with grain transport in China more than tripled from 5.64 million-ton in 1990 to 17.75 million-ton in 2015. The most significant contributor was maritime transport for imported grain which increased nearly tenfold from 0.85 million-ton to 8.77 million-ton. In terms of domestic transport, the greatest contributor would be the grain transported by railway, which increased 2.86 times from 1.31 million-ton to 3.77 million-ton. The carbon emissions of road transport nearly doubled from 2.60 million-ton to 4.99 million-ton. The inland and coastal waterway contributed the least proportion of carbon emissions, which grew from 0.88 million-ton to 0.99 million-ton (Fig 4a).

From the perspective of grain consumption structure, the carbon emission of transported staple grain increased by 32% (from 3.41 million-ton to 4.51 million-ton) between 1990 and 2015, which is much lower than transported animal-feed grain (373.86%) and grain for industry and other uses (978.82%) (Fig. 4b).

We further break down the change in grain transport-related carbon emissions to the provincial level. Gansu is the only province (among the total of 32 provinces/municipalities) that experiences a reduction in carbon emissions of grain transport in China between 1990 and 2015 (green-coloured areas in Fig 4c). The grain transport-related carbon emission increase is generally higher in the south and east of the country than in the north and west.

We applied a multi-scenario analysis to identify the impacts of multiple factors on grain transport carbon emissions (see Fig 5a). Specifically, we built a baseline scenario where the production, consumption of grain and transport infrastructure varies as in the real world and two alternative scenarios which control the grain consumption structure and transport network respectively (please refer to the Scenario Analysis in the Method section for more details). By comparing the modelling results under different scenarios, we found that grain production displacement domestic and overseas contributed 7.88 million-ton, accounting for 67.11% of the increased carbon emissions in China between 1990 and 2015. The change of grain consumption structure and population growth contributed 2.87 million-ton (24.44%) and 1.19 million-ton (10.10%), respectively. However, the development of transport infrastructures, such as newly built highways and railways in western China, helped reduce 0.32 million-ton of carbon emissions associated with grain transport, equivalent to nearly one third of the increment related to population growth (see Fig 5a).

At the provincial level, there were 24 (out of 31) provinces or municipals where the grain production displacement contributed the most to the increase in grain transport-related carbon emission (beige-coloured areas in Fig 5b). The grain consumption structure change primarily drove the increase in transport-related carbon emissions in 5 provinces (orange-coloured areas in Fig 5b). The rise in meat production in these provinces has led to a considerable growth in demand for feed grains, which greatly increased the carbon emissions associated with grain transport accordingly. Population growth was the primary driver of the increase in grain transport-related carbon emissions in Ningxia province (red-coloured area in Fig 5b), whereas in Gansu, (green-coloured area in Fig5b) transport infrastructure development (e.g. the highway and railway network in northwest and southwest China) was the primary reason that caused a reduction in grain transport-related carbon emission during 1990-2015.

In order to explore the implications of the grain-transport-related carbon emissions on the land-use policies in China, we also estimated the carbon intensity (kg CO_2 emission equivalent per ton of grain) of grain transport at both national and prefecture levels. At the national level, grain for industrial & other uses had the highest transport-related carbon intensity, which grew from 12.20 kgCO_2e/ton to 25.28 kgCO_2e/ton between 1990 and 2015. Meanwhile, the carbon intensities for transported staple grains and animal-feed grains also grew from 12.12 kgCO_2e/ton and 12.75 kgCO_2e/ton to 24.70 kgCO_2e/ton and 19.97 kgCO_2e/ton respectively. We further disaggregated the grain transport-related carbon intensity to the prefecture level on both the production and consumption sides (Methods equation [16] and [17]). The model results suggest that grain consumed in prefectures in the south and east coastal areas had higher transport-related carbon intensities than in other parts of China, except Xizang (Tibet) and Qinghai Provinces in the Qinghai-Tibet Plateau, which has a harsh environment for grain production and relatively poor transport infrastructure (Fig. 6a). For instance, the average transport-related carbon intensity of grain consumed within the south-coastal Guandong Province (58.32 kgCO_2e/ton) was almost four times higher than that in Hubei Province in Central China (15.00 kgCO_2e/ton). On the supply side, the transport-related carbon intensity of grain produced in prefectures in northern China is estimated to be generally higher than in southern China (Fig. 6b). For instance, the average transport-related carbon footprint of grain produced in the northeastern Province of Heilongjiang (37.68 kgCO_2e/ton) was 15.63 times more than that in the southern province of Hainan (2.41 kgCO_2e/ton). This result reflects the fact that the Northeast China is the traditional grain-export region of the country. Extended Data Table.2 summarises each province's average transport-related carbon intensity of grain by production and consumption.

Discussion and Conclusion

China is facing dual challenges of reducing carbon emissions and feeding the largest population in the world[36,37]. On the one hand, the country has announced its ambitious national strategy to achieve peak carbon emissions by 2030 and to be carbon neutral by 2060[38]. A series of carbon emission targets have been set up in its 14th five-year plan (2021-2025)[39]. The agriculture department plays a key role in achieving carbon emission targets. However, the extended distance of grain transport and the associated rising carbon emissions have not received sufficient attention. In this research, we found that 72% of prefectures in China experienced a greater separation between their population centres and the cropland centres that feed them. This distance between the national mean centres of grain production and consumption extended by 150.39 km during 1990 - 2015. The fast-growing demand for imported grain has further increased the total transport distance of grain consumed in China. Consequently, as we estimated, the total carbon emissions of grain transport more than tripled during the 25 years.

On the other hand, securing the food supply to its growing population has been a long-standing challenge for China. To maintain self-sufficiency, China has endeavoured to keep its total amount of cropland despite the great pressure of rapid and massive urbanisation. One of the consequences has been cropland and grain production displacement2[2,40], which, as we estimate, contributed more than 60% of the increase in carbon emissions of grain transport between 1990 and 2015. In 2018, a revised cropland protection policy was introduced in China to allow cross-provincial cropland displacement (before that, displacement must be fulfilled within the same province). This new policy is expected to intensify grain production displacement across the country[23,41] and further increase carbon emissions of transporting grain from production to consumption areas. Here we argue for more synergic considerations of the emission impact of increasing the food-miles in agricultural policies. Based on this research, we provide the following policy suggestions for reducing the carbon emissions of grain transport in China.

First, we found that the eastern and southern coast of China with the highest population density have almost the highest transport-related carbon intensity for grain consumption, whereas areas with the highest grain output have the highest transport-related carbon intensity for grain supply. In comparison, central China (e.g. Hubei and Henan Province) has relatively low transport-related carbon intensity on both supply and consumption sides; however, both the proportions of grain output and the population of central China to the whole country declined during 1990 - 2015. We, therefore, suggest that encouraging and facilitating the development of central China as a major grain production or economic centre with a higher population density could help reduce the total gain transport distance and associated carbon emissions.

Second, our model results show that the change in gain consumption structure contributed 24.44% of the increase in grain transport carbon emissions in China between 1990 and 2015. Although the environmental impacts of food consumption structure change in China is not a new topic[42,43], we provide new insights from the different perspectives of its impact on grain consumption and transport. Our results show that the fast-growing grain consumption for feeding animals and industrial & other uses has been accompanied with rising transport-related carbon intensity, indicating that more meat and grain-based snacks are consumed in modern China. Given that meat, snacks, and alcoholic drinks are usually with much higher added value than staple grains, we suggest that building a more localised supply chain for those high added value commodities at the downstream value chain of grain production could both benefit local economies and help reduce carbon emissions related to grain transport. This echoes the 'local food' movement in some western countries[44-47].

Third, we found that the improvement of transport infrastructure, especially the development of the railway network in western China, had offset part of the increased grain transport carbon emissions driven by grain production displacement, change of consumption structure, and population growth. Since the carbon emission per ton-km of railway and waterway transport is much lower than that of road transport, we suggest that further increasing railway & waterway transport capacity is important for reducing the pressure of rising emissions from grain transport. Moreover, as the carbon-intensive road transport contributed nearly 50% of the domestic grain transport emissions in 2015, and its market share of long-distance grain transportation has been increasing between 1990 and 2015, we also argue that technological evolution in clean energy and electric high gross vehicles can play an important role in reducing the grain transport-related emissions in the future.

Lastly, our modelling results indicate that maritime transport for imported grain contributes the most significant part of the carbon emissions of grain transport. China's massive demand for grain import has drawn controversy both domestically for concerns about national food safety and internationally for related environmental impact in grain export countries. This study contributes new insights to the impact of grain import from the perspective of transport-related carbon emissions. However, we would like to caution against the seemingly tempting conclusion that grain import should be replaced by domestic production because a massive increase in grain production within China could 1) be simply impossible given China's land, water, and ecosystem capacities; 2) require higher volume of inland transport with much higher carbon emission intensity than maritime transport; and 3) lead to further cropland displacement which in turn increase the total transport-related carbon emissions. Future research is needed to comprehensively and systematically examine the environmental impact of the grain supply chain not only in China but also in relevant grain export countries to provide mitigation suggestions from the global perspective.

Grain production displacement is not a unique phenomenon in China but a common issue in many countries across the world[1,2]. The negative environmental impacts of grain production displacement need to be taken better account of in land use and agriculture policy-making practices. This paper demonstrates a systematic evaluation framework to estimate the carbon emissions of grain transport and identifies the emission impact of grain production displacement as well as other factors. Although a few simplified assumptions were adopted in the modelling process, our estimation results of the increased food miles (ton-km) and related carbon emissions were validated through robust model calibration and a Monte Carlo simulation-based sensitivity analysis to check the potential uncertainty introduced with the input parameters (Supplementary Fig. 3). In a wider context, our research findings contribute to a better understanding of the life cycle environmental impact within the food supply chain. The methodology proposed in this study is applicable to a wide range of other commodities that involve trans-regional production and consumption, both in China and other countries.

Methods

Modelling Framework

Modelling grain transport, in terms of flow and transport mode, based on the distribution of supplies and demands is essential for understanding the impacts of urbanisation and cropland displacement on grain transport. Since the 1950s, many efforts have been made to model commodity or population flows between places, including multi-regional input-output models[48], linear programming[49, 50], spatial price equilibrium models[51,52], and SIM[31,32,53,54]. In transport geography, SIM are the most commonly used approach for modelling the flows of freight or people between locations based on the distribution of supply and demand.

Extended Data Fig.4 illustrates the modelling framework we applied to estimate the carbon emissions associated with grain transport in China. We first estimated the grain supply and demand of China at the prefecture level, then adopted the descriptive spatial statistics methods to reveal the spatial distribution of grain supply and demand over time. Then, we identified the shortest route between each pair of sources of grain supply and demand in China by three different transport modes: road, railway and waterway (including both inland waterway and coastal transport by sea), and estimated the transport costs between each pair of supply and demand based on the distance and the corresponding transport mode. As a full interaction matrix of real grain flows was not available from published data, a doubly constrained SIM was adopted to generate the spatial flows of grain between prefectures according to the transport cost, grain production levels at the origin and grain consumption levels at the destination, whereby the ton-km of grain between each pair of prefectures in China was estimated. Then, we estimated the carbon emissions of grain transport for each possible origin-destination pair of prefectures based on the ton-km of grain, the corresponding transport modes and carbon emission conversion factors. Finally, we applied a what-if scenario analysis to identify the impacts of multiple factors (e.g. cropland displacement, development of transport infrastructure) on carbon emissions of grain transport at the prefecture level. Details of each step are explained as below.

