



A new method of hotspot analysis on the management of CO₂ and air pollutants, a case study in Guangzhou city, China

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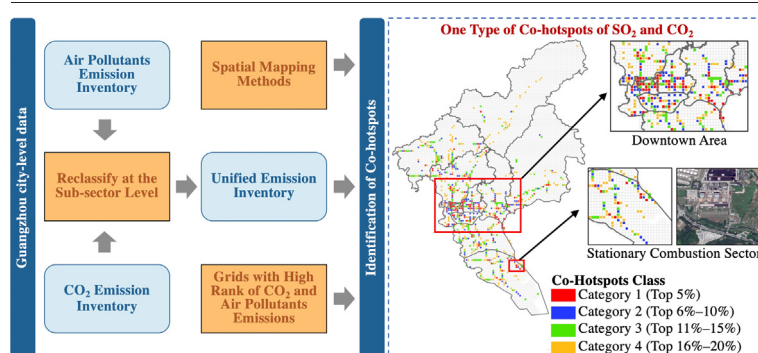
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HIGHLIGHTS

- This study established a unified emission inventory for both CO₂ and air pollutants.
- Stationary combustion and transportation contributed most to CO₂ and air pollutants.
- The developed hotspot analysis enabled accurate identification of high-emission grids.
- Most CO₂ and air pollutants were attributed to the top 10 % emission grids in Guangzhou.

GRAPHIC ABSTRACT



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ABSTRACT

Emission inventory plays an important role in designing effective emission control strategies. Currently, there is unbalanced development of CO₂ and air pollutant emission inventories in China and the spatial information of both cannot be obtained simultaneously, which prevents a collaborative control strategy. In this study, we developed a unified emission inventory including both CO₂ and air pollutants, then utilized spatial mapping methods to identify the co-hotspots of both CO₂ and air pollutants at a high spatial resolution (1 × 1 km²). We applied Guangzhou city as a case study to illustrate the method. The results showed that CO₂ and air pollutants were mainly emitted from the stationary combustion sector and the transportation sector. These two sectors contributed 95 %, 67 %, and 93 % to total CO₂, SO₂, and NO_x emissions, respectively. Up to 86 %, 86 %, 66 %, and 72 % of total CO₂, SO₂, NO_x, and PM_{2.5} emissions were attributed to the top 10 % emission grids with 1 × 1 km² resolution. However, our results showed high emission grids were not surrounded by other high emissions for all types of emissions analyzed in this study. The co-hotspot analysis enables accurate identification of high-emission grids, which helps environment managers to prioritize resource allocation when designing control strategies. Our study underscores the importance of managing CO₂ and air pollutants simultaneously at the city level.

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1. Introduction

China faces dual challenges of climate change and air pollution. To battle against the climate challenge, China, as the world's largest CO₂ emitter (BP, 2021), pledged to implement aggressive actions in the Climate Ambition Summit (Climate Ambition Summit, 2020) to reach the CO₂ emission peak before 2030 and carbon neutrality by 2060. On the other hand, China implemented stringent clean air policies to address air pollution (State Council of the People's Republic of China, 2013, 2018). Despite the noticeable improvement in air quality, air pollution is still a critical problem in China. About 30 % of Chinese cities still fail to meet the national fine particulate matter (PM_{2.5}) standard (i.e., an annual average of 35 µg/m³) in 2021, let alone the 5 µg/m³ standard by the World Health Organization (World Health Organization, 2021). Besides, there is a lack of synergy in CO₂ mitigation and air pollution control under current policies (Zhang et al., 2022). To address both challenges, effective emission control strategies are needed. Studies have shown that a comprehensive emission inventory is crucial for effective emission control strategies and policies as it provides foundations to formulate effective environmental management plans based on the emission characteristics, the major contribution of different sources, and the spatial profile of the emissions (Crippa et al., 2020; D'Avignon et al., 2010).

Currently, there is an unbalanced development between CO₂ and air pollutant emission inventories in China. In the past decade, the air pollutant emission inventory had been well established (Li et al., 2017; Zhang et al., 2009), which provided comprehensive and sufficient support for the Chinese government to address its air pollution problem. For example, the Multi-resolution Emission Inventory for China (MEIC) provided an open-access dataset that estimated the anthropogenic emissions in China (MEIC, 2021). The latest version was developed in 2021, with an update to the 2020 inventory and a spatial resolution of 27 × 27 km². In contrast, the CO₂ emission inventory in China is less developed. The national greenhouse gas (GHG) inventory was only updated to the year of 2014, and the 2016 version was still under development (MEE, 2018). Furthermore, the

guideline for provincial GHG inventory was published in 2010 (NDRC, 2011). Some studies (C40 Cities, 2021; WRI China, 2015) tried to construct the CO₂ emission inventory at the provincial or city level. However, these inventories were developed for research purposes and the data were not publicly available. The inventory results were not comparable among different studies due to different inventory scopes and calculation methods applied, which limited the broader application of these inventories (Xu, 2018). A lack of a systematic CO₂ emission inventory in China prevents cities from understanding the emission characteristics and formulating targeted control measures, and thus, greatly hinders China's ability to achieve its ambitious CO₂ mitigation goals.

Considering the differences between CO₂ and air pollutant emission inventories, two challenges should be addressed to better facilitate city-level CO₂ emission reduction and air pollution control. First, there is a mismatch in the sectors of CO₂ and air pollutant emission inventories. Currently, the CO₂ emission inventory mainly refers to the 2006 IPCC (Intergovernmental Panel on Climate Change) Guidelines for National GHG Inventory (Eggleston et al., 2016), the 2019 Refinement to the 2006 IPCC Guidelines for National GHG Inventory (IPCC, 2019), and Guidelines for Provincial GHG Inventory (NDRC, 2011); while the air pollutant emission inventory mainly refers to the technical guidelines issued by the Ministry of Ecology and Environment (MEE, 2014a, 2014b). As such, two independent categories of guidelines led to distinct inventory structures and classification and a unified emission inventory was missing. Second, previous studies usually mapped either CO₂ (Cai et al., 2018a) or air pollutant (Bai et al., 2020; Qi et al., 2017) emissions separately.

