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Research article

Source data supported high resolution carbon emissions inventory for urban areas of the Beijing-Tianjin-Hebei region: Spatial patterns, decomposition and policy implications

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ABSTRACT

This paper developed internationally compatible methods for delineating boundaries of urban areas in China. By integrating emission source data with existing official statistics as well as using rescaling methodology of data mapping for 1 km grid, the authors constructed high resolution emission gridded data in Beijing-Tianjin-Hebei (Jing-Jin-Ji) region in China for 2012. Comparisons between urban and non-urban areas of carbon emissions from industry, agriculture, household and transport exhibited regional disparities as well as sectoral differences. Except for the Hebei province, per capita total direct carbon emissions from urban extents in Beijing and Tianjin were both lower than provincial averages, indicating the climate benefit of urbanization, comparable to results from developed countries. Urban extents in the Hebei province were mainly industrial centers while those in Beijing and Tianjin were more service oriented. Further decomposition analysis revealed population to be a common major driver for increased carbon emissions but climate implications of urban design, economic productivity of land use, and carbon intensity of GDP were both cluster- and sector-specific. This study disapproves the one-size-fits-all solution for carbon mitigation but calls for down-scaled analysis of carbon emissions and formulation of localized carbon reduction strategies in the Jing-Jin-Ji as well as other regions in China.

1. Introduction

Cities account for 71–76 per cent of carbon emissions from energy activities in the world and thus are target for carbon reduction efforts (IPCC, 2014). The United Nations population estimate predicts global population growth between 2012 and 2050 to mainly occur in cities (United Nations. Department of Economic and Social Affairs. Population Division., 2015). World CO_2 emissions, as well as its spatial distribution, would be significantly altered if anticipated rapid urbanization would occur and the per capita urban energy consumption would increase in Africa, non-OECD (Organization for Economic Co-operation and Development) countries and Asia (IEA, 2014).

In the context of rapid industrialization and urbanization in China, the activities related to energy were even more important than other parts of the world. From 1973 to 2013, China's total primary energy supply, electricity generation, fuel consumption, and CO_2 emissions from combustion had been increasing by 14.5, 71, 10.2, and 20.7 per cent annually, respectively. This is about 5, 10.7, 4.3, and 8 times that of the world average, respectively (Table 1) (IEA, 2015). Consequently, the Chinese government has taken several measures for upgrading energy mix and increasing energy efficiency for achieving low carbon development (State Council, 2011).

Most recently, changing urban design for the Beijing-Tianjin-Hebei (Jing-Jin-Ji) capital region has been initiated by the State Council of China. It is aimed to differentiate sectoral focus by locality and to enhance regional collaboration for environmental protection, carbon reduction, industrial development and provision of public services (Xinhua Net, 2015). Carbon emissions inventory

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Table 1
Energy supply and consumption and energy-related CO_2 emissions, comparing China with the world, 1973–2013.

	World			China's share		
	1973	2013	Average annual rate of increase	1973	2013	Average annual rate of increase
Total primary energy supply (TPES) (Mtoe)	6100	13,541	2.90%	7.0%	22.3%	14.46%
Electricity generation (TWh)	6131	23,322	6.68%	2.9%	23.5%	71.01%
Fuel consumption (Mtoe)	4667	9301	2.36%	7.9%	21.0%	10.23%
CO_2 emissions from combustion (Mts)	15,515	32,190	2.56%	6.0%	28.0%	20.67%

Note: Authors' compilation based on *Key World Energy Statistics* published by the International Energy Agency in 2015.

as well as its spatial distribution form a basis for building evidence-based development and carbon mitigation strategies that can potentially lead to regionally aligned green growth in the Jing-Jin-Ji capital region.

In the past, several attempts have been made to construct carbon emissions inventories for Chinese cities. However, a Chinese 'city' refers to an administrative region, usually comprising urban areas as well as a large proportion of non-built-up areas such as agricultural and forest land. Consequently, carbon emissions calculated for Chinese cities based on officially defined city boundaries do not capture similar human settlements as in literature studying urban carbon emissions in other countries, and pose challenge for international comparison. Furthermore, those results can hardly inform the Chinese government in urban planning or formulating space-based mitigation strategies. As a remedy, Montgomery (2008) suggested to follow boundaries of central business districts of Beijing and Dhakal (2009) suggested to only include urban districts but to leave out counties. Although the above modifications for calculating carbon emissions of Chinese cities can improve precision of analysis, those boundaries are still administratively defined and do not accurately capture features of urban forms and human settlements.

Thus, scholars are faced with the following two challenges in advancing analysis on carbon emissions from Chinese cities: (1) defining boundaries of analysis taking into consideration levels of human activities; and (2) obtaining disaggregated data on human activities for constructing high resolution carbon emissions inventories for the above specified urban areas within administratively defined 'Chinese cities'. However, only modest efforts have been made to advance alternative methods for documenting carbon emissions for Chinese cities. For example, Cai and Zhang (2014) experimented with four different methods for defining boundaries of urban extents: administrative boundary, district boundary, built-up area, and urban proper and derived CO_2 emissions of the Tianjin municipality by adopting those four methods which reported as large as 654% of difference in results. They concluded urban extent is appropriate for understanding spatial patterns of CO_2 emissions in China and for making international comparisons. Explorations have also been made on spatial analysis of CO_2 emissions in Japan (Makido et al., 2012), Asia (Marcotullio et al., 2012) and the U.S. (Gurney et al., 2009; Parshall et al., 2010; Zhou and Gurney, 2011). Furthermore, although researchers have invented statistical methods for disaggregating carbon emissions to small geographical areas (Seya et al., 2016), high resolution carbon inventories constructed from emission source data are scarce due to challenges in data availability and computation.

China is expected to reach an urbanization rate of 70–75 per cent by 2050 (Institute for Scientific Research on Chinese Cities, 2009). In the meantime, the Chinese government is aiming for CO_2 emissions to peak around 2030 (The White House and Office of the Press Secretary, 2014). Thus, it is important to gain a good understanding of the complex socio-ecological system and to instrument sectoral and space-based strategies for carbon mitigation (Duit et al., 2010). This paper makes a contribution to both Chinese policymaking and the academic literature by (1) developing internationally compatible method for delineating boundaries of urban extents based on population density in the Jing-Jin-Ji region, (2) constructing 1 km gridded high resolution carbon emissions inventory by data rescaling and mapping of emission source data and official statistics, (3) comparing urban with non-urban extents and adopting cluster analysis for identifying spatial patterns of CO_2 emission across the Jing-Jin-Ji region, and (4) decomposing CO_2 emissions by the following four driving forces, using Kaya equation: population, urban design (land area per capita), economic productivity of land use (GDP generated per unit land area), and carbon intensity (CO_2 emissions per unit GDP). The study is a forerunner in bridging science and policy by the construction of the high resolution carbon emissions inventory to a human scale for the identified 213 urban extents, identification of spatial and sectoral patterns, and decomposition of driving forces of CO_2 emissions. Those results will inform carbon mitigation and regionally aligned development strategies in the Jing-Jin-Ji region. Furthermore, methodology adopted in this study for integrating emission source data and official statistics as well as data rescaling and mapping can be replicated for other localities and can inform formulation of locally appropriate carbon reduction strategies.

2. Methodology and data

2.1. Basic information about Jing-Jin-Ji region

Jing-Jin-Ji region, the national capital region, with two centrally directly-controlled municipalities (Beijing and Tianjin, CDCM) and Hebei province, is the biggest urbanized region in Northern China. The region covers 216,760 km^2 of land, inhabited by a total population of 107.7 million in 2012 (National Bureau of Statistics, 2013). Fig. 1 illustrates 13 administratively defined cities altogether in the Jing-Jin-Ji region, namely, Beijing, Tianjin, and 11 prefectural level cities[1] in the Hebei province.