Exploring Spatial Distribution of Grain Supply and Demand 1990 – 2015

The grain demand of each prefecture was estimated based on three types of grain consumption: staples, animal-feed, and industrial & other uses. The staple grain consumption was estimated based on the number of urban and rural residents in each prefecture. The animal-feed grain consumption was estimated by applying statistics on the production of meat to the corresponding grain-to-meat ratios. Due to the lack of relevant official statistics data, the grain for industrial and other uses was estimated by applying a fixed ratio factor to the population. Thus, the consumption of grain for each prefecture was calculated as equation [1].

$$D_j = {}^{I}GR * Pop_j + {}^{R}_{U}GR * {}_{U}Pop_j + {}^{R}_{R}GR * {}_{R}Pop_j + {}^{F}_{P}GR * {}_{P}Mt_j + {}^{F}_{O}GR * {}_{O}Mt_j \quad [1]$$

where Pop_j, ${}_{U}Pop_j$, and ${}_{R}Pop_j$, are the total population, urban population, rural population in prefecture j; ${}_{P}Mt_j$ and ${}_{O}Mt_j$ represent the meat outputs in prefecture j; the urban and rural population, pork and other meat output of each prefecture in 2000, 2005, 2010 and 2015 were obtained from the statistical yearbook of each province. The corresponding numbers for 1990 were extracted from the 1990 census and 1990 agricultural survey. ${}^{R}_{U}GR$ and ${}^{R}_{R}GR$ are the staple grain consumption per capita for urban residents and rural residents, respectively, which are collected from the Statistical Yearbook of China. ${}^{F}_{P}GR$ and ${}^{F}_{O}GR$ represent the feed conversion rate for pork and other meat. ${}^{I}GR$ represents the grain for industry (and other uses) per capita, the value was estimated based on the grain balance equation [2]:

$${}^{D}S + {}^{I}S = \sum D_j + E \quad [2]$$

where ${}^{D}S$ and ${}^{I}S$ represent the total domestic grain supply and imported grains, E represents the grain export for the year. Since the domestic grain supply, grain import and export are available in the statistic yearbook of China, the only unknown value ${}^{I}GR$ can be solved. Extended Data Table 1 summarises the key metrics and the data source of this research.

We adopted the mean centre approach to explore the change of spatial pattern of grain supply and demand (as well as the cropland and population, Extended Data Fig. 1); the mean centre is expressed as equation [3]:

$$\bar{s} = \left(\mu_x, \mu_y\right) = \left(\frac{\sum_{i=1}^{n} x_i W_i}{\sum_{i=1}^{n} W_i}, \frac{\sum_{i=1}^{n} y_i W_i}{\sum_{i=1}^{n} W_i}\right) \quad [3]$$

where $\bar{s}$ represents the mean centre of grain supply or demand, the coordinates are denoted as μ_x and μ_y; x_i and y_i are the coordinates of the county i, and the weighting factor W_i represents the grain supply or demand at the county i.

The same approach was applied to obtain the prefecture-level centroids of grain supply and demand. Thus, the transport distance in this research means the distance of the lowest-cost path between the mean centres of grain supply and demand at the prefecture level. More details regarding the transport modal choice cost and measurement issues are discussed in the next section.

Modelling the Modal Choice and Transport Cost

In this study, we considered three major ways to transport domestic grain (Extended Data Fig. 5). 1) pure road transport: grain was transported by High Gross Vehicles (HGV) directly from the origin to the destinations via the road network; 2) road – railway transport: grain was first transported from the origin to the closest railway station by road, then carried by train to the destination railway station, followed by road transport to the final destination; 3) road-waterway transport: similar to the road - railway transport, this type of transport trip included road transport between origin/destination and the wharves plus waterway (including both inland waterway and the coastal seaway) transport between wharves[55]. With the transport network data, we estimated transport costs between each pair of origin and destination by three different modes (i.e. pure road, road-railway and road-waterway). Then we picked the transport mode with the lowest cost as the modal choice for the specific grain transport trip (Equation [4] – [6]). For import/export grains, we modelled the transport route as two legs: maritime transport between the overseas supply/demand and one of the 14 harbour cities (prefectures) in China by bulk carriers and inland transport as domestic grain (Equation [7]). By abstracting the overseas source of supply and demand as a virtual offshore location, we can integrate the transport for both domestic grain and import/export grain into a unified transport model (Extended Data Fig. 5).

For simplicity, the transport cost is measured by road distance equivalent, which consists of two parts: the variable cost relevant to the transport distance and the transport mode; and the fixed cost incurred during the transshipment process. Since the transport cost via railway and waterway were generally lower than road for the same distance, we introduced relative costs ratio (RCs) to convert the railway and waterway distance to the road distance equivalent, so the transport costs for three different modes are comparable. In addition, we introduced transshipment costs (TCs) as fixed (irrelevant to the distance) costs when changing transport mode at train stations or wharves. The transport model is expressed as equation [4] – [7].

$$d_{ij} = \min\left(d_{ij}^{RD}, d_{ij}^{RD-RL}, d_{ij}^{RD-WT}\right), \qquad i,j \in [1{,}347] \qquad [4]$$

$$d_{ij}^{RD-RL} = d_{im}^{RD} + TC^{RL} + RC^{RL} * d_{mn}^{RL} + d_{nj}^{RD}, \quad i,j \in [1{,}347] \qquad [5]$$

$$d_{ij}^{RD-WT} = d_{ip}^{RD} + TC^{WT} + RC^{WT} * d_{pq}^{WT} + d_{qj}^{RD}, \quad i,j \in [1{,}347] \qquad [6]$$

$$d_{ij} = d_{ic} + TC^{WT} + d_{cj}, \quad i = 348 \; or \; j = 348 \qquad [7]$$

Where d_{ij} represents the transport cost between location i and j, superscripts RD, RL and WT indicate road, railway, and waterway, respectively. Thus d_{ij}^{RD} represents the cost between location i and location j by road transport, and d_{ij}^{RD-RL} and d_{ij}^{RD-WT} represent the cost by road-railway and road-waterway mode, respectively. Subscript m and n are the identifiers of train stations. Thus d_{im}^{RD} represents distance between the location of origin i to the nearest train station m (or wharf p), and d_{nj}^{RD} is the distance between the destination location j and the nearest train station n (equation [5]). A similar method was applied to represent the road-waterway mode using subscriptions p and q to identify wharves (equation [6]).

Since the number and the boundary of prefectures in China varied over time, we chose the 2010 prefecture boundary data as the basic unit to ensure consistency and make the results comparable. There are 347 prefectures in China and an extra virtual source of supply/demand overseas, the transport cost d_{ij} can be represented as a 348 x 348 matrix. When $i,j \in [1{,}347]$, d_{ij}represents the cost of domestic grain transport. The diagnose value of the matrix represents the cost of intra-prefecture transport, which is measured by the average distance between the counties within the prefecture by road transport. When i = 348, d_{ij} represent the transport cost for imported grain; d_{ic} represents the cost of maritime transport from the virtual overseas location of supply to one of the harbour prefectures in China; and d_{cj} represents the inland transport cost between the harbour prefecture to the final destination (i.e. prefecture j), which can be estimated based on Equation [4]-[6]. And when j =348 d_{ij} indicates the transport cost for export grain, d_{ic} indicates the inland transport and d_{cj} indicates the cost of maritime transport. The ESRI ArcGIS software was implemented to conduct these analyses.

RC^{RL} and RC^{WT} are the two relative cost converters for railway and waterway, respectively. Considering the transport cost per ton-km for railway and waterway are lower than for road transport, these two relative cost converters need to be smaller than 1. TC^{RL} and TC^{WT} are the transhipment costs for railway and waterway. The exact values for RCs and TCs were calibrated against the official transport statistics (e.g. average distance and market-share of railway or waterway transport etc., Supplementary Table 1), the calibration process is described in the Model Calibrating section in Supplementary Information.

Modelling the spatial flows of grain in China

We adopted a doubly constrained SIM[53] to estimate the volume of grain transported between each pair of supply and demand prefectures. The SIM allocates the flows when both the grain supply and demand of each prefecture (or the virtual source of supply/demand overseas) are known or estimated). This can be expressed as the equations below:

$$\widehat{m}_{ij} = A_i O_i B_j D_j f(d_{ij}),\ \ (i,j = 1,2,3 \ldots.r) \quad [8]$$

$$\sum_j \widehat{m}_{ij} = O_i, \qquad (j = 1,2,3 \ldots.r) \quad [9]$$

$$\sum_i \widehat{m}_{ij} = D_j, \qquad (i = 1,2,3 \ldots.r) \quad [10]$$

$$A_i = \frac{1}{\sum_i B_j D_j f(d_{ij})}, \qquad (i = 1,2,3 \ldots.r) \quad [11]$$

$$B_j = \frac{1}{\sum_j A_i O_i f(d_{ij})}, \qquad (j = 1,2,3 \ldots.r) \quad [12]$$

$$f(d_{ij}) = \exp(-\beta \cdot d_{ij}) \quad [13]$$

where $\widehat{m}_{ij}$ in equation [8] represents the volume of grain transported from location i to location j; O_i represents the output of grain at the source of supply i, and D_j represents the demand for grain at location j. d_{ij} is the integrated transport cost of grain moved from location i to location j, which was estimated by the transport model (Equation [4]-[7]). Both the equations [9] and [10] show how the SIM is doubly constrained at both the supply and demand sides. A_i and B_j are balancing factors to ensure the equation [9] and [10] hold. Since A_i and B_j are dependent on each other, Equation [11] and [12] are solved iteratively. The unknown parameter β was calibrated with the RCs and TCs together against the observed transport statistics (Please refer to the Model Calibrating section in the Supplementary Information).

Estimating Carbon Emissions

The carbon emission associated with the transport of grain was estimated based on the ton-km of grain transported by each transport mode multiplied by the corresponding carbon emission conversion factor (equation [14] - [17]).

$$C_{ij}^T = \widehat{m}_{ij} * d_{ij}^{RD} * CF^{RD} + \widehat{m}_{ij} * d_{ij}^{RL} * CF^{RL} + \widehat{m}_{ij} * d_{ij}^{WT} * CF^{WT} \quad [14]$$

$$\mathrm{C}^T = \sum_i^n \sum_j^n C_{ij}^T \quad [15]$$

$$^{D}C_j^T = \sum_i^n \mathrm{C}_{ij}^T \quad [16]$$

$$^{S}C_i^T = \sum_j^n \mathrm{C}_{ij}^T \quad [17]$$

where C_{ij}^T Equation [14] represents the carbon emission associated with grain transport from prefecture i to j. C^T, $^{D}C_j^T$ and $^{S}C_i^T$ in Equation [15] – [17] represent the total grain transport related carbon emission and those carbon emissions by prefecture from demand and supply perspectives. Thus, we can further break down the grain transport-related carbon emission of by different use of grain (Equation [18] – [20]):

$$^{R}C_j^T = {}^{D}C_j^T * ({}^{R}_{U}GR * {}_{U}Pop_j + {}^{R}_{R}GR * {}_{R}Pop_j)/D_j \quad [18]$$

$$^{F}C_j^T = {}^{D}C_j^T * ({}^{F}_{P}GR * {}_{P}Mt_j + {}^{F}_{O}GR * {}_{O}Mt_j)/D_j \quad [19]$$

$$^{I}C_j^T = {}^{D}C_j^T * {}^{I}GR * Pop_j/D_j \quad [20]$$

where $^{R}C_j^T$, $^{F}C_j^T$ and $^{I}C_j^T$ indicate the transport-related carbon emission of grain for staple, animal feed and industry & other uses. In this paper, we only estimated the carbon emission of grain transport; thus, the transport-related carbon emission for feed grains only involved the transport of grain from the croplands to the animals. Meat transport is beyond the scope of this research.