To bridge the above gaps, we developed a unified emission inventory of CO₂ and air pollutants to address the core issues on data sources, inventory structure, and spatial distribution. Based on the unified emission inventory, our study mapped both CO₂ and air pollutant emissions at a high spatial resolution (1 × 1 km²), which allowed us to identify high emission grids for both emissions, namely the “co-hotspots”. The unified emission inventory developed in this study could provide better support for designing and implementing collaborative control strategies for Chinese cities.

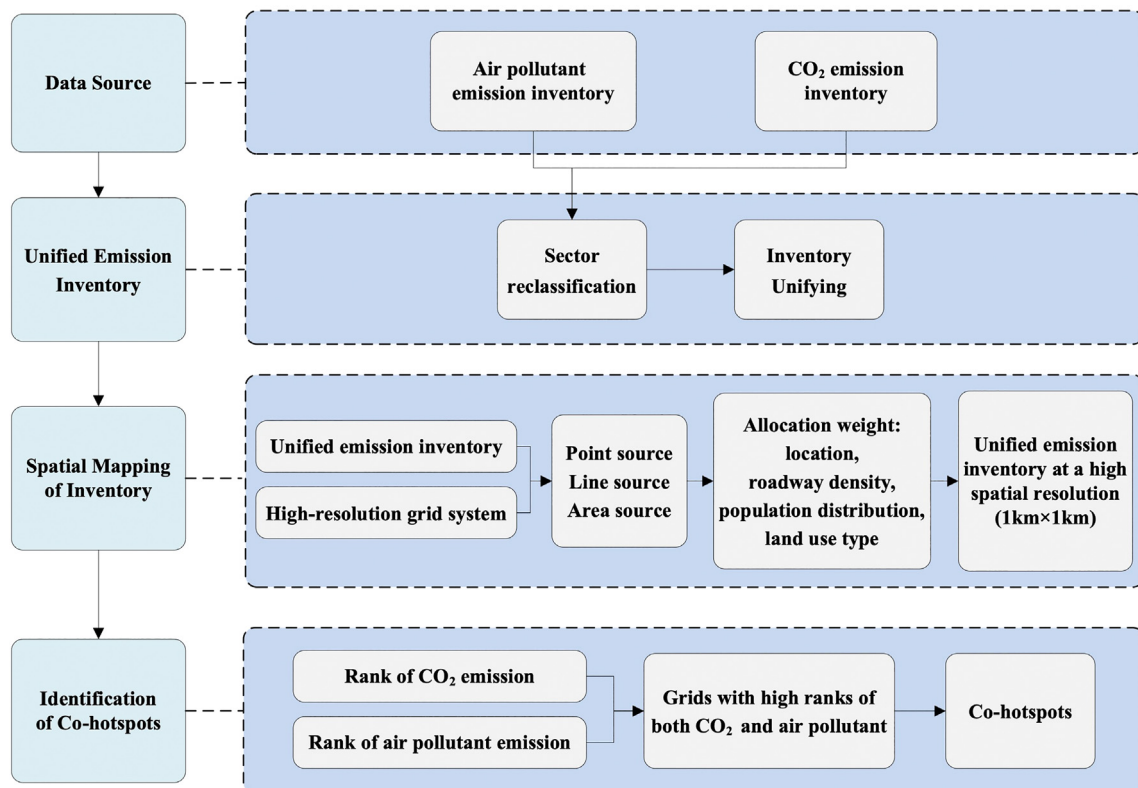


Fig. 1. The overall framework to develop a unified emission inventory and identify co-hotspots of both CO₂ and air pollutant emissions.

2. Data sources and methods

Fig. 1 presents the framework for the development of a unified emission inventory and the identification of co-hotspots. Based on the existing CO₂ and air pollutant emission data, a unified emission inventory was first established by reclassifying both emission inventories at the same sub-sector level. The spatial mapping methods we developed previously (Cai et al., 2018a; Cai et al., 2019b) were then used to allocate the unified emission inventory. Finally, co-hotspots of both CO₂ and air pollutant emissions were identified according to their ranks across all spatial grids.

2.1. Study area

Guangzhou city is a developed city located in the Pearl River Delta region and a national low-carbon pilot city in China. We used Guangzhou as a case study to develop and illustrate the method in this study. The air quality in Guangzhou has improved in recent years. PM_{2.5} concentrations were reduced from 36 µg/m³ in 2015 to 30 µg/m³ in 2019 due to strict air pollution control measures. However, the CO₂ emissions in Guangzhou have increased steadily since 2005. The basic information about Guangzhou city, including the districts, population, and roadway distribution, is presented in Fig. 2. We included 7556 grids with 1 × 1 km² resolution based on the administrative boundary of Guangzhou city and chose 2018 as the study year.

2.2. Data sources

The CO₂ emission inventory was compiled by the China City Greenhouse Working Group (CCG, 2020) and sourced from the China High-Resolution Emission Database (CHRED) 3.0 (Cai et al., 2018a; Cai et al., 2019a, 2019b). CHRED 3.0 Database was compiled by utilizing bottom-up, enterprise-level point-source data. We focused on CO₂ emissions from fossil fuel combustion and industrial processes, instead of those from land use, land-use change, and forestry. The air pollutant emission inventory was

compiled by referring to the technical guidelines issued by the Ministry of Ecology and Environment (MEE, 2014a, 2014b) and city-level environmental statistics (National Bureau of Statistics, 2020). Overall, seven air pollutants (sulfur dioxide (SO₂), nitrogen oxides (NO_x), particulate matter (PM_{2.5}, PM₁₀), volatile organic compounds (VOCs), carbon monoxide (CO), and ammonia (NH₃)) were included, covering emissions from point, line, and area sources. The gridded population data were sourced from the Resource and Environment Science and Data Center compiled by the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences (CAS Institute of Geographic Sciences and Natural Resources Research, 2021).

