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Structural patterns of city-level CO_2 emissions in Northwest China

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Abstract: In Northwest China, quantifying city-level CO_2 emissions is fundamental to CO_2 alleviation but encounters difficulties in data availability and quality. Further, structuring city-level emissions could be conductive to CO_2 reduction. This study applies a practical methodology to 16 northwestern Chinese cities to grasp their historical trajectories of CO_2 emissions. Then, structuring CO_2 emissions is explored in terms of industrial structure, energy mix and urban-rural disparities for 8 northwestern Chinese cities. Results show that: (1) for 16 cities (2010-2015), capital and industrial cities generated most emissions. Meanwhile, CO_2 emissions were mostly incompatible with CO_2 intensity, but consistent with CO_2 per capita; (2) for 8 cities (2006~2015), energy producing sectors, heavy manufacturing sectors, and coal remained major drivers of emissions. Then, the interconnection between industrial structure and energy mix exerted temporally varying impacts on emissions from energy producing sectors and heavy manufacturing sectors. Besides, urban gas consumption and rural coal use continued affecting most of household consumption emissions and household consumption emissions per capita. Moreover, the interplay between emissions and population was changed when emissions by energy type were decomposed among urban and rural households; and (3) uncertainty results averagely fall in the range of -39% to 6%. Finally, implications for CO_2 reduction and future work are proposed.

Highlights

- CO_2 intensity differs from CO_2 emissions and CO_2 per capita across most cities
- Structural changes in CO_2 emissions are city-specific in Northwest China (2006~2015)
- Energy producing sectors and coal are still main drivers of emissions
- Rural coal use remains a vital concern to curb rural household consumption emissions
- The interplay between emissions and household population changes with energy types

Keywords: City; CO_2 emissions; Northwest China; Structural patterns; Temporal changes

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1. Introduction

Climate change has been regarded as one of six sustainability challenge across the globe (Pandey et al., 2011). Climate change mitigation and adaptation need joint endeavors at spatial levels (Peters, 2010). China, the world's largest CO_2 emitter since 2006 (Mi et al., 2017a), has strived to achieve peak CO_2 emissions by 2030 (Climate Council, 2014) and the commitment of reducing CO_2 emissions intensity (i.e. carbon emissions per unit of gross domestic product) in 2030 by 60-65% as compared with the 2005 level (The Chinese Government, 2015). Besides, to meet this objective, the State Council of China has set tailored targets of CO_2 reduction at the province level to ensure fairness because provinces are different significantly in resource endowment, economic development levels and energy consumption patterns (Chang and Chang, 2016). Furthermore, Chinese cities, marked by the high concentration of economic activities and population, have made contributions to about 85% of total CO_2 emissions, while cities of the United States and Europe have accounted for 80% and 65%, respectively (Dhakal, 2009, 2010). Therefore, Chinese cities are considered to be vital participants of assuming CO_2 responsibilities (Shan et al., 2019a).

City-level absolute emissions have gained support in academia although city-scale carbon mitigation policies have been correlated with CO_2 intensity. Supportive reasons are as follows: (1) absolute emissions and CO_2 intensity may generate varied directions in guiding CO_2 reduction. For instance, although the service sector of a city is less emission intensive, the city is also likely to contribute to a large amount of CO_2 emissions (Zheng et al., 2018); (2) although some studies hold that absolute emissions as a single indicator could only assess partial carbon performance (Zhang and Wei, 2015; Zhou et al., 2010), absolute emissions could be more effective than CO_2 intensity when multi-faceted factors are considered together in an integrated and optimization model (Mi et al., 2015); (3) absolute emissions could be measured based on carbon footprint concept which helps generate improvements in climate policy making, cooperate carbon management, lifestyle assessment, and public awareness (Lin et al., 2015; Pandey et al., 2011; Schaltegger and Csutora, 2012); (4) the need to study absolute emissions is stronger after understanding the published reports on CO_2 inventories in China are only confined to the national level, instead of the city level (Shan et al., 2017); and (5) although CO_2 per capita could reflect regional disparities and then are considered as more acceptable than absolute values in emissions distribution (Criado and Grether, 2011), the related main focus is on the national scale with the strict prerequisite that the convergence in CO_2 per capita is supposed to exist (Criado and Grether, 2011).