CF represents the carbon emission conversion factors, the superscripts RD, RL and WT denote the transport modes of road, railway, and waterway. Due to the lack of officially published carbon emission conversion factors in China, the CF values were extracted from GHG Conversion Factors 2015, published by the Department of Energy and Climate Change UK[56] and widely used in assessing CO_2 and other greenhouse gas emissions by different industry sectors. Considering that the auto emission standards adopted in China (National Standards IV in 2015) are equivalent to the UK standards (Euro IV in 2015) since 2000, it is reasonable to use the UK GHG Conversion Factors to proximate the corresponding factors in China. Extended Data Table 3 shows the conversion factors for each transport mode.

Scenario Analysis

From a transport geography perspective, transport flows are basically determined by three factors: the locations of supply and demand areas, the volume of goods to be transported, and the transport network[57,58]. Thus, it is reasonable to assume that the difference in carbon emissions of grain transport in China between 1990 and 2015 could be mostly attributed to the following factors, i.e. grain production displacement, change in demand for grain (due to changing population and grain consumption structure) and development of transport infrastructure.

It was difficult to quantify the consumption structure change and infrastructure development directly; To identify the impacts of these three factors on carbon emissions, we adopted a what-if scenario simulation approach. We built two alternative scenarios along with the baseline scenario, where we assume all the factors vary as in the real world. For each alternative scenario, we control one factor and allow the other two to vary through time as the baseline scenario. By comparing the modelling results between the baseline and the alternative scenarios, the impacts of different factors can be identified. The baseline scenario and two alternative scenarios are specified as follows:

- Baseline Scenario: all three factors, i.e. distribution of grain production, grain consumption structure, and transport infrastructure development, were modelled based on the observed data from 1990 and 2015.

- Alternative Scenario 1 "unchanged transport network" scenario): we assumed the transport infrastructure remained as in 1990, while the other two factors changed as the Baseline Scenario. Under this scenario, we generated the transport cost matrix for 1990 and 2015 based on the transport network of 1990 and modelled the grain flows with the exact cost matrix.

- Alternative Scenario 2 "unchanged grain consumption structure" scenario): we assumed the grain consumption structure (the per capita demand for three types of grain) for urban and rural residents remained as in 1990, while the other two factors changed as the Baseline Scenario. We estimated the demand for grains in 1990 and 2015 by prefecture based on the assumption and modelled the flow of grain flows with the assumed consumption structure.

The differences in the modelling results between the baseline scenario and the "unchanged transport network" scenario revealed the impact of transport infrastructure development on grain transport carbon emission. And the difference between the baseline scenario and the "unchanged consumption structure" scenario identified the contribution of the change in grain consumption structure to transport-related carbon emission. Then the rest of the increment of grain transport carbon emission between 1990 and 2015 was attributed to grain production displacement.

Data Sources

The grain supply for China includes the grain produced domestically and those imported from overseas. The domestic grain supply of each prefecture in 1990 was aggregated from China County-Level Data on Population and Agriculture, Keyed 1:1M GIS Map[59]. The grain output of each prefecture in 2000, 2005, 2010 and 2015 was extracted from the yearbook of each province. According to the NBSC, the vast majority of the imported grain are soybeans from the Americas (e.g. Brazil and the U.S.); considering the average international transport distance of the imported grain of China[15], the source of imported grain was abstracted into a virtual point, which is 20000km east of the coast of China. The administrative boundary data of China were obtained from China Data Lab[60]. The transport network data for different years were extracted from CIESIN[61] and OpenStreetMap. The volumes of imported and exported grain for each year was collected from the NBSC[20].

Uncertainty and Sensitivity Analysis

Considering the uncertainty that might be introduced by the conversion factors, we adopted a Monte Carlo simulation-based sensitivity analysis to investigate the robustness of the modelling results. The process of the sensitivity analysis is reported in the Sensitivity Analysis section in the Supplementary Information.

Data Availability

All the data used in this study are publicly available; see Methods and Supplementary Information for descriptions of the source data. Source data are provided with this paper.

Code Availability

The custom code and algorithm used for this study are available in Methods and Supplementary Information.

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Author Contribution Statement

C.Z. and X.K. conceptualized and designed the study. C.Z. and L.T. collected the original data. C.Z. developed model framework and compiled the figures. C.Z. and C.W. interpreted the data and analysed the results. C.Z. drafted the manuscript and C.W., G.C., Y.L. and A.T. reviewed the manuscript and contributed to the revisions.

Competing Interests Statement

The authors declare no competing interests.

Tables

Figure Captions

Fig.1 Change of Grain Production and Consumption in China (1990-2015): *a) The Local Indicators for Spatial Association (LISA) map of population growth by county, b) LISA map of the change of cropland area by county, c) Change of distance between the mean centres of population and cropland at the prefectural level; d) Cartogram of the change of distance between the mean centres of population and cropland (rescaled by the population of each prefecture); e) net-flow (production-consumption) of grain at the prefecture level in 1990, green tones indicate net-exporters, while yellow to red tones indicate net-importers; and f) net-flow of grain at the prefecture level in 2015.*

Fig.2 Inter-provincial Flow of Grain Transport in China (1990 and 2015). *Each arc on the outer ring indicates a province, coloured by the region. The length of the arc represents the grain flux (inflow + outflow) of the province. The ribbons between the two arcs represent the grain flows between the export provinces and the import provinces, and the colour of each ribbon matches the colour of the export province. The width of the ribbon indicates the volume of the transported grain.*

Fig.3 Inter-provincial Flow of Grain by Transport Mode in 1990 and 2015. *Each arc on the outer ring indicates a province, coloured by the region. The length of the arc represents the grain flux (inflow + outflow) of the province. The ribbons between the two arcs represent the grain flows between the export provinces and the import provinces, and the colour of each ribbon matches the colour of the export province. The width of the ribbon indicates the volume of the transported grain.*

Fig. 4 Change in Carbon Emissions (million tons CO_2e) of Grain Transportation. *a) Grain Transport-related Carbon Emissions by Transport Mode 1990-2015; b) Grain Transport-related Carbon Emissions 1990-2015 by Use of Grain; c) Change in Grain Transport-related Carbon Emissions 1990-2015 by Province, China.*

Fig.5 Driving Factors of Increased Carbon Emission. *a) Drivers of increased carbon emission of grain transport (million tons CO_2e) at national level; b) primary drivers of the changes in grain transport-related carbon emissions (million tons CO_2e) at provincial level; c) contribution of different factors to the changes in grain transport-related carbon emission (million tons CO_2e) by province*

Fig.6 Transport-related Carbon Intensity (kgCO_2e/ton) at the Prefecture Level (2015) *from: a) grain consumption perspective, and b) grain production perspective*