2.2. Data

Data used in the analysis is all from the year of 2012. Following Cai and Zhang (2014), for building 1 km gridded carbon emissions inventory for sources in Scope 1 and Scope 2[2] for the Jing-Jin-Ji

[1] All territories in China are classified into the following four administrative levels, from the highest to the lowest: province/autonomous region/centrally directly controlled municipality, prefectural level city, county/county-level city/district, and township/village.

[2] Scope 1 includes all direct emissions that occur within the territorial boundary of the city. Scope 2 includes indirect emissions that occur outside the city boundary as a result of activities that occur within the city, which are limited to electricity consumption, district heating, steam and cooling. Scope 3 includes other indirect emissions and embodied emissions that occur outside the city boundary as a result of activities of the city, including electrical transmission and distribution losses, embodied emissions in fuels and imported goods, etc. (Cai and Zhang, 2014).

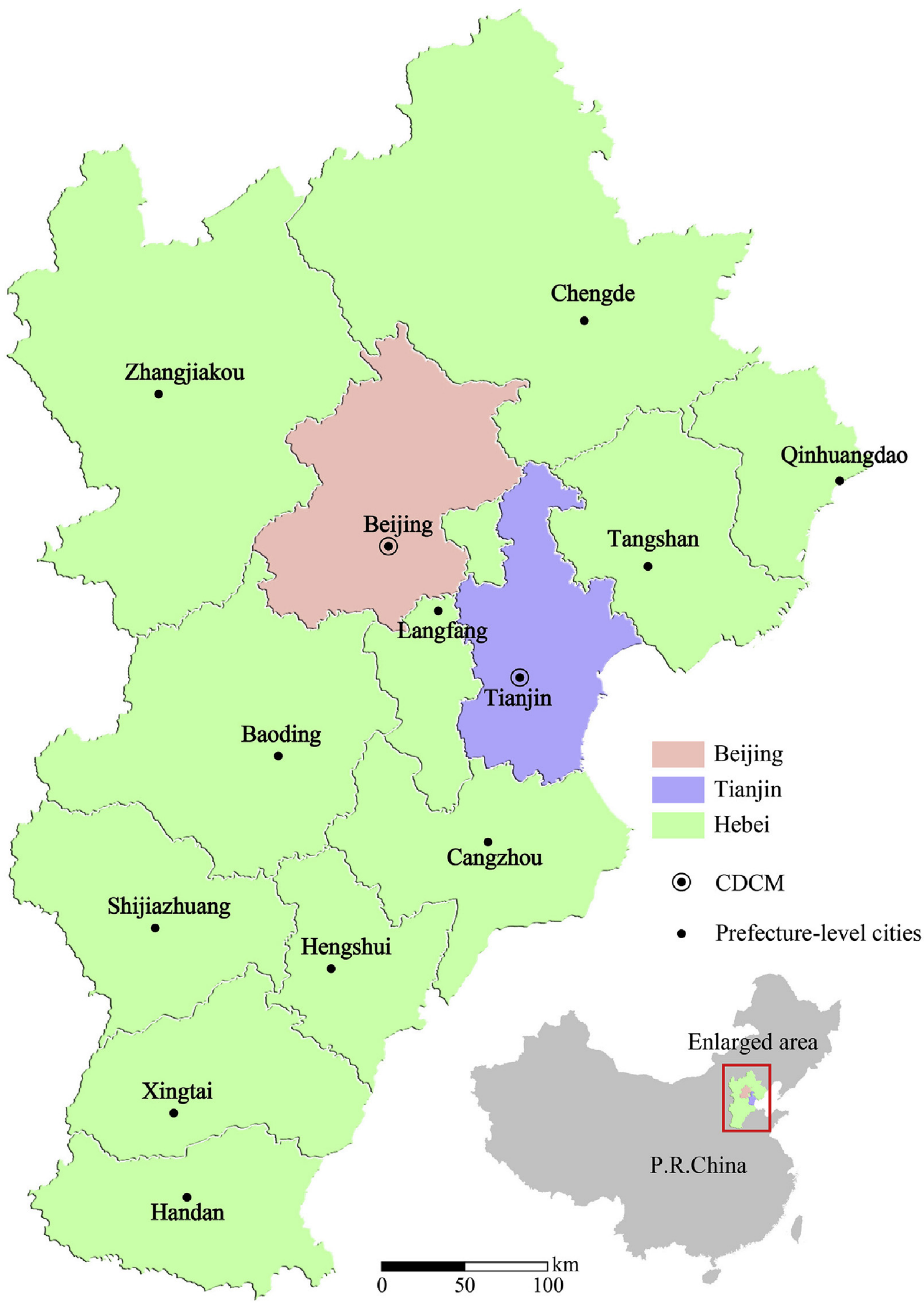

Fig. 1. Map of Jing-Jin-Ji region.

region, we compiled data from multiple sources. Data sources include the following: (1) Industrial key emission sources (facility level data) and industrial non-key emission sources collected from China industrial facility database (Wang et al., 2014) (detailed information on facility level data is available from SI, Supplementary Information); (2) energy consumption data by urban residents, agriculture and rural households, at a provincial level, reported by the Chinese Energy Statistical Yearbook 2013 (Department of Energy Statistics of National Bureau of Statistics, 2013); and (3) transport energy use, calculated by the authors using the same methods as in Cai et al. (2012) with data updated to the year of 2012 (Cai et al., 2012). Care has been taken to avoid double counting and we have conducted validity test to compare official provincial statistics with the results of aggregation to provincial level from point sources. Table 2 reports spatial resolution of data available for CO_2 emissions sources, with corresponding number of observations and shares of total emission specified.

Socio-economic data, at a county/district level was obtained

Table 2
Features of data for CO_2 emissions sources.

CO_2 emissions sources	Sectors	Spatial resolution	Number	Share of total CO_2 emission
Combustion	Industrial key emission sources	Point	12,991	74.33%
	Industrial non-key emission sources	Prefecture	13	10.60%
	Urban household	County/district	204	3.69%
	Transport	Province	3	5.19%
	Agriculture	Province	3	0.58%
	Rural household	Province	3	1.88%
Industrial processes		Point	187	3.73%

from provincial statistical yearbooks of Beijing (Beijing Bureau of Statistics, 2013), Tianjin (Tianjin Bureau of Statistics, 2013), and Hebei (Hebei provincial government, 2013). Population statistics, at a township level was collected from the provincial population and employment statistical yearbooks (Population Census Office under the State Council and Department of Population and Employment Statistics of the National Bureau of Statistics, 2012). Landscan, the high spatial resolution population dataset (30″ × 30″ globally, and about 0.7 km^2 in the Jing-Jin-Ji region) complemented the official statistics for allocating proxy (Bhaduri et al., 2007). Land cover data from GlobeLand30 (National Geomatics Center of China, 2014) was used to allocate CO_2 emissions from energy consumption by urban households, agriculture and rural household.

The town/township is the basic unit of the urban extent and forms the basis on which social and economic data are aggregated in this paper. But the county/district is the smallest unit on which official statistics are routinely reported. The only exception is population data, which was reported at a township level in the *Sixth Nationwide Population Census for 2010* (Population Census Office under the State Council and Department of Population and Employment Statistics of the National Bureau of Statistics, 2012). Therefore, the population of each urban extent is aggregated from towns/townships. GDP of each county/district is allocated to towns/townships proportional to population size, then aggregated for each urban extent. Average income of each urban extent is calculated by the population weighted towns/townships income which is equal to income of the county/district they belong to.