To calculate city-scale absolute emissions, comparisons have been conducted among scope 1 (direct emissions from onsite fossil fuel consumption), scope 2 (indirect emissions from consuming energy such as purchased electricity, stream and heat) and scope 3 (other indirect emissions) (Lombardi et al., 2017). In addition, as for the accounting systems involved, concepts and contents of territorial, production- and consumption-based systems have been introduced (Lombardi et al., 2017), making accounting boundaries clear. Thus, two main methods have been widely applied, including the IPCC method and the lifecycle assessment (LCA). The IPCC method is a top-down method to track territorial CO_2 emissions (Shan et al., 2017; Yang et al., 2017). By contract, LCA is a method featuring a system thinking that the environmental influences of a product, process or activity on their entire lifecycle could be examined through process-based, input-output-based and hybrid LCA, encompassing both a top-down thinking and a bottom-up one (Lin et al., 2013; Mi et al., 2016; Wang et al., 2016; Yang et al., 2018). However, data constraints have challenged the city-level absolute emissions accounting. For one thing, existing data for energy consumption and industrial products have failed to aid in comparative assessments. It is because megacities and some capital cities are equipped with energy balance tables and other energy information while other cities are not (Guan et al., 2017; Shan et al., 2017; Xi et al., 2011; Xie et al., 2007). For another, other kinds of data (e.g. remote sensing images, interviews with local households and/or local officials, alongside published reports and literatures) could not probably perform well in data consistency and accuracy (Shan et al., 2017), or lack uncertainty analyses (Tong et al., 2018). Facing these two challenges, China Emission Accounts and Datasets (CEADs, www.ceads.net) has completed the methodology capable of being applied to different data status at the city level (Shan et al., 2017), along with case studies (Xu et al., 2018).

Structuring calculated CO_2 emissions over time and space in an absolute manner had increasingly been regarded as the potential approach to discontinuing CO_2 emissions (Cai et al., 2018; Liu et al., 2010; Liu et al., 2012; Tan and Lu, 2015). On one hand, structural analysis techniques (basically including structural decomposition analysis, index decomposition analysis and production-theoretical decomposition analysis) (Li et al., 2017a; Wei et al., 2017) and econometric models (Guan et al., 2018; Meng et al., 2011) have been widely employed in exploring structural patterns in the form of aggregate relative importance, without discussing the role of absolute values in absolute emissions. On the other hand, structural patterns (in the form of absolute values) of absolute emissions have been investigated more at the national level than at the city level. But the national-level angles could inform cities in and outside China of how to structure absolute emissions with respect to industrial structure, energy mix and the urban-rural disparity. It is because: (1) identifying key sectors and forming clusters could be beneficial to improving material efficiency, promoting sustainable consumption and production, and achieving environmental sustainability (Liang et al., 2013; Wang and Liang, 2013); (2) the role of primary energy mix (Marrero, 2010), renewable energy greening energy structure and associated feasible matching with fossil fuel demand (Foidart et al., 2010) has been highlighted in CO_2 reduction; and (3) To alleviate HCE in an efficient and fair manner, it is crucial to explore urban-rural divides in HCE (Wiedenhofer et al., 2017), HCE by energy type (Fan et al., 2015), HCE per capita (Gill and Moeller, 2018), and HCE per capita by energy type (Roberts, 2010).

Northwest China consists of five provinces and autonomous regions. The environment in this area is fragile under climate change threats when it comes to the glacial melt water and river runoff in Xinjiang (Shi et al., 2007), permafrost thawing and glacial retreat on Qinghai-Tibetan Plateau (Chen et al., 2013), and potential environmental threats such as water shortage and CO_2 increments (Li et al., 2015). High CO_2 emissions, the vital contributor of climate change, have become one of the main problems in western China (Guan et al., 2017) where CO_2 intensity has continued being higher than the national average or the level of eastern and central China (Guan et al., 2017; Liang et al., 2016). Besides, western China has been suffering from CO_2 leakage and environmental inequality due to its trade with other regions in and outside China (Feng et al., 2013; Mi et al., 2017b). Moreover, CO_2 emissions induced by peasants and herdsmen were not fallen outside the research agenda, highlighting the equity in CO_2 responsibility allocation (Qu et al., 2013).