2.3. Methods

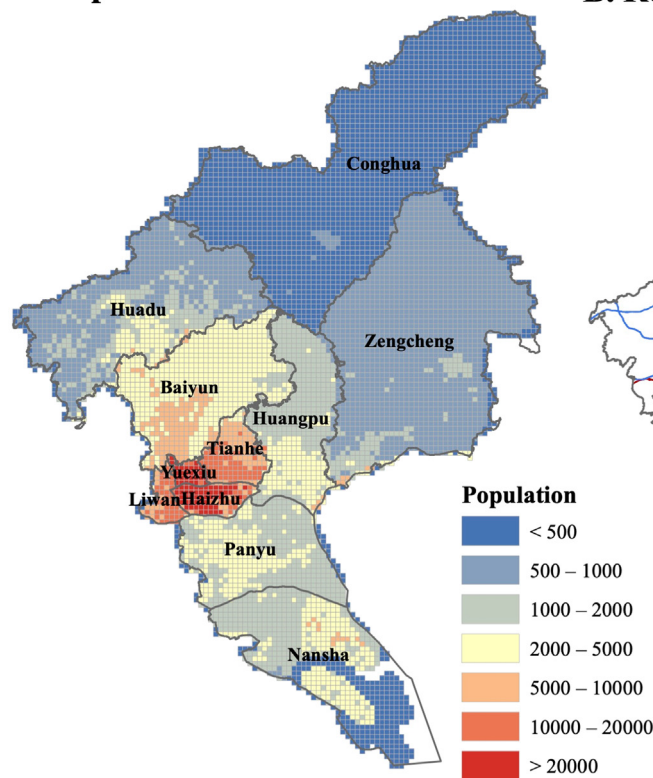
2.3.1. Establish a unified emission inventory of CO₂ and air pollutants

To establish a unified emission inventory, we examined the data sources, emission inventory structure, and classification at the sub-sector level. Originally, there were six major emission sectors (industry energy, industrial processes, agriculture, transportation, residential building, and service building) in the CO₂ emission inventory and ten major emission sectors (stationary combustion, industrial processes, agriculture, transportation, solvent use, waste disposal, oil and gas storage and transportation, dust, biomass burning, and other emission sources) in the air pollutant emission inventory. Using the classification method of the air pollutant emission inventory as the standard, we reclassified the sectors of the CO₂ emission inventory so that CO₂ and air pollutant emissions from the same emission sources would be categorized into the same sub-sector. As such, we established a unified emission inventory that integrated both CO₂ and air pollutant emissions. A detailed description of the reconciliation of sub-sectors between the inventory of CO₂ and air pollutant could be found in the Supplementary Material.

2.3.2. Spatial mapping of the unified emission inventory

Based on the unified emission inventory with emissions from point sources, line sources, and area sources, we allocated emissions into specific

A. Population Distribution



B. Roadways Distribution

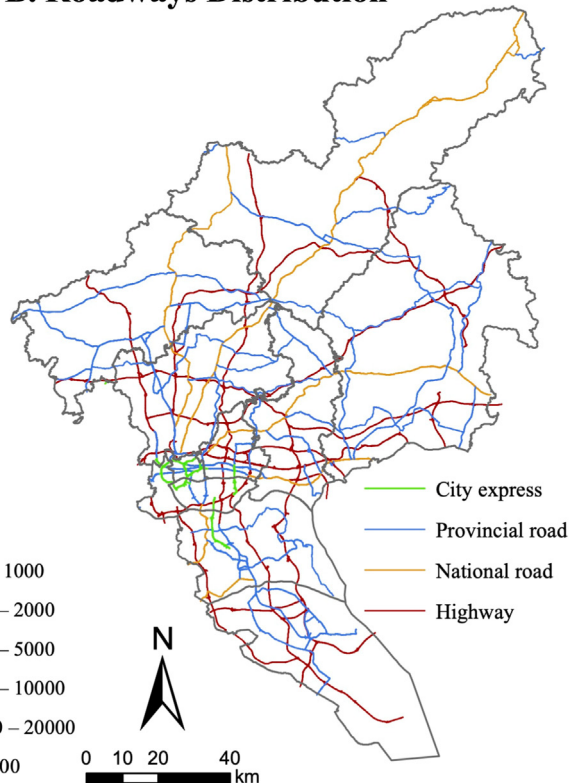


Fig. 2. The distributions of (A) Population and (B) Roadways in Guangzhou in 2018.

grids and obtained a high-resolution emission inventory using the ArcGIS platform. For each grid, detailed information including CO₂ and air pollutant emissions with sectoral classification could be obtained. The detailed methods of the spatial mapping process can be found in our previous work (Cai et al., 2018a; Cai et al., 2019b). Briefly, point source emissions, such as power plants or industries, were assigned to the grid based on the location information. We calibrated the locations of point sources using longitude and latitude data. For line source emissions (e.g., road transportation sub-sector), the emissions were allocated to the grid based on the density of roadways. For the waterway sub-sector, the emissions were allocated based on the automatic identification system, which recorded the ships' navigation speed, time, and location. For area sources, such as the service or residential buildings sector, the emissions were allocated to the grid based on the distribution of population and land use type.

2.3.3. Spatial autocorrelation analysis

Further, we used Moran's index (Moran, 1948) to analyze the spatial autocorrelation pattern of CO₂ and air pollutant emissions. As shown in Eq. (1), Moran's index is used to examine the spatial autocorrelation between the grid value and the values of neighboring grids.

$$I = \frac{n \sum_{i=1}^n \sum_{j=1}^n w_{ij} (x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^n \sum_{j=1}^n w_{ij} (x_i - \bar{x})^2} \quad (1)$$

where I is the Moran's index, ranging between -1 and 1 : a higher index represents stronger spatial autocorrelations, while an index equal to zero represents no autocorrelation; n is the number of spatial units indexed by i and j (the space coordinate); x refers to the variable (CO₂, SO₂, NO_x, and PM_{2.5} emissions); $\bar{x}$ denotes the mean of x ; and w_{ij} is a matrix of spatial weights of unit i and j .