2.3. Urban extents

City in China refers to a region or a level of political jurisdiction instead of aggregation of human settlement as discussed in literature (Cai and Zhang, 2014; Dhakal, 2009; Montgomery, 2008). Neither land use patterns nor level of human activities are differentiated by administratively defined city boundaries. Thus, we adopted the urban area standards (Table S1 in SI) set by the *China Fifth Nationwide Population Census (CFNPC)* (National Bureau of Statistics, 1999), which is comparable to urban extents defined by the OECD countries (OECD, 2010a, b), for creating carbon emissions inventories. Based on the county/district and town/township GIS data as well as census data, we identified 213 urban extents for the Jing-Jin-Ji capital region (Fig. 2). SI submitted together with this paper provides detailed information on how the urban extents were derived.

2.4. Building of 1 km resolution gridded CO_2 emissions data

Based on previous research (Cai and Zhang, 2014; Wang et al., 2014), we improved the spatial mapping process (Fig. S3 of the SI), built the 1 km gridded spatial mapping system and constructed CO_2 emissions inventory for our identified 213 urban extents. The scope and calculation of CO_2 emissions are reported in SI.

2.5. Kaya equation for decomposing CO_2 emissions

For understanding drivers of CO_2 emissions from the urban extents in the Jing-Jin-Ji region, we constructed the following Kaya equation for decomposition. Population and carbon intensity of GDP are conventional variables used in previous studies (IEA, 2015; Wang et al., 2012, 2015). Land area per capita was previously adopted by Singh and Kennedy for capturing urban design effect on energy usage (Singh and Kennedy, 2015). Economic productivity of land use was thus created by the authors for balancing the Kaya equation.

$$CO2 = population \times \frac{area}{population} \times \frac{GDP}{area} \times \frac{CO_2}{GDP}$$

where, CO2 = carbon emissions of an urban extent; population = number of residents in an urban extent; area = land area of an urban extent; and GDP = gross domestic product of an urban extent.

The Kaya equation indicates that there are four drivers for increasing CO_2 emissions: (1) urban population, (2) urban design (land area per capita), (3) economic productivity of land use, and (4) CO_2 intensity. For controlling for systematic differences resulted from different sizes of urban extents, we conducted cluster analysis based on population, GDP, and land area, and used cluster adjusted standard error in regression analysis.

3. Results

3.1. Validity of the bottom-up approach in building carbon inventories for urban extent

For validity check, CO_2 emissions of Beijing, Tianjin, and Hebei in 2012 were also calculated using national energy statistics (Department of Energy Statistics of National Bureau of Statistics, 2013) and the results were compared with that derived from the bottom-up approach based on the 1 km gridded data. As shown in Fig. 3, compared with the reference approach, CO_2 emissions derived from the bottom-up approach for Beijing and Tianjin were only 0.61 and 7.06 per cent lower, respectively, but that for Hebei was 17.82 per cent higher.

It is important to note that Beijing is the capital city of China and both Beijing and Tianjin are centrally directly-controlled municipalities. Their higher administrative status makes it possible for them to be highly selective in attracting investments by size, industry and other preferences. Furthermore, they both are equipped with better bureaucracies and consequently better statistical data on energy activities. Therefore, a good consistency was observed in comparing CO_2 emissions derived from source data and from aggregated statistics.

Hebei province, in particular, has hosted many small scaled industrial facilities, most of which heavily rely on coal. Fossil fuel energy consumption of those small-sized plants was hardly

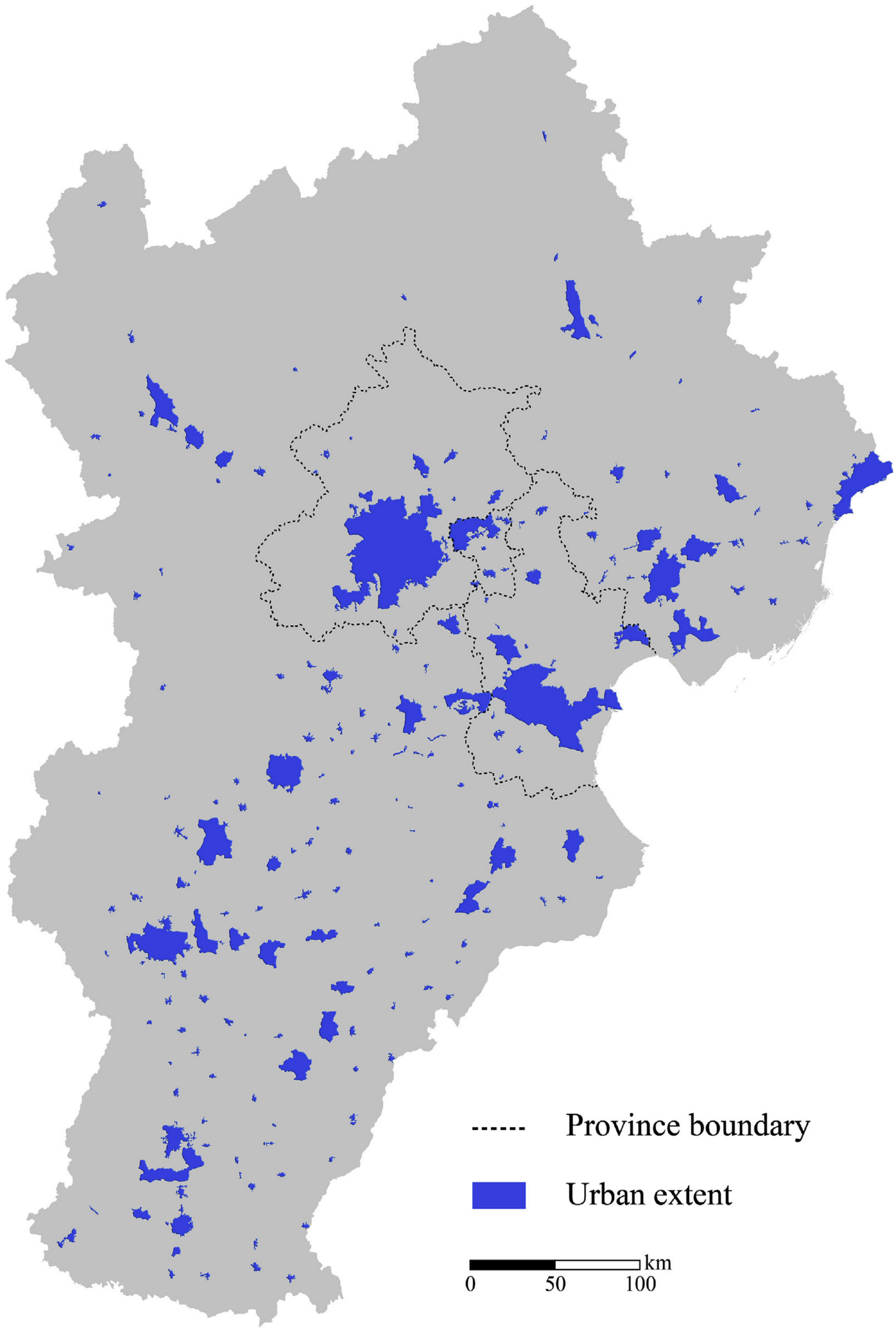

Fig. 2. Urban extents in the Jing-Jin-Ji capital region.

reported in energy balance table of Hebei province where the capacity of bureaucracies is relatively weak. Therefore, it is understandable that CO_2 emissions calculated from source data was bigger than that from official statistics. Similarly, Guan et al. (2012) reported discrepancies in CO_2 emissions calculated for China, with results derived from provincial data using a bottom-up approach larger than that from national statistics by 18.09 per cent.