When it comes to absolute CO_2 emissions and associated structural patterns in northwestern Chinese cities over time, research gaps are as follows: (1) absolute emissions have not been paid more attention to in CO_2 alleviation than CO_2 intensity (Guan et al., 2017; Li et al., 2016). Further, northwestern Chinese cities have encountered constraints in data availability (Guan et al., 2017; Xie and Fan, 2014) and quality (Xie et al., 2007); (2) spatiotemporal measurements of emissions have not been enough although current researches for other areas have emphasized spatial, temporal or spatiotemporal changes of emissions (Shan et al., 2018; Tong et al., 2018; Xu et al., 2018); (3) detailed comparative analyses across cities have not been sufficient; (4) regarding structural patterns of absolute emissions in light of industrial structure and energy mix, studies have mainly focused on decomposition techniques (Guan et al., 2017), and econometric methods (Yang and Meng, 2019) to gain the relative importance of influential factors, rather than the absolute shares of these factors, in absolute emissions; and (5) although some studies have explored HCE and HCE per capita (Li et al., 2016), and HCE from peasants and herdsmen (Qu et al., 2013), urban-rural disparities in HCE by energy type and HCE per capita by energy type have not been explored.

Therefore, to explore the historical trajectory of CO_2 emissions and emissions-related indicators, 16 cities (2010 ~ 2015) are taken as an example. Then, to grasp the structural patterns of emissions in terms of industrial structure, energy mix and urban-rural divides, 8 cities are chosen from the above 16 cities to cover a longer time period (i.e., from 2006 to 2015). Also, socioeconomic indicators in relation to CO_2 emissions and HCE are analyzed. The reminder is organized as follows: section 2 introduces the methodology and data, section 3 illustrates CO2 emissions of northwestern Chinese cities, section 4 provides socioeconomic indicators of northwestern Chinese cities, and section 5 summarizes conclusions, policy implications, and future work.

2. Methodology, data and datasets

2.1. Scope

The territorial accounting system is employed in this study. Then, the IPCC method within the city boundary is applied to calculate the emissions from fossil fuel combustion and industrial process. It does not measure the emissions from imported energy and heat used during the inter-city transportation process. There are some merits of using this accounting system although calculating both direct and indirect emissions could help provide a holistic view of CO_2 inventory. First, the territorial accounting system could contribute to coping with difficulties in data availability and quality. On the contrary, it is both labor- and time-consuming to measure indirect emissions based on input-output tables for most Chinese cities (Mi et al., 2016). Second, this system could inform domestic energy and emissions intensities of 47 socioeconomic sectors, which is another limit facing the application of input-output model(s) in Chinese cities (Mi et al., 2016). Third, this system could provide information to develop other accounting systems as it helps form structural patterns of emissions in light of industrial structure, energy mix and the urban-rural disparity (Mi et al., 2017a). Finally, this system could help fill the research gaps mentioned in section 1.

2.2. Emission accounts

CO_2 emissions in this study are divided into energy- and process-related emissions. In detail, energy-related emissions are measured in the Eq. (1). Further, the emissions factors are based on the experiment results of 4243 state-owned coal mines in China (Liu et al., 2015b) and from (Shan et al., 2019a). Then, when diverse data situations in northwestern Chinese cities are considered, the different formulas proposed in Shan et al. (2017) could help with comparative city-level studies in a consistent manner.

$$CE = \sum_m \sum_n CE_{mn} = \sum_m \sum_n AD_{mn} \times NCV_m \times EF_m \times O_{mn}, m \in [1,17], n \in [1,47] \quad (1)$$

Where CE are energy-related CO_2 emissions. CE_{mn} refer to CO_2 emissions from sector n consuming fossil fuel m, AD_{mn} represents the consumption of fossil fuel m by sector n, NCV_m is net caloric value, EF_m stand for emission factors and O_{mn} is oxygenation efficiency. $m \in [1,17]$ consists of 3 primary energy sources (i.e. coal, oil and gas) and 14 secondary energy sources transformed from primary energy sources. $n \in [1,47]$ is composed of primary, secondary and tertiary industry, as well as their sub-sectors.

Also, the process-based CO_2 emissions are from 9 industrial processes and calculated in Eq. (2). It is noted that process-based emissions are caused by the chemical and physical reactions during the production process, rather than the energy combustion by industrial sectors.

$$\mathrm{CP} = \sum_p AD_p \times EF_p, p \in [1,9] \quad (2)$$

Where CP are CO_2 emissions from industrial process p, AD_p represents the production of industrial process p, and EF_p is the emission factor of industrial process p. $p \in [1,9]$ consists of 9 industrial processes such as cement and lime production (Shan et al., 2019b).