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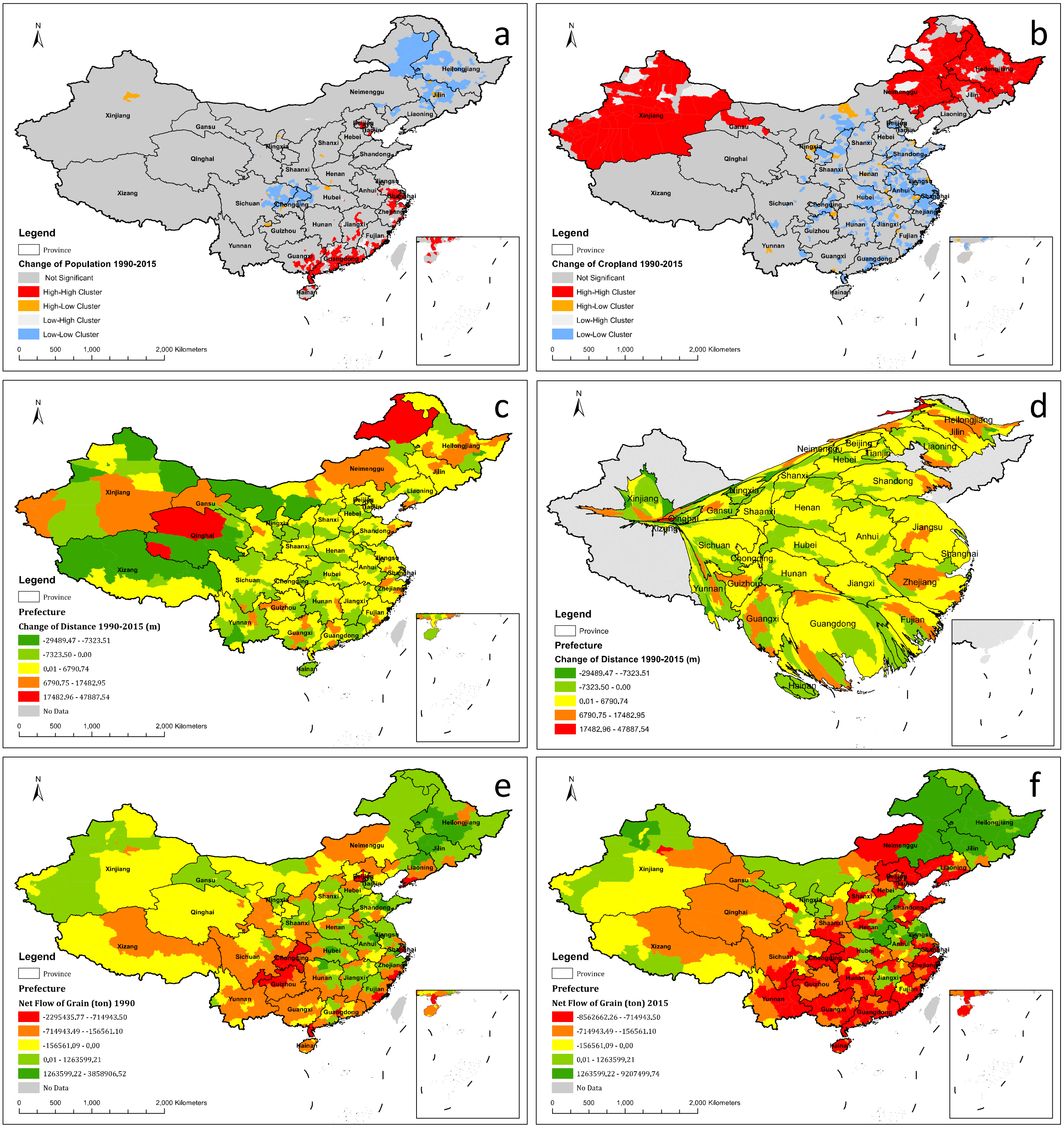
a
Legend
Province
Change of Population 1990-2015
Not Significant
High-High Cluster
High-Low Cluster
Low-High Cluster
Low-Low Cluster
0 500 1,000 2,000 Kilometers
b
Legend
Province
Change of Cropland 1990-2015
Not Significant
High-High Cluster
High-Low Cluster
Low-High Cluster
Low-Low Cluster
0 500 1,000 2,000 Kilometers
c
Legend
Province
Prefecture
Change of Distance 1990-2015 (m)
-29489.47 - -7323.51
-7323.50 - 0.00
0.01 - 6790.74
6790.75 - 17482.95
17482.96 - 47887.54
No Data
0 500 1,000 2,000 Kilometers
d
Legend
Province
Prefecture
Change of Distance 1990-2015 (m)
-29489.47 - -7323.51
-7323.50 - 0.00
0.01 - 6790.74
6790.75 - 17482.95
17482.96 - 47887.54
e
Legend
Province
Prefecture
Net Flow of Grain (ton) 1990
-2295435.77 - -714943.50
-714943.49 - -156561.10
-156561.09 - 0.00
0.01 - 1263599.21
1263599.22 - 3858906.52
No Data
0 500 1,000 2,000 Kilometers
f
Legend
Province
Prefecture
Net Flow of Grain (ton) 2015
-8562662.26 - -714943.50
-714943.49 - -156561.10
-156561.09 - 0.00
0.01 - 1263599.21
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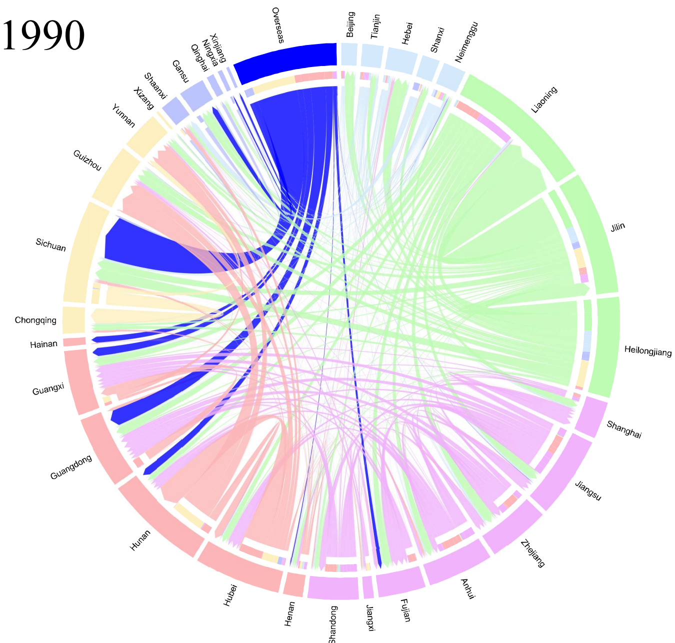
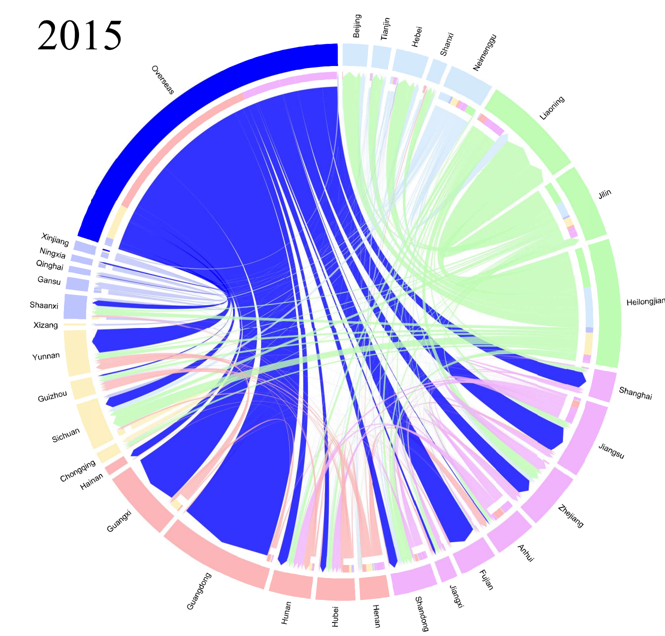
No Data
0 500 1,000 2,000 Kilometers

1990

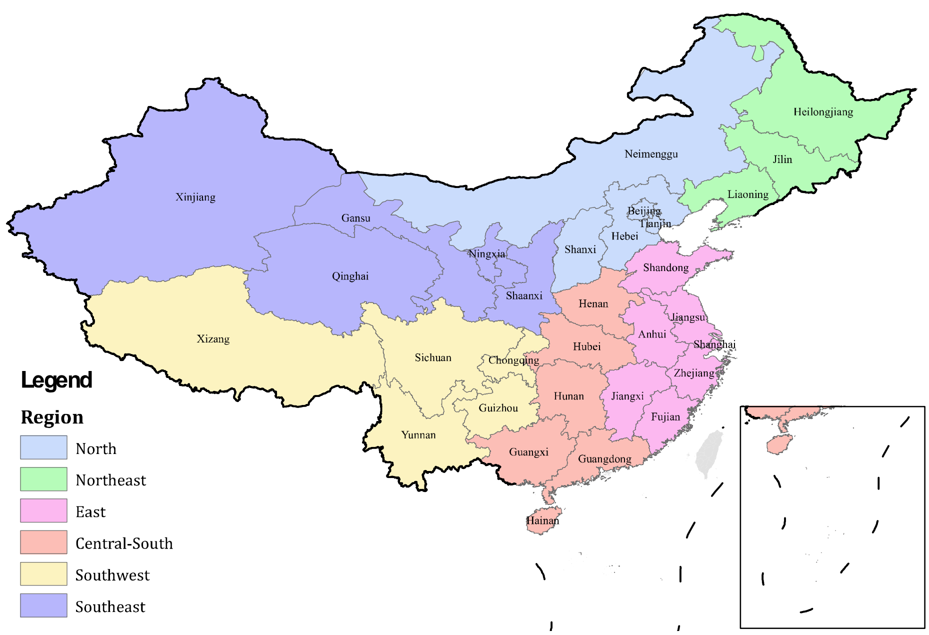


Overseas
Beijing
Tianjin
Hebei
Shanxi
Neimenggu
Liaoning
Jilin
Heilongjiang
Shanghai
Jiangsu
Zhejiang
Anhui
Fujian
Jiangxi
Shandong
Henan
Hubei
Hunan
Guangdong
Guangxi
Hainan
Chongqing
Sichuan
Guizhou
Yunnan
Xizang
Shaanxi
Gansu
Qinghai
Ningxia
Xinjiang

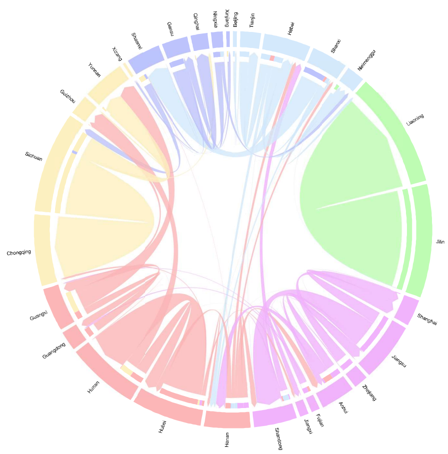
2015



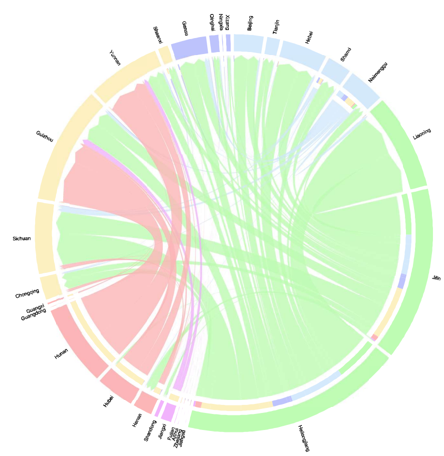
Overseas
Beijing
Tianjin
Hebei
Shanxi
Neimenggu
Liaoning
Jilin
Heilongjiang
Shanghai
Jiangsu
Zhejiang
Anhui
Fujian
Jiangxi
Shandong
Henan
Hubei
Hunan
Guangdong
Guangxi
Hainan
Chongqing
Sichuan
Guizhou
Yunnan
Xizang
Shaanxi
Gansu
Qinghai
Ningxia
Xinjiang



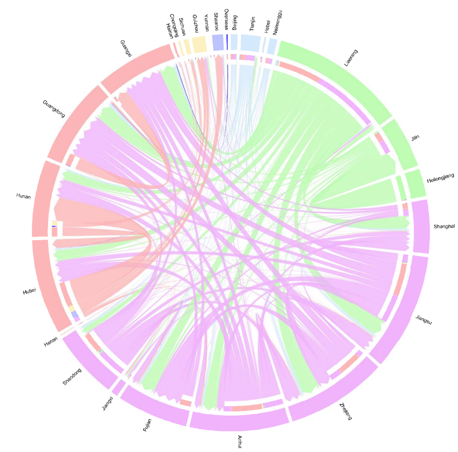
Heilongjiang
Jilin
Neimenggu
Liaoning
Xinjiang
Gansu
Beijing
Tianjin
Hebei
Shanxi
Ningxia
Qinghai
Shandong
Shaanxi
Henan
Jiangsu
Anhui
Xizang
Sichuan
Hubei
Shanghai
Chongqing
Zhejiang
Legend
Region
North
Northeast
East
Central-South
Southwest
Southeast
Guizhou
Hunan
Jiangxi
Fujian
Yunnan
Guangxi
Guangdong
Hainan



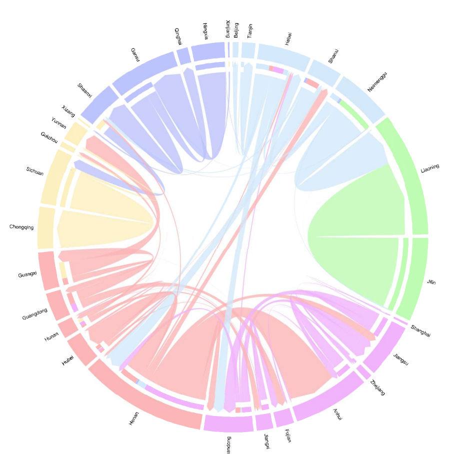
Inter-provincial flow of grain by road 1990



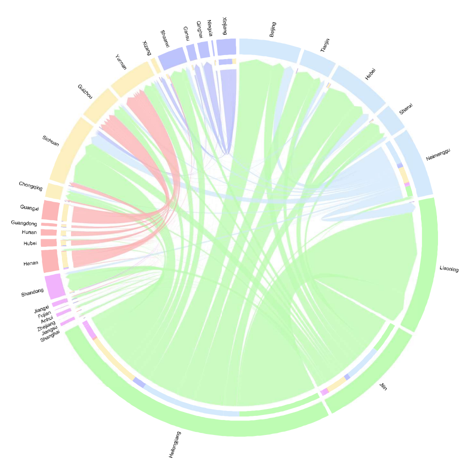
Inter-provincial flow of grain by railway 1990