2.3.4. Identify hotspots of CO₂ and air pollutant emissions

After establishing the unified emission inventory at a high spatial resolution, we identified the grids of both high CO₂ and air pollutant emissions

spatially, namely the “co-hotspots”. Taking CO₂ and SO₂ emissions as an example, we first ranked all the grids of Guangzhou city from high to low according to their CO₂ or SO₂ emissions independently. Based on the ranks of CO₂ or SO₂ emissions, we classified the grids into five categories, including category 1: top 5 %, category 2: top 6 %–10 %, category 3: top 11 %–15 %, category 4: top 16 %–20 %, and other: the remaining emission grids. Based on the categories of CO₂ and SO₂ emissions, we identified the grids in which CO₂ and SO₂ were both in categories 1–4 as co-hotspots of CO₂ and SO₂. In this study, four types of co-hotspots were identified, including (1) SO₂ and CO₂, (2) NO_x and CO₂, (3) PM_{2.5} and CO₂, and (4) SO₂, NO_x, PM_{2.5}, and CO₂. SO₂, NO_x, and PM_{2.5} were the major focus of air pollutants under current air pollution control policies.

3. Results

3.1. Characteristics of the unified emission inventory

Fig. 3 presents the classification of the unified emission inventory for sub-sectors. In Fig. 3, the blue shadings represent the sectors of the air pollutant emission inventory; the green shadings represent the sectors of the CO₂ emission inventory; the grey shadings represent the sub-sectors; and the orange shadings represent the unified emission inventory.

Specifically, the stationary combustion sector of air pollutant emission inventory corresponds to the industrial energy sector (including the sub-sectors of power and heat generation, power transmission, mining and manufacturing, and other industries) and residential buildings sector (including the sub-sectors of urban and rural buildings) of the CO₂ emission inventory. The industrial processes sector of the air pollutant emission inventory covers more sub-sectors compared to the CO₂ emission inventory. CO₂ emissions from the industrial processes sector are mainly attributed to iron and steel production and cement production, and thus, the contributions from other sub-sectors such as nonferrous metal production and paper industry are not included. The on-road transportation sector for both inventories are consisted of the same sub-sectors, including passenger vehicles (private cars and taxis), commercial vehicles (freight trucks

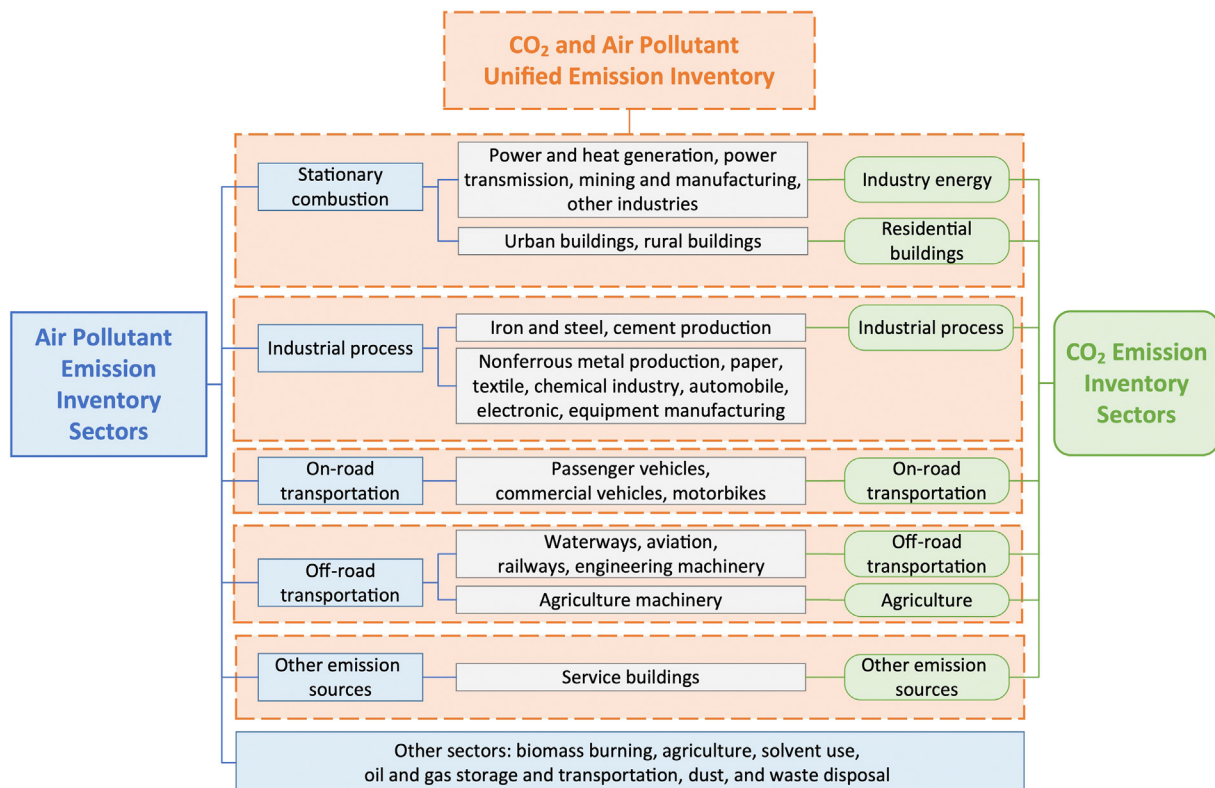


Fig. 3. Reclassification of the air pollutant (blue shading) and CO₂ emission inventory (green shading) by sub-sectors (grey shading).