In total, CO_2 emissions of the Jing-Jin-Ji region in 2012 derived from the bottom-up approach, based on the 1 km gridded data were 11.4 per cent higher than that from the reference approach. We considered this discrepancy to be acceptable.

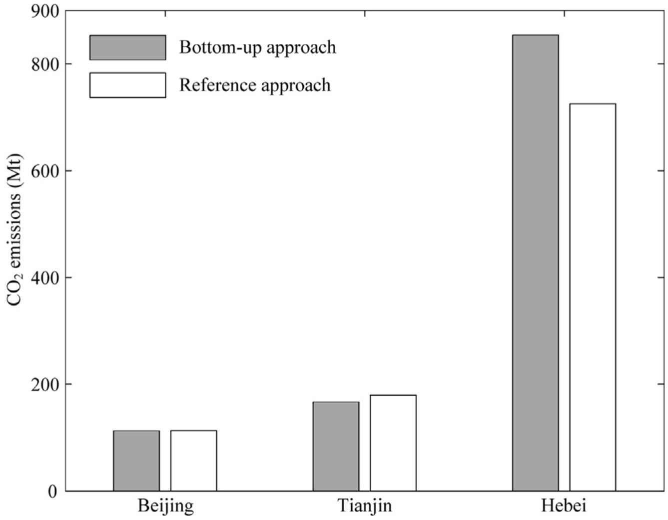

Fig. 3. Comparing CO_2 emissions using the bottom-up approach based on the 1 km gridded data with reference approach based on national energy statistics.

3.2. 1 km gridded CO_2 emissions of the Jing-Jin-Ji region

As illustrated in Fig. 4, hotspots of CO_2 emissions in the Jing-Jin-Ji region were all located in the identified urban extents. In Beijing and Tianjin, urban extents hosted grids with high (10,000–100,000 ton) and super-high (>100,000 ton) CO_2 emissions, flagging large emission sources such as coal fired power plants and/or cement plants. In Hebei province, except for Chengde (specialized in tourism) and Hengshui (specialized in food and beverage industry), urban extents in the other prefectural level cities all contained grids of high CO_2 emissions. Overall, the Jing-Jin-Ji region was home to a large number of emission sources.

Figs. 5 and 6 illustrate the spatial distribution of CO_2 emissions from industrial and household sources. It is clear that not only the magnitude but also the variation in CO_2 emissions are much larger for industrial than household sources, across different urban extents.

3.3. Spatial outlook of CO_2 emissions from urban extents in the Jing-Jin-Ji region

Table 3 reports the identified urban extents in aggregated figures, located in Beijing, Tianjin, and Hebei, along the dimensions of land area, GDP, population, and direct carbon emissions from industry, agriculture, households, and transport in 2012. It is clear that the urban extents had disproportionally highly concentrated human and economic activities, compared with their land areas. The 15, 16, and 182 urban extents only occupied 16.98, 17.45, and 4.17 per cent of land area in Beijing, Tianjin, and Hebei, but hosted 85.96, 68.78, and 32.69 per cent of population, generated 82.01, 74.71, and 42.74 per cent of GDP, and emitted 83.51, 59.51, and 40.67 per cent of CO_2 emissions (direct), respectively. At the same time, there exist regional disparities in urban design, industrial development, and composition of CO_2 emissions.

The urban extents in the Hebei province are more concentrated but composed of high emission and/or less advanced industries than that in Beijing and Tianjin, measured by total, per capita, and per unit GDP CO_2 emissions from industry. In Hebei, per capita CO_2 emissions from industry in urban extents were 14.55 ton, higher than the provincial average (11.52 ton) in 2012. Thus, urban extents in Hebei province were industrial centers. However, urban extents in Beijing and Tianjin had per capita industrial CO_2 emissions lower than their provincial averages. That implies urban extents in Beijing and Tianjin bear diverse functions beyond hosting industrial facilities (Table 3).

Urban extents in Beijing, Tianjin, and Hebei had 6.61, 16, and 51.02 per cent higher per capita CO_2 emissions from households than provincial averages in 2012 (Table 3).

Urban extents in Beijing, Tianjin, and Hebei had equal per capita CO_2 emissions (0.01 ton) from agriculture in 2012, lower than provincial averages (0.03, 0.06, and 0.07 ton, respectively), indicating agricultural activities were concentrated more in non-urban areas in the Jing-Jin-Ji region (Table 3).

Urban extents in Beijing, Tianjin, and Hebei had 10.4, 45.28, and 50 per cent lower per capita CO_2 emissions from transport than provincial averages in 2012, respectively, indicating the advantages of urbanization in carbon reduction (Table 3).

Except for Hebei (15.46 vs. 12.40 ton), per capita total direct CO_2 emissions from the urban extents in Beijing and Tianjin were both lower than their provincial averages: 5.8 vs. 5.97; 11.13 vs. 12.87 ton (Table 3). The results are in line with findings from cities in developed countries which demonstrated carbon efficiency of urbanization.

All the 213 urban extents in the Jing-Jin-Ji region were classified into the following four clusters by population, GDP, and land area: mega, large, medium, and small (see Fig. 7). Descriptive statistics on those clusters are reported in Table 2 in SI. Beijing had 1 mega and 14 small urban extents; Tianjin had 1 mega, 2 medium and 13 small urban extents; and Hebei had 10 large, 18 medium, and 154 small urban extents. Fig. 5 illustrates the spatial distribution of CO_2 emissions from those four clusters of urban extents.

3.4. Decomposing CO_2 emissions from identified urban extents in the Jing-Jin-Ji region

Table 4 shows regression results from the Kaya decomposition equation. We expect as a whole, the following four clusters – mega-, large-, medium-, and small-sized urban extents would exhibit different patterns in CO_2 emissions. Furthermore, we expect impacts of the four drivers, namely, population size, urban design (land area per capita), economic productivity of land use (GDP per unit land area), and carbon intensity (CO_2 emissions per unit GDP) to be also cluster specific. Thus, we took into consideration the interaction terms between cluster and the four drivers. The results show that CO_2 emissions from industry, household, agriculture, transport, and indirect sources were driven by different factors.

Population size, urban design, economic productivity of land use, and carbon intensity all drove up CO_2 emissions from industry for all the urban extents. Industries in large-sized urban extents had more CO_2 emissions than those in small-sized urban extents. Within mega, large, and medium-sized urban extents, population size was found to have negative relations to CO_2 emissions from industry. Lower the urban density, smaller the CO_2 emissions from industry was observed for large and medium-sized urban extents. In mega and medium-sized urban extents, higher carbon intensity of GDP, the more CO_2 emissions from industry was observed (column A, Table 4).

Column (A), (B), (C), (D), and (E) report results of the following five regression models constructed for direct CO_2 emissions from industry, household, agriculture, and transport, and indirect CO_2 emissions.