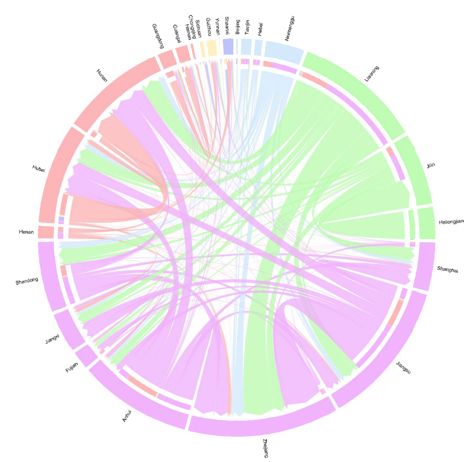
Inter-provincial flow of grain by waterway 1990



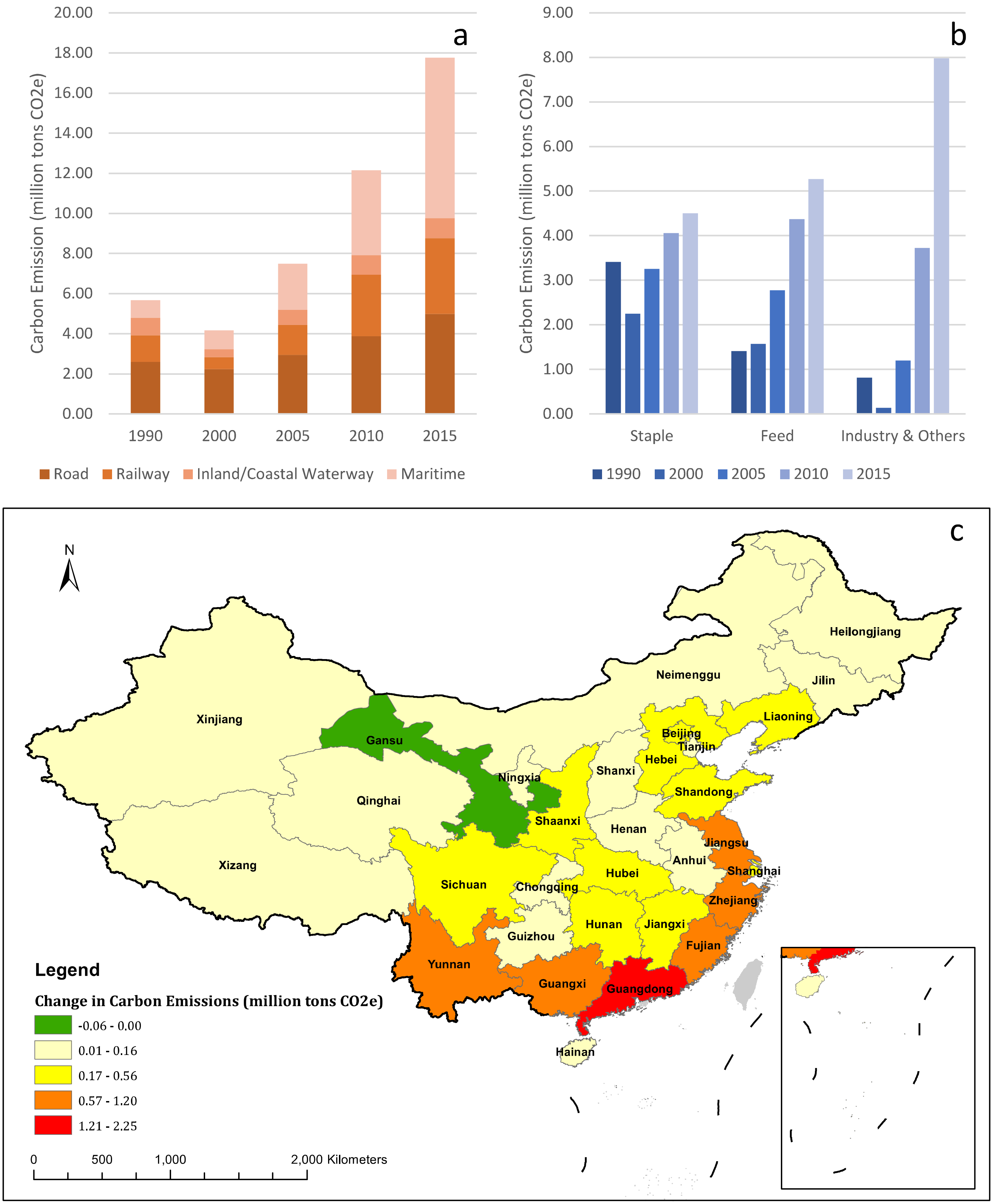
Inter-provincial flow of grain by road 2015



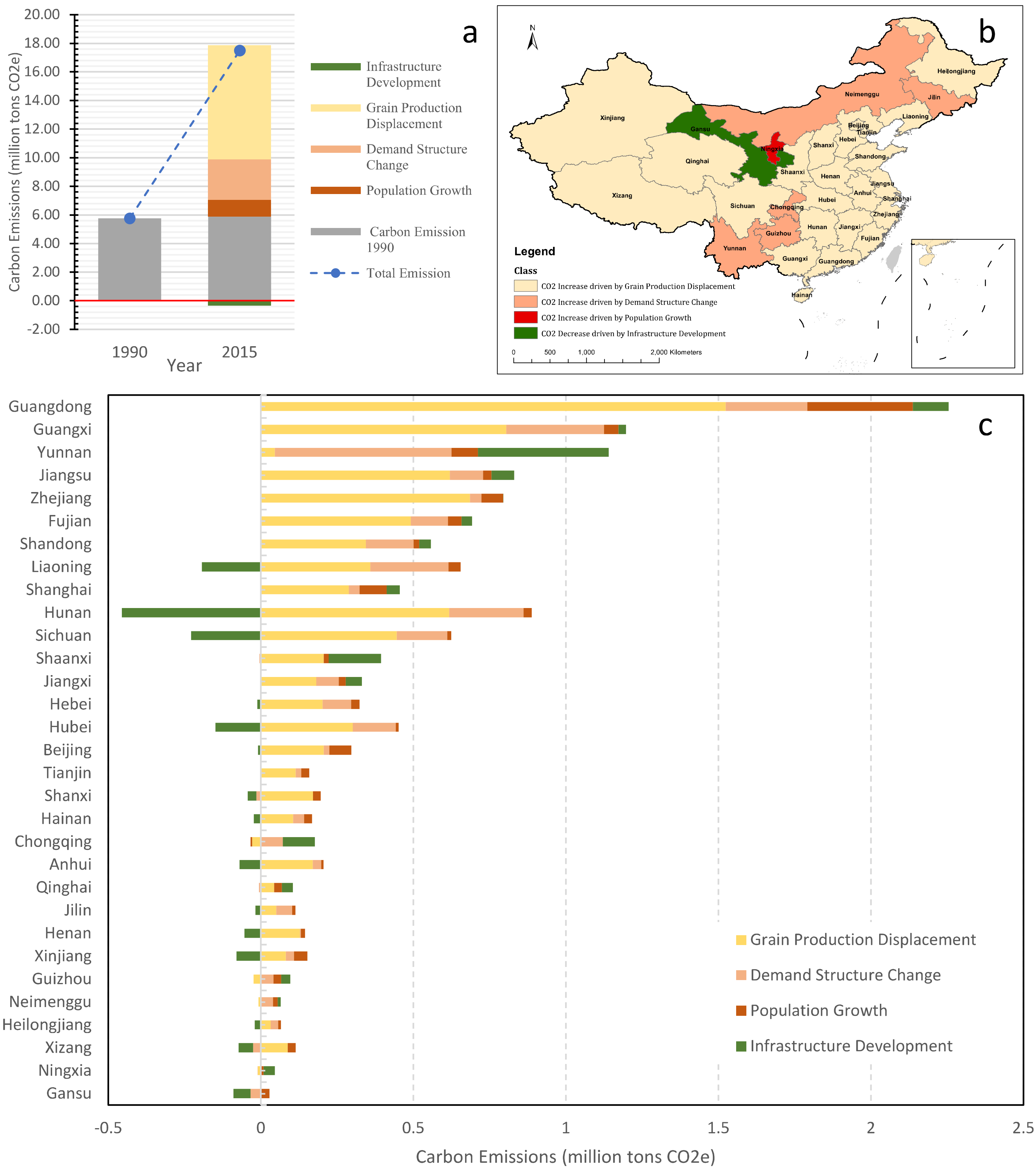
Inter-provincial flow of grain by railway 2015