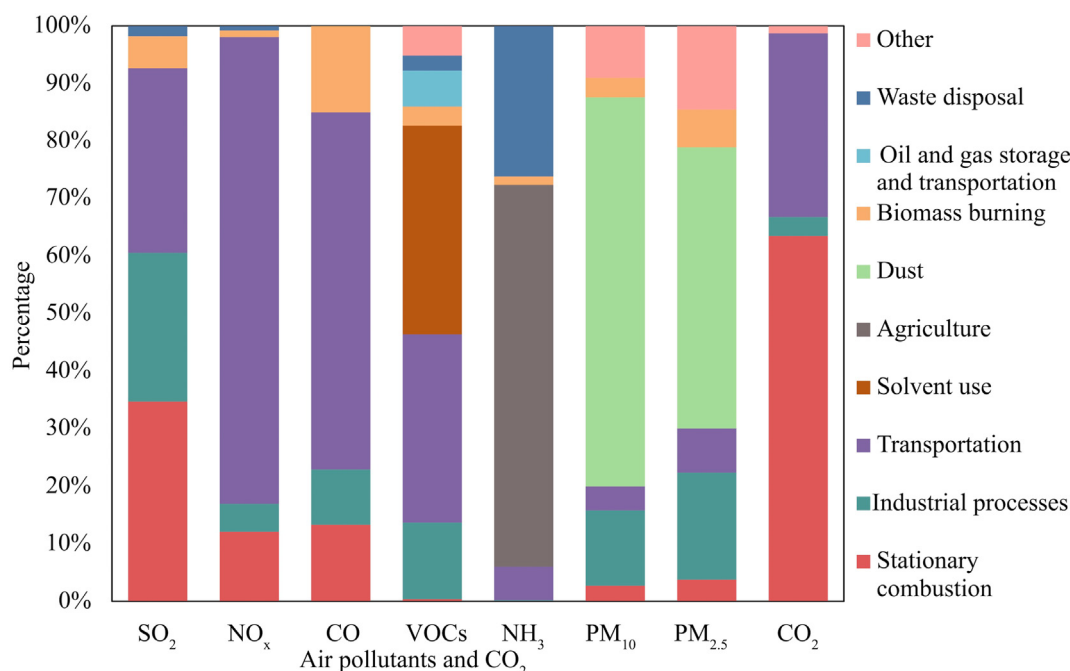


Fig. 4. Sectoral contribution to CO₂ and air pollutant emissions in Guangzhou in 2018.

and buses), and motorbikes. For the off-road transportation sector, both inventories cover waterways, aviation, railways, and engineering machinery. It should be noted that agriculture in the CO₂ emission inventory represents the emission from agriculture machinery, and thus, belongs to the off-road transportation sector of the air pollutant emission inventory.

Based on the unified emission inventory, the sectoral contribution to CO₂ and air pollutant emissions in Guangzhou in 2018 could be obtained, as shown in Fig. 4. The detailed sectoral CO₂ and air pollutant emissions data could be found in Supplementary Table S1. We find that the stationary combustion sector and the transportation sector in particular contribute substantially to both CO₂ and air pollutant emissions. In 2018, these two sectors contribute 95 %, 67 %, and 93 % to total CO₂, SO₂, and NO_x emissions in Guangzhou. More specifically, stationary combustion is a major contributor to both CO₂ and SO₂ emissions, which accounts for 63 % and 35 % of total CO₂ and SO₂ emissions, respectively. The transportation sector is the dominant contributor to NO_x emissions (81 %) and the second-largest contributor (32 %) to CO₂ emissions. Recently, CO₂ emissions from the transportation

sector increase rapidly from 12 Million tons in 2015 to 20 Million tons in 2018 in Guangzhou (Cai et al., 2018a). The transportation sector also contributes 33 % and 32 % to total VOCs and SO₂ emissions, respectively. Therefore, mitigations aiming at controlling the emissions of the stationary combustion and the transportation sectors would have great potential to achieve the co-reduction of both CO₂ and air pollutant emissions. We also find the following sectors contribute substantially to air pollutant emissions, but not to CO₂. For example, the industrial processes sector is a major contributor to total VOCs (13 %), PM_{2.5} (19 %), and PM₁₀ (13 %) emissions. Nevertheless, it accounts for only 2.5 % of total CO₂ emissions. Also, the agriculture and waste disposal sectors are both major contributors to the total NH₃ emissions, but not to CO₂ emissions.

3.2. The spatial distribution of the unified emission inventory

Fig. 5 presents the spatial distributions of air pollutants (SO₂, NO_x, and PM_{2.5}) and CO₂ emissions in Guangzhou in 2018. For SO₂ emissions

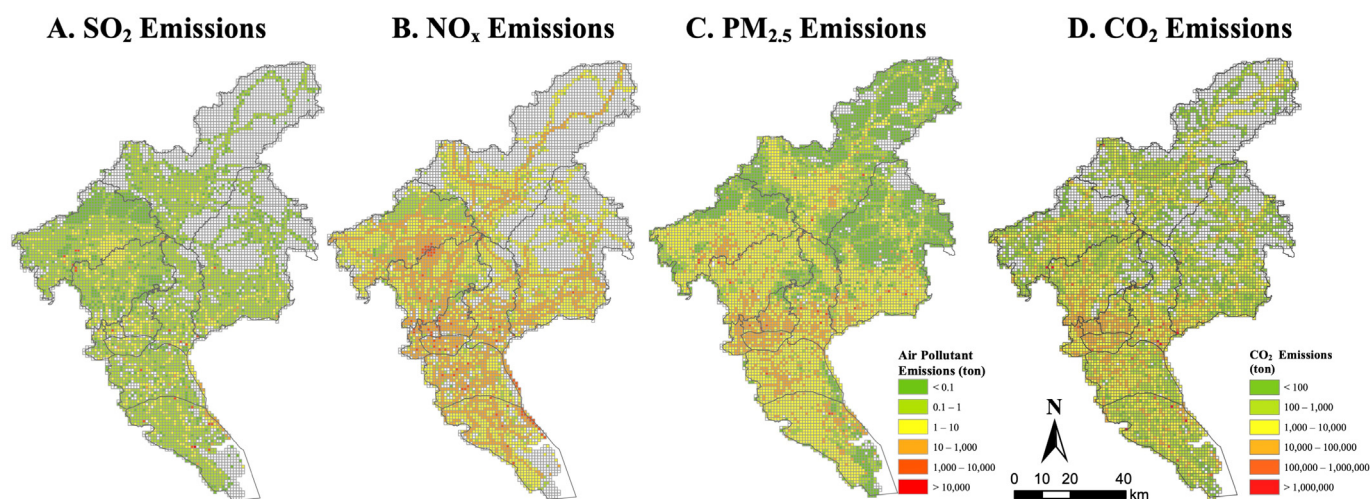


Fig. 5. The spatial distribution of air pollutants (A) SO₂, (B) NO_x, (C) PM_{2.5}, and (D) CO₂ annual emissions in Guangzhou in 2018. The grids in grey color represent no emission.