Population size was observed to be positively associated with CO_2 emissions from household for all the urban extents. Large-sized urban extents were associated with lower CO_2 emissions from household than those small-sized. Within mega, large, and medium-sized urban extents, population size was found to be positively related to CO_2 emissions from household. We observed

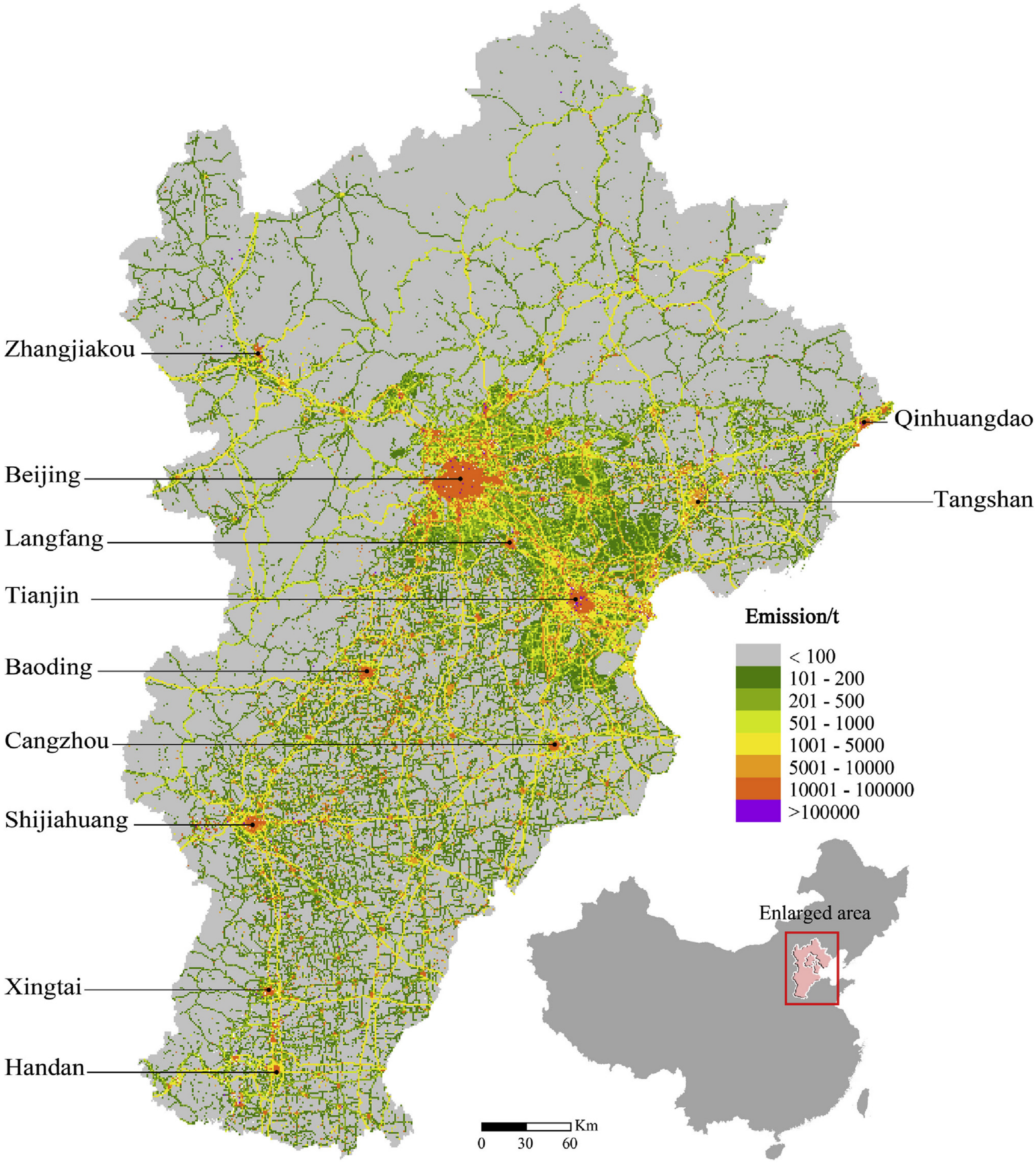

Fig. 4. 1 km gridded CO_2 emissions map of Jing-Jin-Ji region for 2012.

that land area per capita (less compact urban design) was positively associated with CO_2 emissions from household for large-sized urban extents. Economic productivity of land use was found to be negatively associated with CO_2 emissions from household for large-sized urban extents. Carbon intensity of GDP was found to be negatively associated with CO_2 emissions from household for mega, large, and medium-sized urban extents (column B, Table 4).

Population size and compact urban design were both positively associated with CO2 emissions from agriculture for all urban extents. Large and medium-sized urban extents were associated with lower CO_2 emissions from agriculture than those small-sized. Population size had positive relation to CO_2 emissions from agriculture for mega, large, and medium-sized urban extents. Less compact urban design was associated with higher CO_2 emissions from agriculture for large and medium-sized urban extents. Economic productivity of land use was found to be negatively associated with CO_2 emissions from agriculture for large and medium-sized urban extents. Carbon intensity of GDP was found to be

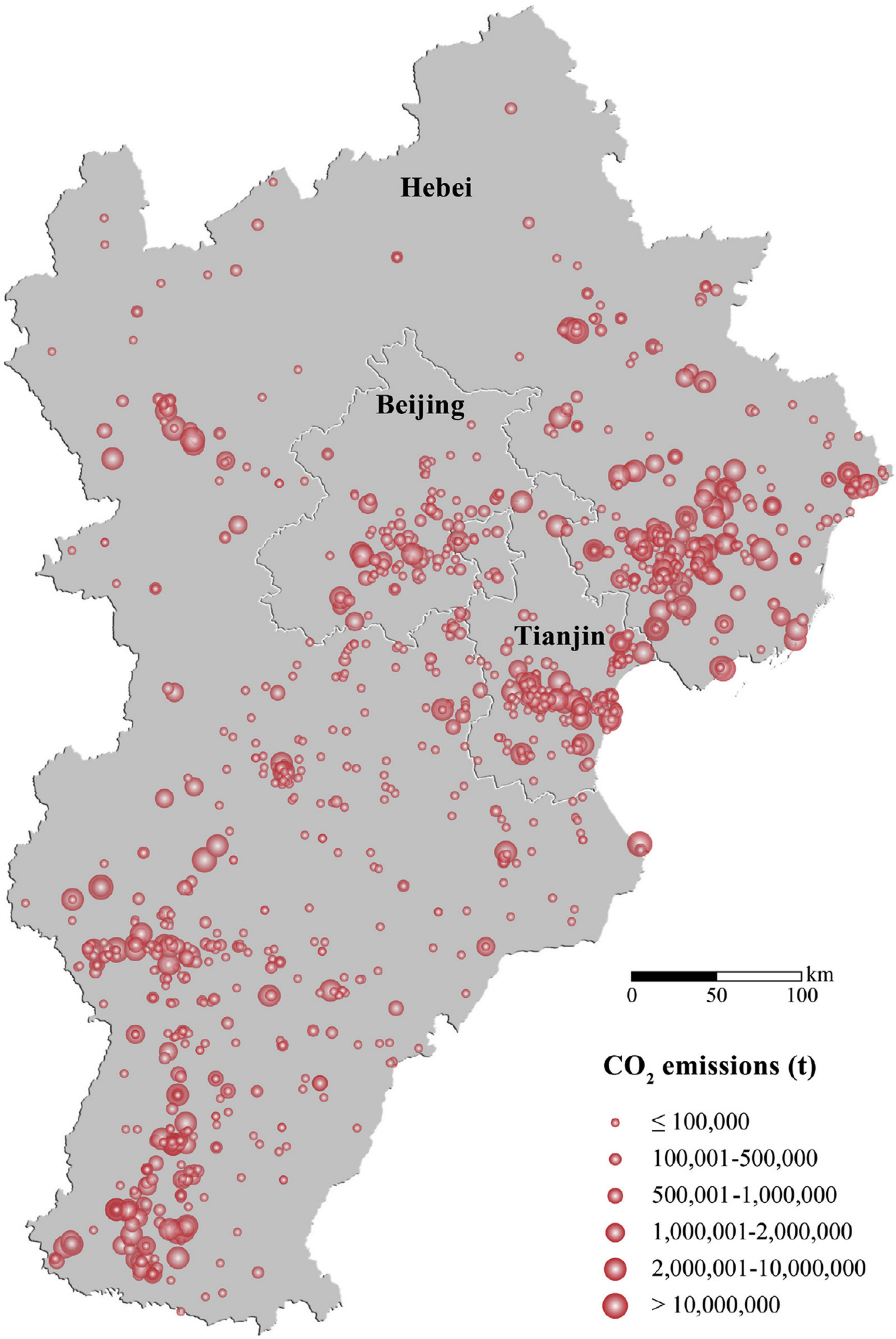

Fig. 5. Spatial distribution of CO_2 emissions of facilities in industrial sector in the Jing-Jin-Ji region for 2012.