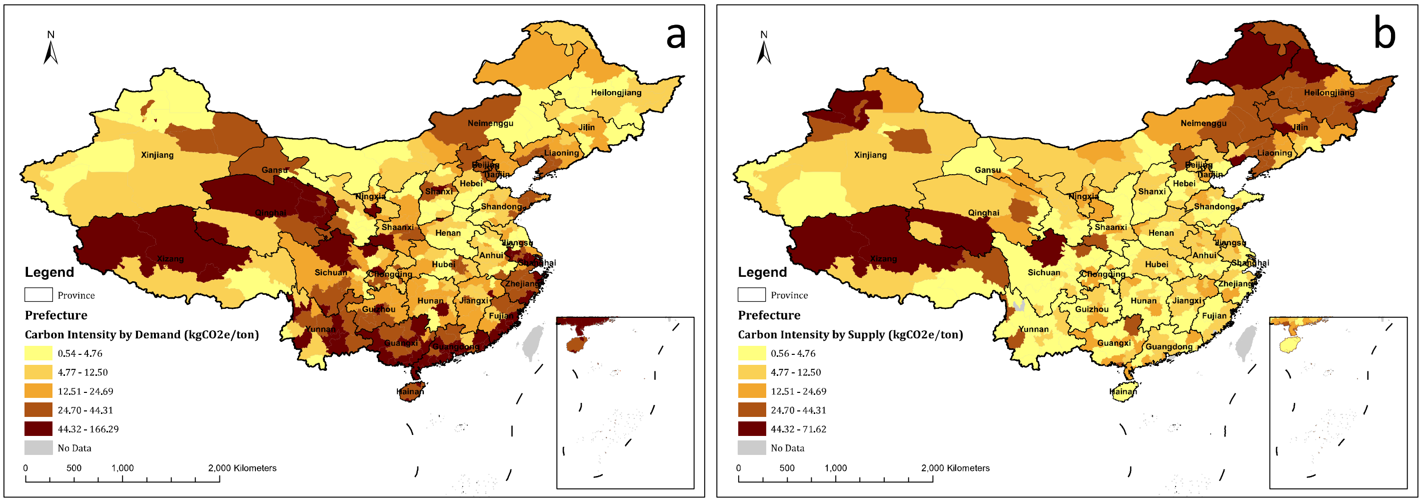


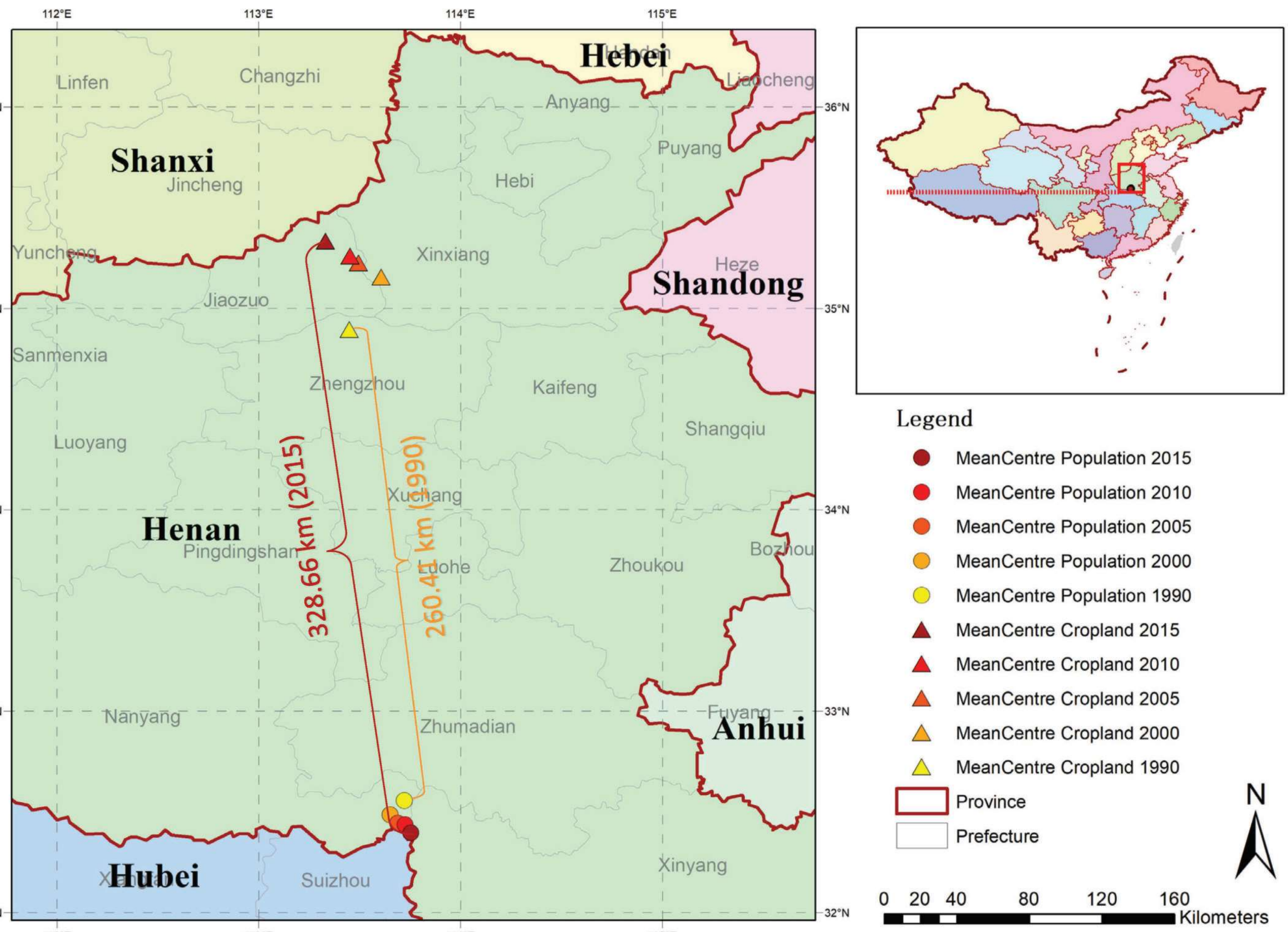
Inter-provincial flow of grain by waterway 2015

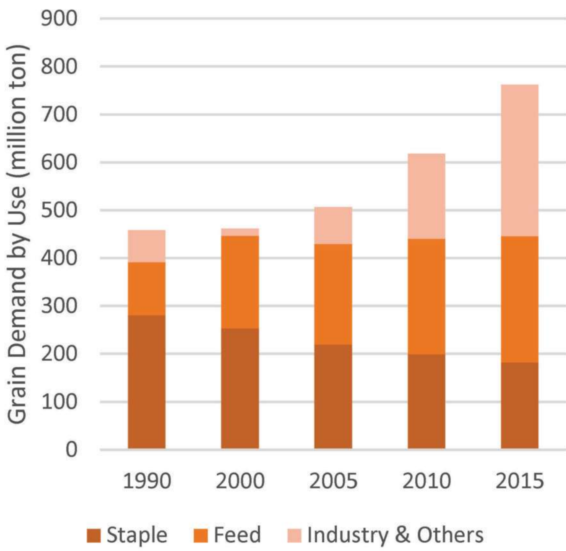


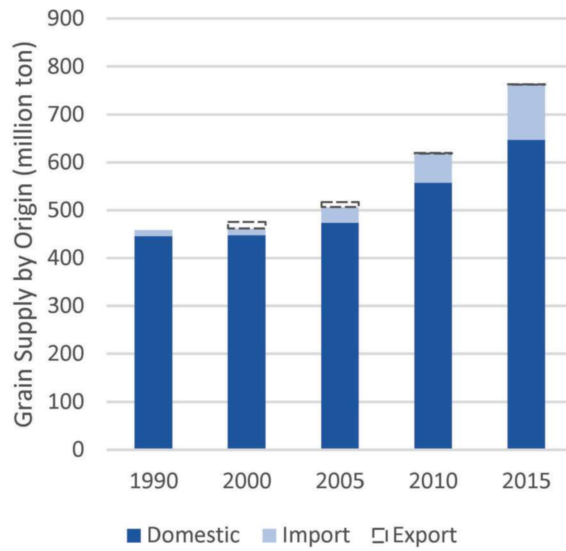
a
Carbon Emission (million tons CO2e)
20.00
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
1990
2000
2005
2010
2015
Road
Railway
Inland/Coastal Waterway
Maritime
b
Carbon Emission (million tons CO2e)
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Staple
Feed
Industry & Others
1990
2000
2005
2010
2015
c
N
Xinjiang
Gansu
Qinghai
Xizang
Neimenggu
Heilongjiang
Jilin
Liaoning
Beijing
Tianjin
Hebei
Shanxi
Ningxia
Shandong
Shaanxi
Henan
Jiangsu
Anhui
Shanghai
Sichuan
Chongqing
Hubei
Zhejiang
Hunan
Jiangxi
Guizhou
Fujian
Yunnan
Guangxi
Guangdong
Hainan
Legend
Change in Carbon Emissions (million tons CO2e)
-0.06 - 0.00
0.01 - 0.16
0.17 - 0.56
0.57 - 1.20
1.21 - 2.25
0
500
1,000
2,000 Kilometers

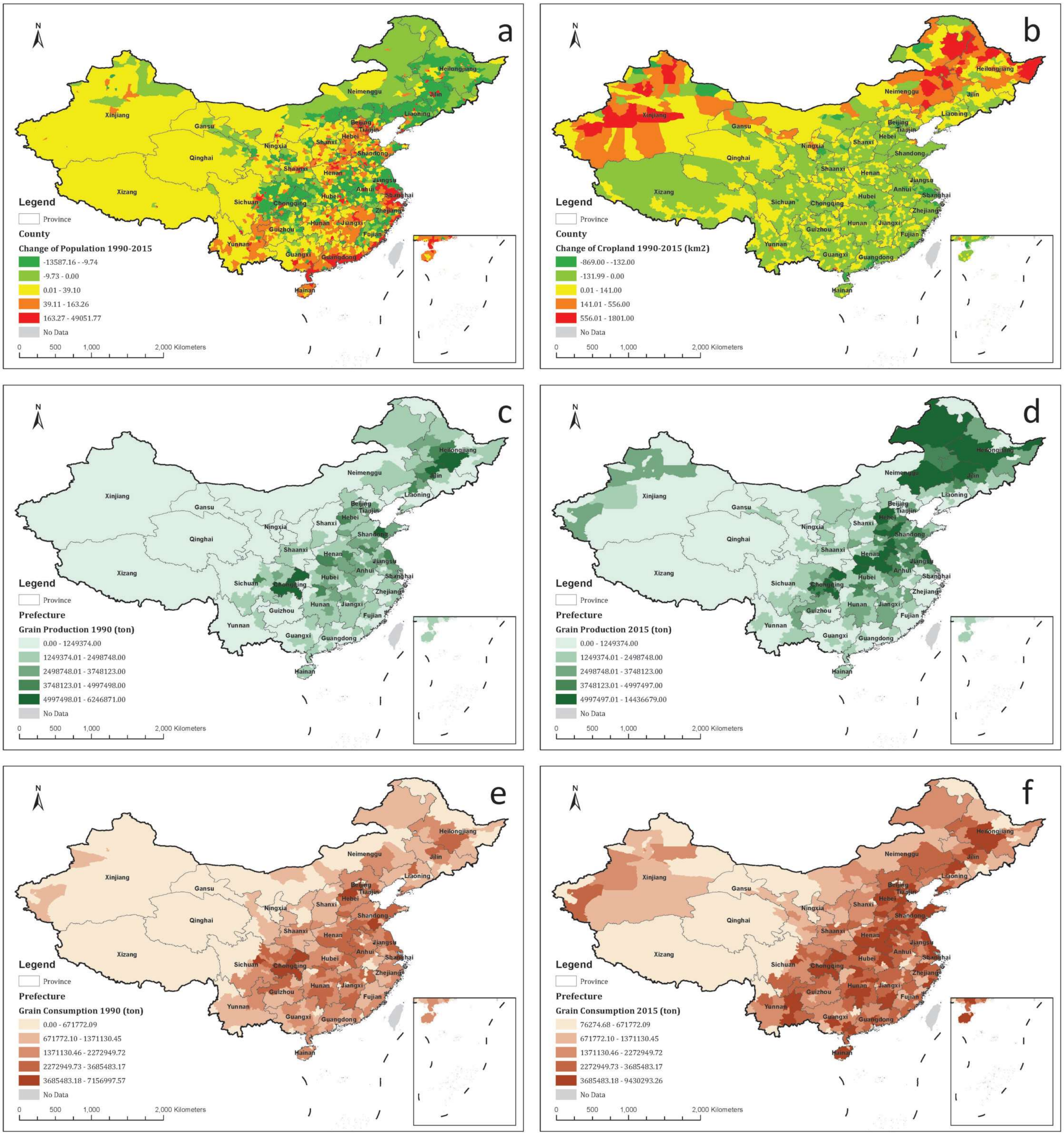

a
20.00
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
-2.00
Carbon Emissions (million tons CO2e)
1990
2015
Year
Infrastructure Development
Grain Production Displacement
Demand Structure Change
Population Growth
Carbon Emission 1990
Total Emission
b
N
Heilongjiang
Jilin
Neimenggu
Liaoning
Xinjiang
Gansu
Beijing
Tianjin
Hebei
Shanxi
Ningxia
Shandong
Qinghai
Shaanxi
Henan
Jiangsu
Anhui
Xizang
Hubei
Shanghai
Sichuan
Chongqing
Zhejiang
Hunan
Jiangxi
Guizhou
Fujian
Yunnan
Guangxi
Guangdong
Hainan
Legend
Class
CO2 Increase driven by Grain Production Displacement
CO2 Increase driven by Demand Structure Change
CO2 Increase driven by Population Growth
CO2 Decrease driven by Infrastructure Development
0
500
1,000
2,000 Kilometers
c
Guangdong
Guangxi
Yunnan
Jiangsu
Zhejiang
Fujian
Shandong
Liaoning
Shanghai
Hunan
Sichuan
Shaanxi
Jiangxi
Hebei
Hubei
Beijing
Tianjin
Shanxi
Hainan
Chongqing
Anhui
Qinghai
Jilin
Henan
Xinjiang
Guizhou
Neimenggu
Heilongjiang
Xizang
Ningxia
Gansu
Grain Production Displacement
Demand Structure Change
Population Growth
Infrastructure Development
-0.5
0
0.5
1
1.5
2
2.5
Carbon Emissions (million tons CO2e)