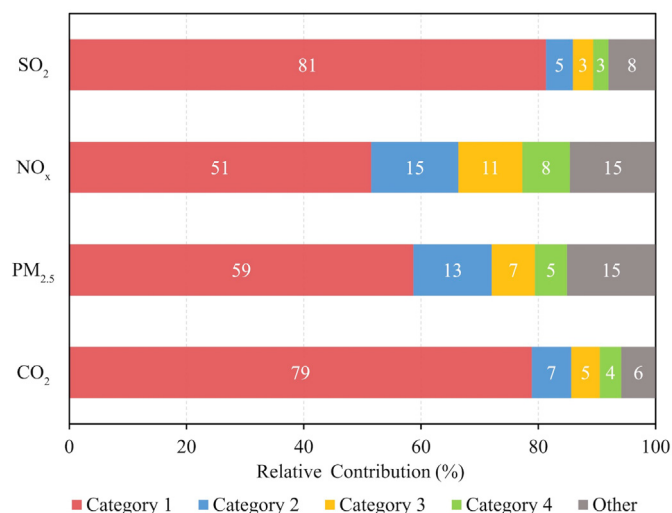


Fig. 6. Relative contribution (%) of different grid categories to total emissions (SO₂, NO_x, PM_{2.5}, and CO₂) in Guangzhou in 2018. According to the emission ranks across all spatial grids, Category 1 represents the top 5 % emission grids for CO₂ or a given air pollutant, Category 2 represents the top 6 %–10 % emission grids, Category 3 represents the top 11 %–15 % emission grids, Category 4 represents the top 16 %–20 % emission grids, and Other represents the remaining emission grids.

(Fig. 5A), the spatial distribution is characterized by extremely large point sources mainly located in the Nansha and Huangpu districts. Specifically, grids with more than 100 tons of SO₂ emissions per year ($N = 64$, the red and light red grids) mainly represent the emissions from the stationary combustion or industrial processes sectors (the power and heat generation, papermaking, and cement production industries). For NO_x (Fig. 5B), high-emission grids are found at the airport (point source), waterways, and roadways (line sources), which are densely distributed in the downtown area (Yuexiu, Tianhe, and Haizhu districts) and near the Baiyun International Airport. For PM_{2.5} (Fig. 5C), high-emission grids are represented by the point sources of major construction sites and the line sources of road transportation. As shown in Fig. 5D, high CO₂ emission grids from point sources (attributed to industrial enterprises in the stationary combustion sector) are mainly located in the Nansha and Huangpu districts, while grids from line sources (attributed to the transportation sector) are distributed in the downtown area. The above results show that air pollutants (SO₂, NO_x, and PM_{2.5}) and CO₂ emissions are unevenly distributed in Guangzhou city.

To better understand the characteristics of air pollutant and CO₂ emissions in Guangzhou, we further analyze the relative contribution of four grid categories to total SO₂, NO_x, PM_{2.5}, and CO₂ emissions (Fig. 6). As illustrated in Figs. 6A–D, we find that the top 10 % emission grids (Categories 1 and 2, see Method for details) contribute 86 %, 66 %, 72 %, and 86 % to total SO₂, NO_x, PM_{2.5}, and CO₂ emissions, respectively. For example, for CO₂, there are 23 grids with more than 0.1 Million tons (the red grids in Fig. 5D), which account for almost all CO₂ emissions in the stationary combustion sector. These emission grids mainly represent the power and heat generation, cement production, iron and steel production, and oil refining industries. Besides, the grid covering the Baiyun International Airport contributes almost 4 Million tons, which accounts for 20 % of total CO₂ emissions in the transportation sector. Other grids with over 10 thousand tons of CO₂ emission are distributed along the major roads in Yuexiu, Tianhe, and Haizhu districts. In addition, high-emission grids are also found in the southeast of Nansha district, representing the emissions from waterway transportation. Overall, the relative contribution results suggest that more than 66 % of total CO₂ or air pollutant emissions are attributable to the top 10 % emission grids (Fig. 6), which should be prioritized for resource allocation in environment management.

As described in the Method section, we use the Moran's index to explore the spatial autocorrelation pattern of high emission grids for CO₂ and air pollutants in Guangzhou, in which higher Moran's indices suggest stronger

spatial autocorrelations whereas indices equal to zero represent no autocorrelations. Our result shows that the Moran's index is less than 0.2 for the emission grids of CO₂, suggesting weak spatial autocorrelation for CO₂ across different emission grids (Glazier et al., 2004; Putra et al., 2020). Similar Moran's indices results are also found for each type of air pollutant (SO₂, NO_x, and PM_{2.5}) across emission grids. As such, high emission grids are not surrounded by other high emissions grids for all types of emissions analyzed in this study.

3.3. Identification of the hotspots

To set priorities in environmental regulation when designing control strategies for CO₂ and air pollutant emissions, we identify the high emission grids of both air pollutants and CO₂, namely the “co-hotspots”, at a spatial resolution of $1 \times 1 \text{ km}^2$, and the results are shown in Fig. 7. As SO₂, NO_x, and PM_{2.5} are the major air pollutants under current air pollution control policies, four types of co-hotspots are identified, including (1) SO₂ and CO₂, (2) NO_x and CO₂, (3) PM_{2.5} and CO₂, and (4) SO₂, NO_x, PM_{2.5}, and CO₂. The co-hotspots are divided into four categories from category 1 (top 5 %) to category 4 (top 16 %–20 %) according to their ranks across all spatial grids (see Method for details).