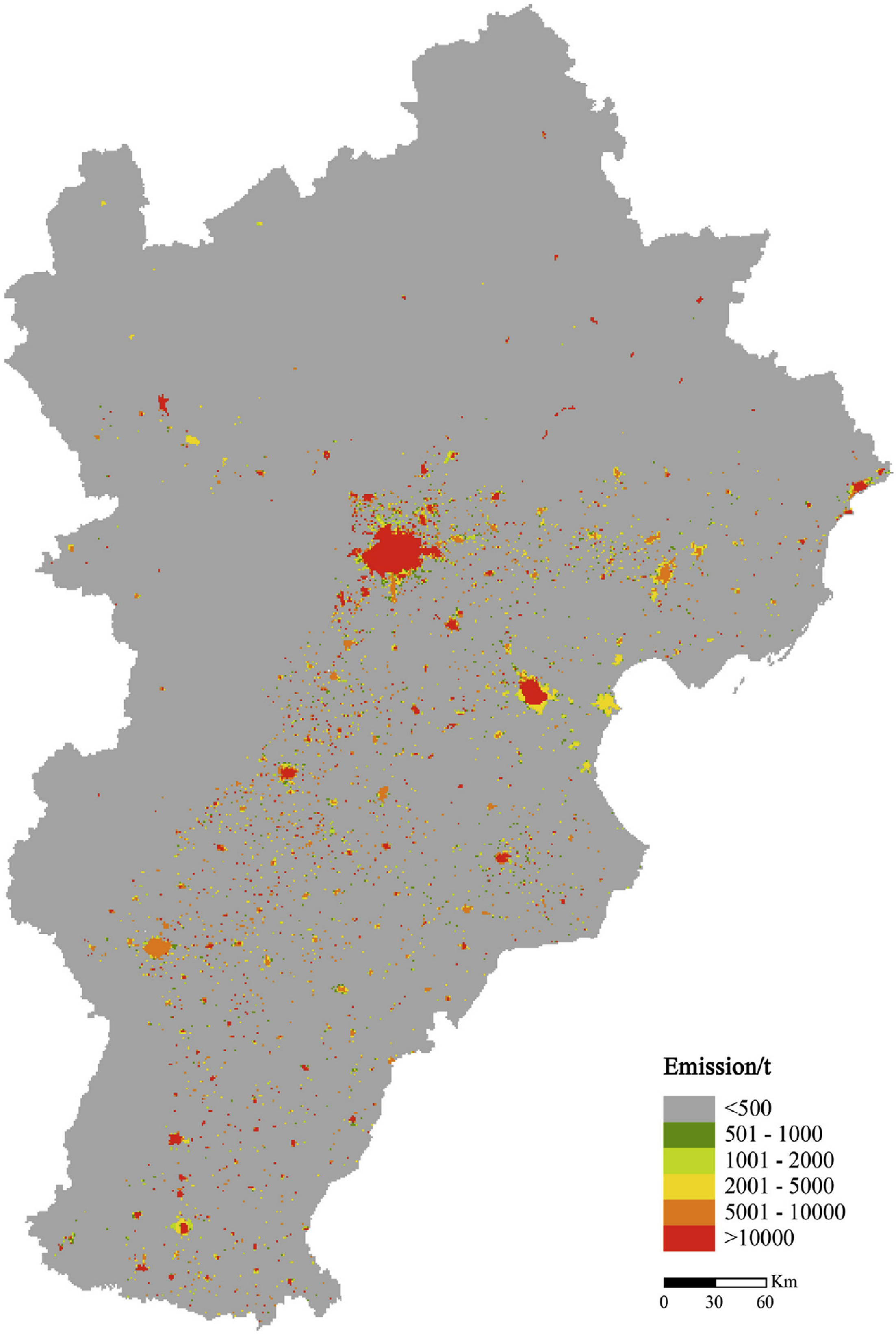

Fig. 6. 1 km gridded CO_2 emissions of household sector of Jing-Jin-Ji region for 2012.

Table 3
Direct CO_2 emissions, GDP, and land area of identified urban extents, relative to administrative regions in the Jing-Jin-Ji region.

Dimension	CO_2 Emissions	Beijing	Tianjin	Hebei
Industry	Urban extent (Mt)	57.03	89.08	342.14
	Share in the region (%)	83.58	61.00	41.29
	Urban extent (per capita, t)	3.38	9.97	14.55
	Region (per capita, t)	3.48	11.24	11.52
Household	Urban extent (Mt)	21.69	5.15	17.29
	Share in the region (%)	91.61	79.20	49.06
	Urban extent (per capita, t)	1.29	0.58	0.74
	Region (per capita, t)	1.21	0.50	0.49
Agriculture	Urban extent (Mt)	0.12	0.11	0.25
	Share in the region (%)	17.67	13.31	4.66
	Urban extent (per capita, t)	0.01	0.01	0.01
	Region (per capita, t)	0.03	0.06	0.07
Transport	Urban extent (Mt)	18.89	5.14	3.86
	Share in the region (%)	77.28	37.29	16.90
	Urban extent (per capita, t)	1.12	0.58	0.16
	Region (per capita, t)	1.25	1.06	0.32
Total direct emissions	Urban extent (Mt)	97.74	99.48	363.54
	Share in the region (%)	83.51	59.51	40.76
	Urban extent (per capita, t)	5.80	11.13	15.46
	Region (per capita, t)	5.97	12.87	12.40
Population	Urban extent (1000 person)	16865.41	8933.92	23517.18
	Share in the region (%)	85.96	68.78	32.69
GDP	Urban extent (billion RMB)	1466.37	963.30	1135.87
	Share in the region (%)	82.01	74.71	42.74
Area	Urban extent (km2)	2786.33	2079.37	7860.00
	Share in the region (%)	16.98	17.45	4.17
Number of urban extent		15	16	182

negatively associated with CO_2 emissions from agriculture for mega and large-sized urban extents (column C, Table 4).

Collectively, population size and compact urban design are positively associated with CO_2 emissions from transport for all urban extents. Large-sized urban extents were associated with lower CO_2 emissions from transport than those small-sized. In particular, population size was found to be positively associated with CO_2 emissions from transport for mega and large-sized urban extents. Economic productivity of land use was found to be negatively associated with CO_2 emissions from transport for medium-sized urban extents. Carbon intensity of GDP was found to be negatively associated with CO_2 emissions from transport for mega-sized urban extents (column D, Table 4).

Population size, less compact urban design, economic productivity of land use, and carbon intensity were all found to be positively associated with indirect CO_2 emissions for all the urban extents. Large-sized urban extents had lower indirect CO_2 emissions than those small-sized but medium-sized urban extents higher than those small-sized. In particular, population size was found to be negatively associated with indirect CO_2 emissions for mega and medium-sized urban extents but positively associated with that from large-sized urban extents. Compact urban design was found to be negatively associated with indirect CO_2 emissions for large-sized urban extents. Economic productivity of land use was found to be positively associated with indirect CO_2 emissions for both large and medium-sized urban extents. Carbon intensity of GDP was found to be positively associated with indirect CO_2 emissions for mega-sized urban extents but negatively associated with that from large and medium-sized urban extents (column E, Table 4).