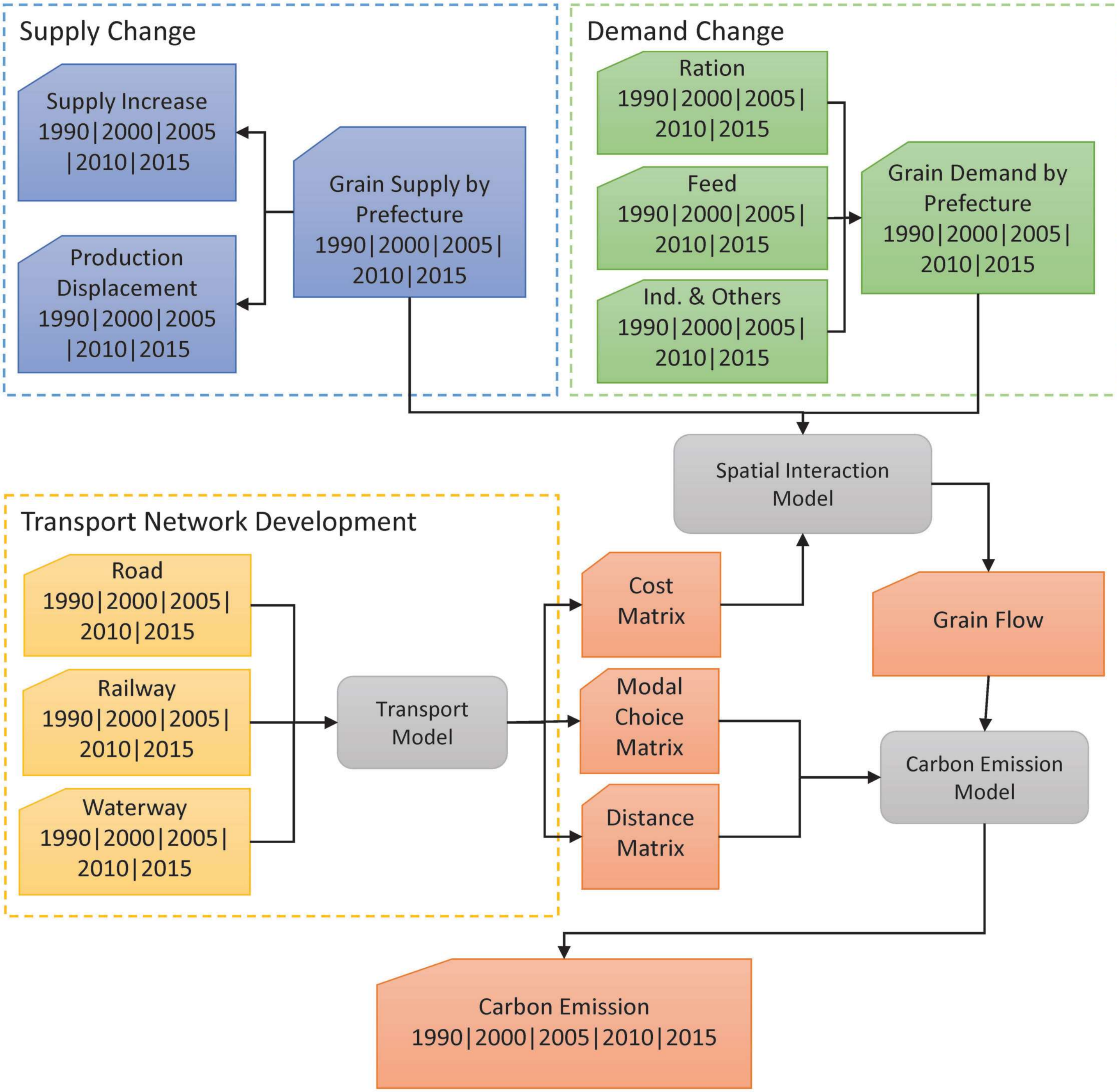

a
N
Legend
Province
Prefecture
Carbon Intensity by Demand (kgCO2e/ton)
0.54 - 4.76
4.77 - 12.50
12.51 - 24.69
24.70 - 44.31
44.32 - 166.29
No Data
0
500
1,000
2,000 Kilometers
Xinjiang
Gansu
Qinghai
Xizang
Sichuan
Yunnan
Neimenggu
Heilongjiang
Jilin
Liaoning
Beijing
Tianjin
Hebei
Shanxi
Ningxia
Shaanxi
Henan
Shandong
Jiangsu
Anhui
Shanghai
Hubei
Chongqing
Zhejiang
Guizhou
Hunan
Jiangxi
Fujian
Guangxi
Guangdong
Hainan
b
N
Legend
Province
Prefecture
Carbon Intensity by Supply (kgCO2e/ton)
0.56 - 4.76
4.77 - 12.50
12.51 - 24.69
24.70 - 44.31
44.32 - 71.62
No Data
0
500
1,000
2,000 Kilometers
Xinjiang
Gansu
Qinghai
Xizang
Sichuan
Yunnan
Neimenggu
Heilongjiang
Jilin
Liaoning
Beijing
Tianjin
Hebei
Shanxi
Ningxia
Shaanxi
Henan
Shandong
Jiangsu
Anhui
Shanghai
Hubei
Chongqing
Zhejiang
Guizhou
Hunan
Jiangxi
Fujian
Guangxi
Guangdong
Hainan

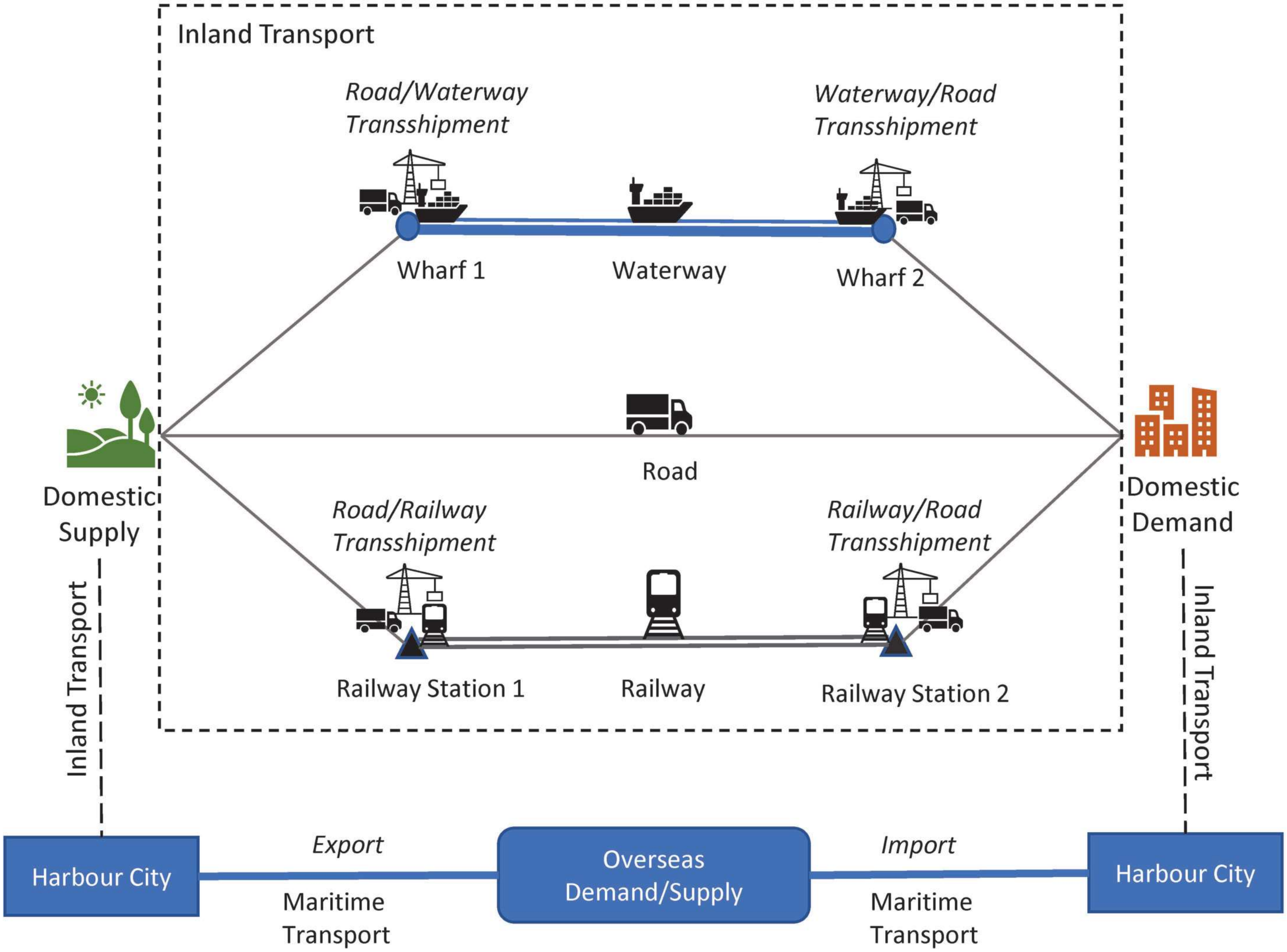

112°E
113°E
114°E
115°E
36°N
35°N
34°N
33°N
32°N
Hebei
Shanxi
Shandong
Henan
Anhui
Hubei
Linfen
Changzhi
Liaocheng
Anyang
Puyang
Jincheng
Hebi
Yuncheng
Xinxiang
Heze
Jiaozuo
Sanmenxia
Zhengzhou
Kaifeng
Luoyang
Shangqiu
Xuchang
Pingdingshan
Luohe
Zhoukou
Bozhou
Nanyang
Zhumadian
Fuyang
Suizhou
Xinyang
328.66 km (2015)
260.41 km (1990)
Legend
MeanCentre Population 2015
MeanCentre Population 2010
MeanCentre Population 2005
MeanCentre Population 2000
MeanCentre Population 1990
MeanCentre Cropland 2015
MeanCentre Cropland 2010
MeanCentre Cropland 2005
MeanCentre Cropland 2000
MeanCentre Cropland 1990
Province
Prefecture
N
0 20 40 80 120 160
Kilometers