As shown in Fig. 7A, the co-hotspots of SO₂ and CO₂ emissions are mainly located in the downtown area (Yuexiu, Tianhe, Liwan, and Haizhu districts), while the rural area (Conghua and Zengcheng districts) generally shows low emission levels. The identified grids are mostly from the stationary combustion sector and the transportation sector, as these sectors account for 67 % and 95 % of total SO₂ and CO₂ emissions, respectively (Fig. 4). In the top 10 % grids (Categories 1 and 2, $N = 112$), there are over 2 tons of SO₂ emissions and 14 thousand tons of CO₂ emissions. The emissions of these 112 grids contribute 31 % and 35 % to total SO₂ and CO₂ emissions in Guangzhou, respectively. The top 10 % grids of SO₂ and CO₂ co-hotspots represent power and heat generation and cement production industries. For example, the grid of Zhujiang Power Plant emitted a large amount of 293 tons of SO₂ and 6 Million tons of CO₂ in 2018.

The co-hotspots of NO_x and CO₂ (Fig. 7B) are mainly distributed along major roadways and from the major point sources of the Baiyun International Airport, Huarun thermal power station, and Maxi industrial park. The combustions of fossil fuel from industrial boilers, diesel vehicles, and aircraft are the main contributors to both NO_x and CO₂ emissions in Guangzhou.

Similar to the spatial pattern of the co-hotspots of NO_x and CO₂, the co-hotspots of PM_{2.5} and CO₂ (Fig. 7C) show an overall pattern of high emissions in the downtown area (Yuexiu, Tianhe, Liwan, and Haizhu districts), where high-density roadways exist. Grids that cover extremely large point sources are also identified, including the power and heat generation and cement production industries, suggesting that the stationary combustion sector is an important source of both PM_{2.5} and CO₂.

Fig. 7D represents the grids with high emissions of multiple air pollutants (SO₂, NO_x, and PM_{2.5}) and CO₂. These co-hotspots are mainly distributed in the downtown area, with scattered grids distributed in the Baiyun and Huangpu districts. Besides, these co-hotspots identified in Guangzhou are mostly accompanied by high population density (Fig. 2A), suggesting that a vast majority of people are being exposed to high levels of air pollutants. As a result, mitigation policies should be prioritized to such co-hotspots to protect the environment and human health.

4. Discussion and policy implication

The unbalanced development in CO₂ and air pollutant emission inventories has been a persisting issue for China. To address this problem, our study establishes a unified emission inventory including both CO₂ and air pollutants. Based on the unified inventory and spatial mapping methods, we identify the high emission grids of both CO₂ and air pollutants and further pinpoint the co-hotspots at a high spatial resolution ($1 \times 1 \text{ km}^2$) in Guangzhou city. The method developed in this study could be easily applied to other cities in China as well as other countries. At present, Chinese

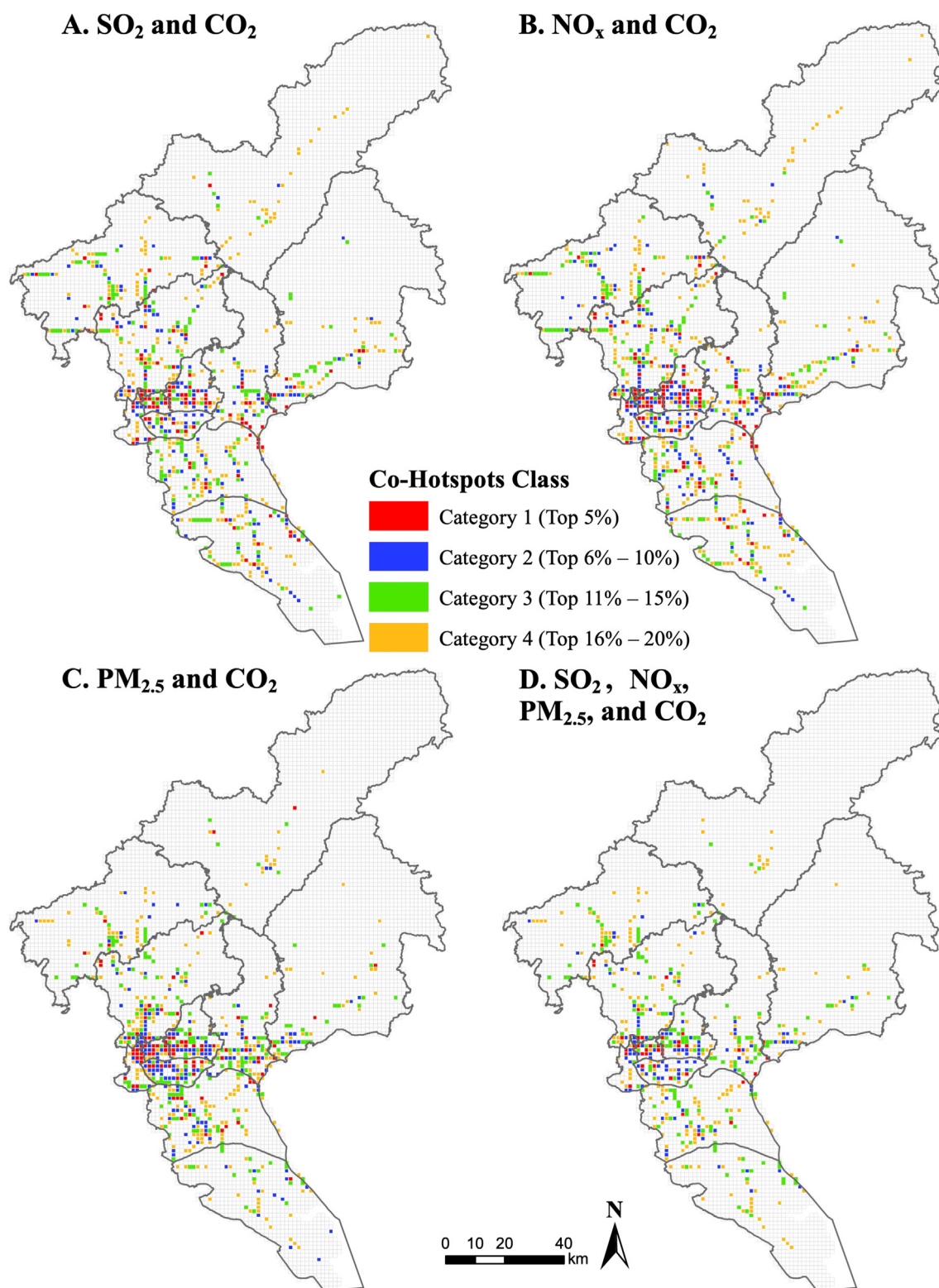


Fig. 7. The co-hotspots of (A) SO₂ and CO₂, (B) NO_x and CO₂, (C) PM_{2.5} and CO₂, and (D) SO₂, NO_x, PM_{2.5}, and CO₂ in Guangzhou in 2018.