4. Discussion and policy implications

4.1. Scale and methods of inventorying CO_2 emissions in cities

As subnational governments take initiatives to combat climate change, it is important to build carbon emissions inventories linked to human activities and urban infrastructure for developing carbon mitigation action plans that can deliver results on the ground. Gurney et al. have advocated for calculating carbon footprint at the level of streets, buildings and communities for cities (Gurney et al., 2015). Obviously, the bottom-up approach based on 1 km gridded data adopted in this paper is useful for achieving a nuanced understanding of CO_2 emissions from urban areas.

4.2. Spatial variations in composition and impacting factors of CO_2 emissions

It is particularly in need for the Chinese government to take into consideration the spatial dimension in policy formulation to suit local conditions. In March 2014, Chinese Government released “New Type of Urbanization” policy with the aim to reach urbanization to 60% by 2020. For the first time, limiting built up land was envisioned and infrastructure investment in order of 6–7 trillion dollars are on pipe line. Managing this urbanization is very important. A top-down approach is the norm in policymaking and implementation in China. However, as this paper has demonstrated, regional disparities exist in both the composition and driving forces of CO_2 emissions from industry, agriculture, household, transport and indirect sources in the Jing-Jin-Ji region. Those differences are the result of unevenly distributed population, industries, and services, besides natural endowments (Wang et al., 2012; Zhang et al., 2015). Similarly, Wu et al. (2016) found different patterns emerged among the 286 Chinese cities in per capita CO_2 emissions by geographical, income and environmental policy groups. Instead of making policies based on administrative jurisdictions, it may be a better approach to target urban extents that share common characteristics in terms of mega, large, medium, and small sizes. Thus, in advancing regional integration and collaboration between different localities in the Jing-Jin-Ji region, differentiated development strategies could be formed for different clusters of urban extents, across Beijing, Tianjin, and Hebei province, the three administrative regions.

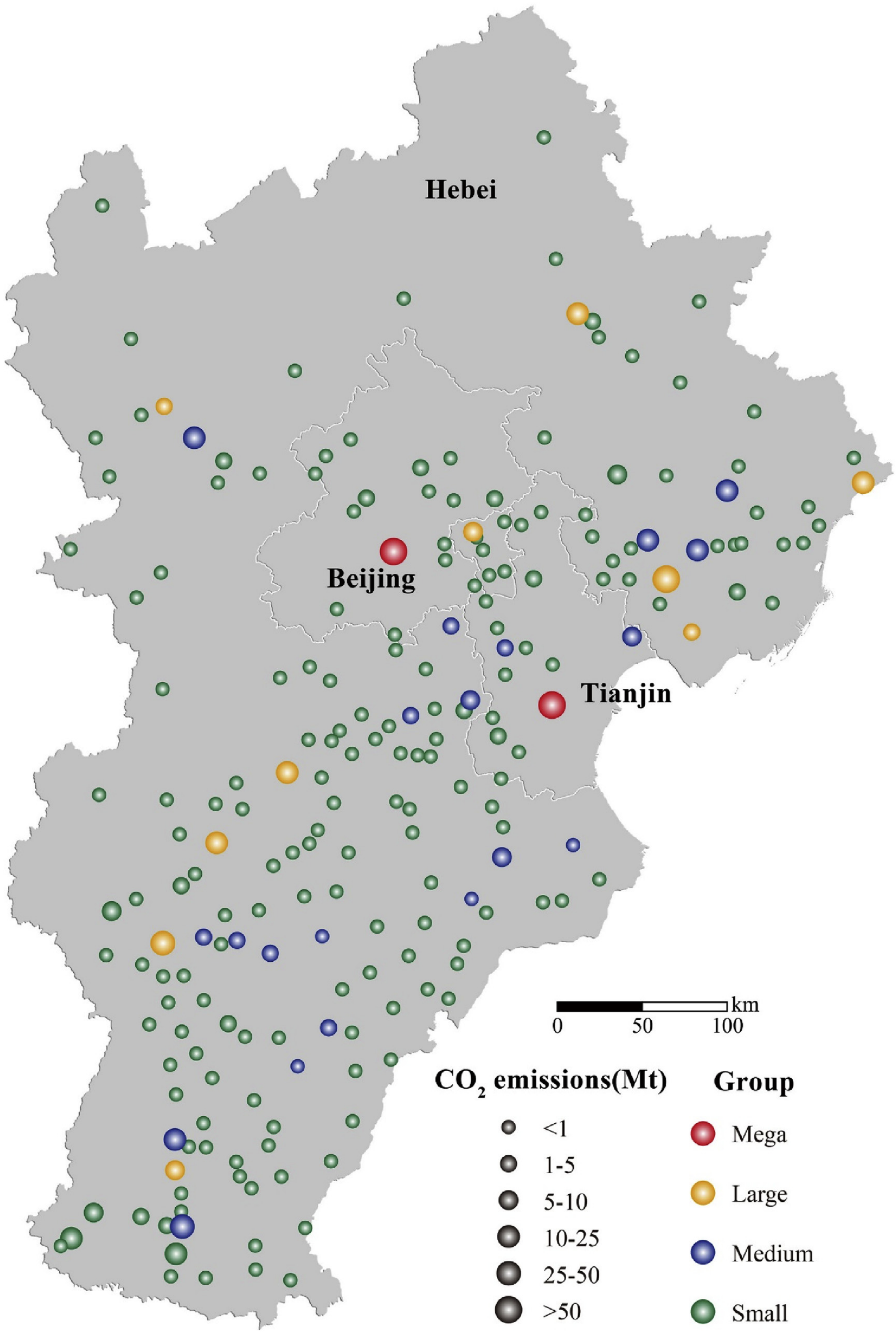

Fig. 7. Spatial distribution of total CO_2 emissions from identified urban extents in the Jing-Jin-Ji region.

Table 4
Decomposition of CO_2 emissions from industry, household, agriculture, transportation, and indirect sources from identified urban extents, considering interaction effects.