Grain Demand by Use (million ton)
900
800
700
600
500
400
300
200
100
0
1990
2000
2005
2010
2015
Staple
Feed
Industry & Others

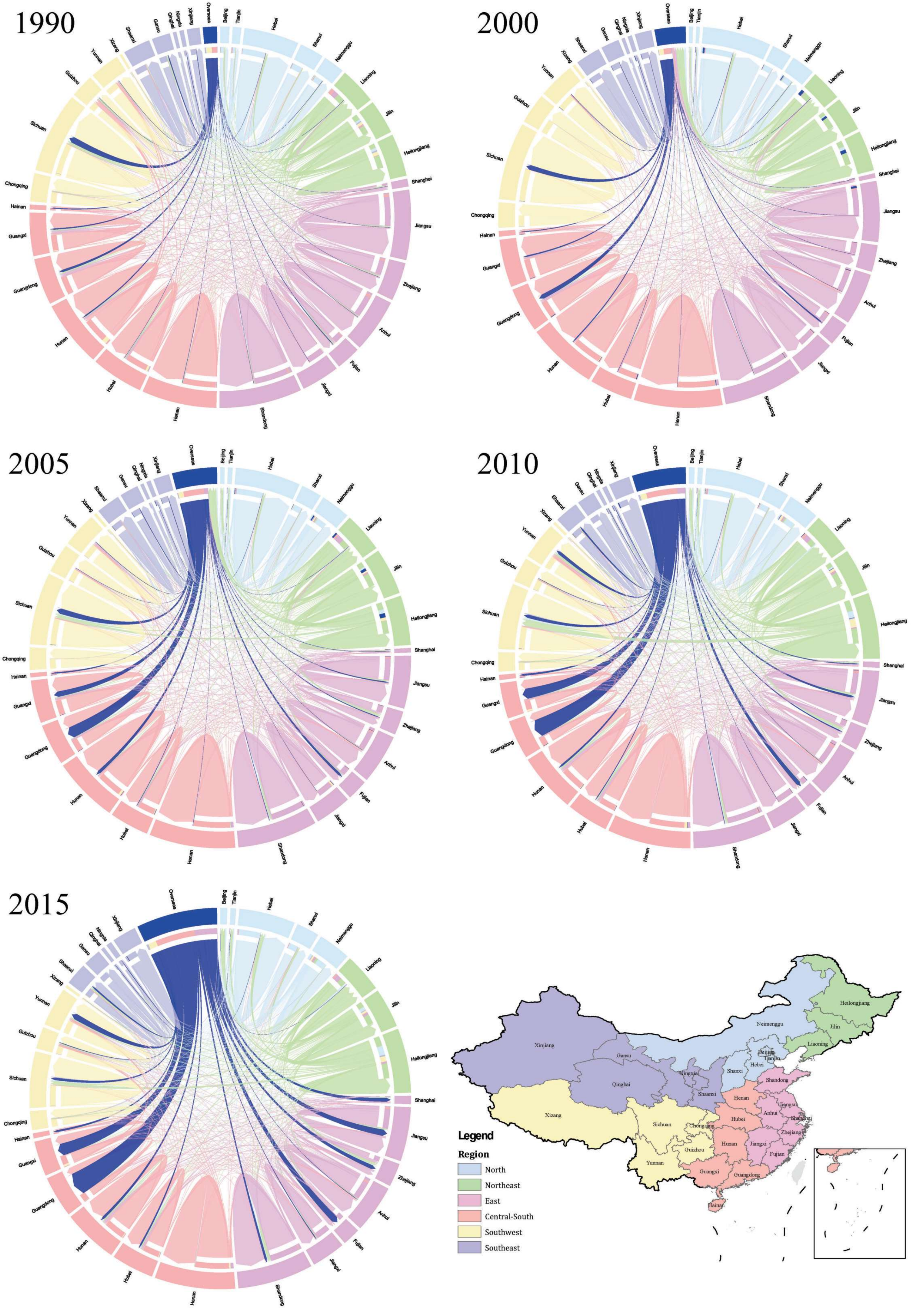

Grain Supply by Origin (million ton)
900
800
700
600
500
400
300
200
100
0
1990
2000
2005
2010
2015
Domestic
Import
Export


a
N
Legend
Province
County
Change of Population 1990-2015
-13587.16 - -9.74
-9.73 - 0.00
0.01 - 39.10
39.11 - 163.26
163.27 - 49051.77
No Data
0 500 1,000 2,000 Kilometers
Xinjiang
Gansu
Qinghai
Xizang
Neimenggu
Heilongjiang
Jilin
Liaoning
Beijing
Tianjin
Hebei
Shanxi
Ningxia
Shandong
Shaanxi
Henan
Jiangsu
Anhui
Shanghai
Sichuan
Chongqing
Hubei
Zhejiang
Guizhou
Hunan
Jiangxi
Fujian
Yunnan
Guangxi
Guangdong
Hainan
b
N
Legend
Province
County
Change of Cropland 1990-2015 (km2)
-869.00 - -132.00
-131.99 - 0.00
0.01 - 141.00
141.01 - 556.00
556.01 - 1801.00
No Data
0 500 1,000 2,000 Kilometers
c
N
Legend
Province
Prefecture
Grain Production 1990 (ton)
0.00 - 1249374.00
1249374.01 - 2498748.00
2498748.01 - 3748123.00
3748123.01 - 4997498.00
4997498.01 - 6246871.00
No Data
0 500 1,000 2,000 Kilometers
d
N
Legend
Province
Prefecture
Grain Production 2015 (ton)
0.00 - 1249374.00
1249374.01 - 2498748.00
2498748.01 - 3748123.00
3748123.01 - 4997497.00
4997497.01 - 14436679.00
No Data
0 500 1,000 2,000 Kilometers
e
N
Legend
Province
Prefecture
Grain Consumption 1990 (ton)
0.00 - 671772.09
671772.10 - 1371130.45
1371130.46 - 2272949.72
2272949.73 - 3685483.17
3685483.18 - 7156997.57
No Data
0 500 1,000 2,000 Kilometers
f
N
Legend
Province
Prefecture
Grain Consumption 2015 (ton)
76274.68 - 671772.09
671772.10 - 1371130.45
1371130.46 - 2272949.72
2272949.73 - 3685483.17
3685483.18 - 9430293.26
No Data
0 500 1,000 2,000 Kilometers


Supply Change
Supply Increase 1990|2000|2005 |2010|2015
Production Displacement 1990|2000|2005 |2010|2015
Grain Supply by Prefecture 1990|2000|2005| 2010|2015
Demand Change
Ration 1990|2000|2005| 2010|2015
Feed 1990|2000|2005| 2010|2015
Ind. & Others 1990|2000|2005| 2010|2015
Grain Demand by Prefecture 1990|2000|2005| 2010|2015
Spatial Interaction Model
Transport Network Development
Road 1990|2000|2005| 2010|2015
Railway 1990|2000|2005| 2010|2015
Waterway 1990|2000|2005| 2010|2015
Transport Model
Cost Matrix
Modal Choice Matrix
Distance Matrix
Grain Flow
Carbon Emission Model
Carbon Emission 1990|2000|2005|2010|2015



Inland Transport
Road/Waterway Transshipment
Waterway/Road Transshipment
Wharf 1
Waterway
Wharf 2
Domestic Supply
Road
Domestic Demand
Road/Railway Transshipment
Railway/Road Transshipment
Railway Station 1
Railway
Railway Station 2
Inland Transport
Inland Transport
Harbour City
Export
Maritime Transport
Overseas Demand/Supply
Import
Maritime Transport
Harbour City


1990
2000
2005
2010
2015
Overseas
Beijing
Tianjin
Hebei
Shanxi
Neimenggu
Liaoning
Jilin
Heilongjiang
Shanghai
Jiangsu
Zhejiang
Anhui
Fujian
Jiangxi
Shandong
Henan
Hubei
Hunan
Guangdong
Guangxi
Hainan
Chongqing
Sichuan
Guizhou
Yunnan
Xizang
Shaanxi
Gansu
Qinghai
Ningxia
Xinjiang
Legend
Region
North
Northeast
East
Central-South
Southwest
Southeast

	1990	2000	2005	2010	2015	Data Source
Domestic Grain Output (million tons)	446.24	462.17	484.02	559.11	648.06	China Statistical Yearbook*
Import Grain (million ton)	12.53	13.56	32.86	60.51	114.39	China Statistical Yearbook
Export Grain (million ton)	0.00	13.78	10.14	1.20	0.47	China Statistical Yearbook
Urban Residents (billion)	0.23	0.46	0.54	0.67	0.77	China Statistical Yearbook*
Rural Residents (billion)	0.91	0.80	0.77	0.67	0.60	China Statistical Yearbook*
Pork Output (million ton)	22.81	39.66	45.55	51.38	56.45	China Statistical Yearbook*
Other Meat Output(million ton)	5.76	20.47	23.83	28.56	31.04	China Statistical Yearbook*
Ration Grain per capita for urban residents (kg/person)	186.73	117.57	110.00	116.43	112.61	China Statistical Yearbook
Ration Grain per capita for rural residents (kg/person)	262.08	250.23	208.85	181.44	159.51	China Statistical Yearbook
Feed Conversion Rate for pork (kg/kg meat)	4.05	3.55	3.30	3.30	3.30	Aubert, 2008; Zhou et al., 2008
Feed Conversion Rate for other meat (kg/kg meat)	3.15	2.55	2.50	2.50	2.50	Aubert, 2008; Zhou et al., 2008
Grain for industry and other uses per capita (kg/person)	85.42	37.91	78.03	154.92	254.11	Author Estimated

*prefecture-level data are collected from the statistical yearbook of each individual province.

Province	Carbon Intensity of Grain Transport for Consumption (kgCO2e/ton)	Carbon Intensity of Grain Transport for Supply (kgCO2e/ton)
Beijing	38.01	7.58
Tianjin	33.00	18.67
Hebei	10.33	4.81
Shanxi	13.66	4.11
Neimenggu (Inner Mongolia)	8.96	32.70
Liaoning	23.09	28.65
Jilin	10.12	32.09
Heilongjiang	4.91	37.68
Shanghai	53.12	9.14
Jiangsu	24.10	8.97
Zhejiang	37.98	4.66
Anhui	8.58	8.89
Fujian	48.94	6.03
Jiangxi	16.15	7.49
Shandong	12.04	6.41
Henan	3.99	7.27
Hubei	15.00	6.17
Hunan	16.19	4.29
Guangdong	58.32	8.31
Guangxi	49.42	11.29
Hainan	43.08	2.41
Chongqing	19.40	6.91
Sichuan	26.53	5.45
Guizhou	25.50	3.87
Yunnan	41.26	3.28
Xizang (Tibet)	48.81	7.66
Shaanxi	26.69	8.37
Gansu	11.89	9.75
Qinghai	49.26	10.95
Ningxia	17.68	14.11
Xinjiang	9.82	22.27

Transport Mode	Carbon Emission Conversion Factor (kgCO2e/ton-km)
Road (HGV)	0.1136
Railway	0.0260
Waterway (Inland and Coastal)	0.0131
Waterway (Maritime)	0.0035