cities face dual challenges of CO₂ emission reduction and air quality improvement. Previous studies have suggested that many CO₂ and air pollutants are emitted from the same sources (Lu et al., 2020; Oh et al., 2019), such as the fossil fuel burning, which is supported by our results in Guangzhou. In Guangzhou city, the energy consumptions were mainly based on fossil fuels in 2018, including 1.19E7, 9.37E6, and 4.41E6 tons of coal equivalent (TCE) of coal, oil, and natural gas, respectively (See

Supplementary Table S2 for details). Co-hotspots in Guangzhou are mainly attributed to the stationary combustion sector or the transportation sector. Besides, the high degree of overlapping in the spatial distribution of both CO₂ and air pollutant emissions indicates a great potential for the city to achieve co-reductions. Given the limited environmental management resource, the hotspot analysis helps to set priorities in environmental regulation so that control measures, especially energy-related measures, targeting

at these hotspots can be implemented to achieve the synergy in reducing both emissions.

Our study has several important policy implications. First, the unified emission inventory that integrates CO₂ and air pollutants solves the inconsistency issue in the structures and classification of current emission inventories. Environmental researchers and policymakers can apply the unified emission inventory to directly assess local emission characteristics (Bai et al., 2020; Qi et al., 2017) and the contribution from different sectors (Bai et al., 2020; D'Avignon et al., 2010), which provides a strong rationale to evaluate the effectiveness of previous control measures (Zhang et al., 2013) and design collaborative control strategies and policies in the future. Our method is also supported by IPCC Inventory Guidelines, which suggests that the integration of compiling GHG and air pollutant inventories can help decision makers understand the benefits of control measures and pool resources efficiently (IPCC, 2019).

Second, detailed information, including CO₂ and air pollutant emissions, sectoral contribution, and major emission sources (such as the power and heat generation plants and the transportation hub), could be identified at each spatial grid using our method. In comparison, previous studies only present the spatial distribution of either air pollutants (Bai et al., 2020; Qi et al., 2017) or CO₂ (Cai et al., 2018a), and thus, lack a comprehensive assessment of both emissions spatially. The identified co-hotspots allow us to discover the distribution pattern of grids with high CO₂ and air pollutant emissions (Glazier et al., 2004; Putra et al., 2020). Previous practice based on hotspots has been shown to be effective in air pollution control (Zhao, 2018). Such practices could also be utilized to reduce both CO₂ and air pollutant emissions, considering the noticeable contribution of co-hotspot grids to total emissions. Areas with densely distributed co-hotspots are of a high priority in resource allocation, which could improve the efficiency of environmental management and lower the cost of environmental enforcement (Cai et al., 2018b; Jiang et al., 2020).

Finally, the spatial resolution of CO₂ and air pollutant emissions (i.e., 1 × 1 km²) is greatly improved compared to the existing Emissions Database for Global Atmospheric Research (10 × 10 km²) (Crippa et al., 2018) and MEIC (27 × 27 km²) inventory (MEIC, 2021). Point and line sources contributed to more than 90 % of total CO₂, SO₂, and NO_x emissions in Guangzhou in 2018. The improved spatial resolution allows us to accurately identify the city-level high-emission areas and associated population exposed to multiple air pollutants. For example, people living in the downtown area of Guangzhou (Fig. 2A) are exposed to higher levels of air pollutants. The improved spatial resolution will help the government to realize environmental justice and design mitigation policies accordingly (Wilson et al., 2010).

Our study is subject to several limitations. First, we only use annual emissions. Temporal variations in CO₂ and air pollutant emissions are not included. For more targeted controls, future studies may focus on the seasonal variability of both CO₂ and air pollutant emissions in the industrial sector, or the weekly variability of both emissions in the transportation sector. Second, we only study the emission inventories in 2018. Future studies could utilize our developed method to conduct analysis over multiple years. In addition, future studies should include other important GHGs, such as nitrous oxide, methane, and fluorinated gases, in the unified emission inventory to set priorities in environmental regulation that controls GHGs and air pollutant emissions simultaneously. Also, the establishment of the unified emission inventory could serve for future studies focusing on climate and health effects. Methods such as the intake fraction or similar calculations could be used to investigate human health and climate effects when designing or optimizing control plans. Finally, the spatial mapping of the emission inventory is subject to uncertainties from both the compiling of the emission inventory and the spatial mapping methods. Emission inventories are subject to uncertainties due to the incompleteness of activity data and emission factors (Eggleston et al., 2016). Our previous study shows that the uncertainty of Guangzhou city's GHG emissions, mainly from CO₂, is about 10 % (Cai et al., 2019a). Further research is warranted to investigate the uncertainty in the spatial distribution and improve the data quality. Even with

these limitations, our results are expected to have important policy implications on the collaborative control of CO₂ and air pollutants for Chinese cities.

CRediT authorship contribution statement

Li Zhang: Conceptualization, Data curation, Methodology, Formal analysis, Visualization, Writing – original draft. **Muchuan Niu:** Formal analysis, Writing – original draft. **Zhe Zhang:** Data curation, Writing – original draft. **Jizhang Huang:** Conceptualization, Data curation. **Lingyun Pang:** Conceptualization, Methodology. **Pengcheng Wu:** Data curation, Visualization. **Cheng Lv:** Data curation, Methodology. **Sen Liang:** Methodology. **Mengbing Du:** Writing – original draft. **Mingyu Li:** Writing – original draft. **Libin Cao:** Methodology. **Yu Lei:** Supervision, Writing – review & editing. **Bofeng Cai:** Conceptualization, Supervision, Visualization. **Yifang Zhu:** Conceptualization, Visualization, Supervision, Writing – review & editing.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2022.159040>.

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