	(A) Industry	(B) Household	(C) Agriculture	(D) Transport	(E) Indirect
Population (POP)	1.236 (31.58)***	0.881 (26.14)***	0.767 (16.64)***	1.095 (12.42)***	0.917 (42.10)***
Urban design (UD)	1.618 (11.67)***	0.183 (1.54)	1.337 (7.13)**	1.453 (3.84)*	0.852 (23.38)***
Economic productivity of land use (LU)	1.433 (8.21)**	−0.061 (1.68)	0.244 (2.87)	0.430 (1.61)	0.808 (17.00)***
Carbon intensity of GDP (CI-GDP)	1.684 (29.55)***	0.009 (0.37)	−0.062 (1.15)	0.006 (0.07)	0.450 (13.14)***
Large	14.543 (5.68)**	−42.312 (34.07)***	−35.359 (49.55)***	−22.909 (6.39)**	−7.935 (15.46)***
Medium	1.433 (0.47)	−10.417 (2.43)	−5.578 (9.08)**	5.395 (1.24)	33.724 (20.62)***
POP × mega	−0.147 (7.34)**	0.699 (102.40)***	0.139 (6.15)**	0.768 (11.51)***	−0.124 (13.90)***
POP × large	−0.660 (16.86)***	2.325 (68.98)***	1.707 (37.04)***	1.103 (12.52)***	1.004 (46.13)***
POP × medium	−0.392 (6.46)**	0.793 (3.14)*	0.244 (4.50)**	−0.389 (2.42)	−1.514 (13.17)***
UD × large	−1.545 (11.14)***	2.042 (17.16)***	1.182 (6.30)**	0.586 (1.55)	2.760 (75.70)***
UD × medium	−0.907 (6.79)**	0.127 (0.63)	0.350 (3.73)*	−0.630 (2.05)	0.276 (1.18)
LU × large	−0.378 (2.16)	−0.713 (19.65)***	−0.666 (7.83)**	−0.438 (1.64)	1.335 (28.09)***
LU × medium	−0.517 (2.76)	−0.048 (1.08)	−0.102 (3.02)*	−0.317 (6.67)**	0.740 (12.81)***
CI-GDP × mega	0.242 (5.46)**	−1.140 (46.81)***	−0.057 (3.46)*	−1.230 (9.54)**	0.186 (8.47)**
CI-GDP × large	−0.127 (2.23)	−1.138 (45.07)***	−0.330 (6.12)**	−0.228 (2.87)	−0.445 (12.99)***
CI-GDP × medium	0.158 (3.21)*	−0.117 (2.99)*	−0.030 (0.41)	−0.150 (1.50)	−0.653 (10.32)***
Constant	−8.596 (3.36)*	−0.784 (0.63)	−6.155 (8.62)**	−5.241 (1.46)	3.729 (7.26)**
Observations	162	201	198	213	205
R-square	0.84	0.75	0.89	0.82	0.90

Note: * significant at 10%; ** significant at 5%; *** significant at 1%. Robust t statistics in parentheses.

4.3. Sectoral differences in composition and impacting factors of CO_2 emissions

Besides spatial dimension, CO_2 emissions demonstrated different features from industry, household, agriculture, transport, and indirect sources, even for urban extents of a same cluster. The results echo the study by Tan and Lu showing sector-specific patterns of CO_2 emissions, moderated by their share in local GDP for the Bohai Rim region (Tan and Lu, 2015). Particularly, large-sized urban extents had lower CO_2 emissions per capita than that from those small-sized for household, agriculture, transport and indirect sources, but not for industry. Compared with others, large-sized urban extents had the highest per capita CO_2 emissions of 33.2 ton (mega-sized, 11.1 ton; medium-sized, 28 ton; small-sized, 11.1 ton), mainly attributable to industrial sources (28.4 ton) (Table 2, SI). Furthermore, compact urban design was found to be negatively associated with CO_2 emissions from households but positively associated with that from industry for large-sized urban extents. Thus, even in a same urban extent, policymakers have to examine carefully development strategies such as increasing population density, adopting compact city design, and/or attracting investments that yield high GDP, as they may have different carbon implications for different sectors (Baiocchi et al., 2015; Guan et al., 2008).

4.4. Limitations of the study

In the above analysis, only carbon emissions from scope 1 and 2 were included but not scope 3, due to data availability and complexity in computation. The scope 3 emissions play an important role in system accounting of urban CO_2 emissions. In future analysis, we aim to consider CO_2 emissions in scope 3 in urban structure such as water supply and use of construction materials. Recent study by Müller et al. shows that embodied emissions in infrastructure if developing countries catch-up with developed countries in terms of per capita infrastructure stock would amount close to one third of carbon budget that we have left to emit till 2050 to stay under 2° climate stabilization (Müller et al., 2013).

Furthermore, this study only used cross-sectional data from the year of 2012 for analysis thus drawing temporal change perspectives is not possible. Existing longitudinal studies on CO_2 emissions have been mainly at a provincial level (Fang et al., 2015). Given the ongoing efforts in compilation of carbon emissions inventories for urban extents in China over time, we aim to conduct more nuanced temporal and spatial analysis for understanding dynamics of carbon implications of China's transformation and driving forces in the future. Of course, with a panel carbon emissions dataset, instead of using Kaya equation for decomposition analysis, we will adopt alternative analytical models for disentangling effects of population, land use, industrial development, and consumption on carbon emissions.

Lastly, data used for this analysis was compiled from multiple sources. It is widely acknowledge both official statistics and self-reported data by industrial facilities involve unintentionally and/or intentionally introduced biases. And the rescaling exercise adopted for mapping carbon emissions to 1 km grid will add one more source of inaccuracy. Unavoidably, those errors have been added up toward our final results on Scope 1 and Scope 2 CO_2 emissions from the 213 urban extents in the Jing-Jin-Ji region, although we have exercised care to the largest extent to avoid errors in calculation.

5. Conclusions

This paper has made a modest step forward on both delineating boundaries for urban areas and compiling carbon emissions inventory using a bottom-up approach, based on data mapped against 1 km grid. We identified altogether 213 urban extents in the Jing-Jin-Ji region. Our constructed carbon inventory for those urban extents resonated well with that derived from official statistics for Beijing, Tianjin, and Hebei province (11.40 per cent higher than the reference approach). Per capita direct CO_2 emissions from the identified urban extents in Beijing and Tianjin were both lower than their provincial averages. Those results suggest the delineated boundaries of urban extents in both Beijing and Tianjin have captured intensive human activities, in line with findings from developed countries such as the U.S. (Brown et al., 2009; Glaeser and Kahn, 2010) and a sample of five representative cities in high income countries (Hoornweg, 2011).

As a whole, the urban extents in the Jing-Jin-Ji region had disproportionally highly concentrated human and economic activities while regional disparities still existed. The comparison between urban extents with non-urban areas as well as cross-regional comparison between Beijing, Tianjin, and Hebei revealed spatial patterns of CO_2 emissions in the Jing-Jin-Ji region. We found the urban extents in the Hebei province were mainly industrial centers but those in Beijing and Tianjin were more service oriented and bear more diverse functions. On average, industries in the Hebei province were more carbon intensive relative to both population and GDP, than those in Beijing and Tianjin.

Across the Jing-Jin-Ji region, average per capita CO_2 emissions from household in urban extents scored higher than provincial averages, reflecting more carbon intensive urban life styles than that in non-urban areas. Human settlements were more evenly spread out and differences in urban and rural life styles were observed less in Beijing than that in Tianjin and Hebei, measured by the smallest margin higher than provincial average of per capita CO_2 emissions from household.

Agricultural activities were concentrated more in non-urban areas across the Jing-Jin-Ji region. Urbanization has exhibited advantages across the Jing-Jin-Ji region in lowering per capita CO_2 emissions from transport. Compared with Beijing and Tianjin, Hebei province had the most climate benefit from urban transport, measured by the highest margin below provincial average of per capita CO_2 emissions from transport.

The decomposition of CO_2 emissions from industry, household, agriculture, transport, and indirect sources revealed population size to be a common driver but carbon implications of urban density, economic concentration, and carbon intensity of GDP were both size- and sector-specific. The 10 large-sized urban extents in Hebei province deserve special attention as they had the highest average per capita CO_2 emissions among all the 213 urban extents in the Jing-Jin-Ji region in 2012 and a same driving force had contradictory climate implications for the industrial and residential sectors. Thus, there is no one-size-fits-all solution for carbon mitigation but policymakers have to be sensitive to local conditions such as size of an urban area and its sector compositions.

Of course, limited by cross-sectional data used in this paper, the above conclusions are far from definite. For supporting evidence-based policymaking for carbon mitigation and sustainable urbanization, we expect to see more emerging research adopting a bottom-up approach in building carbon inventories for urban extents and linking to temporal and spatial patterns of human and economic activities and urban infrastructures. That research can potentially lead to differentiated mitigation strategies by cluster of urban extents and/or by sectors that can help make a difference on the ground.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jenvman.2017.11.038.

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