2.3. Data source

To be compatible with the accounting method of measuring CO_2 emissions in Shan et al. (2017) , data and data processing adjust themselves correspondingly. The first category of data are energy-related data. Energy balance table (EBT), industrial fossil fuel consumption data and industrial products' production data are adopted from the municipal bureau of statistics. So energy accounts could be formed for 47 socioeconomic sectors consuming 17 fossil fuels and for 9 industrial processes. Besides, to avoid double counting, chemical raw materials (introduced as non-energy use in EBT), energy loss during the transportation, and non-burning fossil fuels input during the energy conservation process are removed. However, when these energy-related data are lacking, socioeconomic data (as the second category of data) from the same data source are used to aid in the data processing according to detailed formulas in Shan et al. (2017). The availability status of city-level data could be found in SI from Table S3 to Table S19. The third category of data are the emissions factors we believe suits China and are from (Liu et al., 2015b; Shan et al., 2019a). They are available from (Table S1 and Table S2 in SI). Thus, the final category of data (including remaining emissions factors, net caloric value and oxygenation efficiency representing different combustion technology levels) are from IPCC (2006).

Then, data in relation to this study will be updated in CEADs, a platform where all data available are freely accessible for academic use after registration to achieve the goal of sharing free, transparent and robust data. Updated data cover the CO_2 inventories complied from production and consumption perspectives, energy and socioeconomic inventories at the national, provincial and city levels. Additionally, corresponding methods, applications and publications from CEADs would be the most up-to-date outcomes.

2.4. Uncertainty

Given the uncertainty issues featuring emissions inventories, the corresponding analysis is necessitated to enhance emissions inventories. Monte Carlo simulations are the method empowering the uncertainty to be measured, supported and applied by IPCC (IPCC, 2006). In this study, the term "uncertainty" follows Shan et al. (2018), referring to the upper and lower bounds of a ±48.75 % confidence interval (CI) around the central estimate. Considering the whole process of CO_2 calculation within the territorial accounting system, there are two major uncertainty sources, that is, fossil fuel energy consumption and emissions factors. Also, because industrial processes could consume fewer energy and cause fewer uncertainties, related uncertainty analysis is not involved here, which also follows and is consistent with Shan et al. (2017). In this context, the Monte Carlo simulations are repeated for 20000 times to calculate the uncertainties of total emissions from 16 northwestern Chinese cities (2010-2015), and from 8 northwestern Chinese cities (2006-2015). In addition, the detailed coefficients of variations (CV) of fossil fuel energy use data and emissions factors are adopted according to Shan et al. (2017).

Generally, the uncertainty of total emissions of the cities fall in the range of 10%-20% for non-OECD countries (Marland, 2008; Olivier and Peters, 2002). Also, these results are in consistent with those from Shan et al. (2017). So the results based on the uncertainty analysis turn out acceptable within a 97.5% convenience level. In particular, the uncertainty of total emissions of the 16 cities (2010-2015) is at a range of (-39% to -9%) to (-29% to 6%). Among these 16 cities, Lanzhou is the most important player (-13%, 4%) while Weinan possesses the smallest share (-39%, -29%). Secondly, the uncertainty of total emissions of the 8 cities (2006-2015) is at a range of (-26%, -9%) to (-14%, 6%). Among these cities, Lanzhou contributes the most (-13%, 5%) but Jiayuguan is responsible for the smallest share (-26%, -14%). At the sector level, coal mining and dressing sector accounts for the most to the uncertainty of total emissions, with the average uncertainty ranging from (-20%) to 21%, which could be also impacted by the large uncertainty existing in coal's emission factors and a large number of coal consumption (Shan et al., 2017). However, this result does not align with the results in the context of other regions Shan et al. (2017), which indicates regional disparities also exist in the uncertainty analysis (Shan et al., 2019a).

3. Emissions of northwestern Chinese cities

3.1. Study areas

From 2006 to 2015, CO_2 emissions in northwestern Chinese cities have been influenced specifically in several years. In detail, accompanying the West Development Strategy since 2001, increasing CO_2 emissions has been featuring the urbanization and industrialization phases in Northwest China (Guan et al., 2017; Xie et al., 2007). After the year 2008 when the global financial crisis occurred, although Chinese CO_2 flows have reversed across regions, Northwest remained the largest contributor to CO_2 emissions outflows (Mi et al., 2017b). Policies related to climate change have also been characterized by temporal changes. For provinces in Northwest China, CO_2 intensity was considered as formal since the 12th Five-Year Plan (2011-2015), which had been proposed at the nation level since the 11th Five-Year Plan (2006-2010) (Xu et al., 2017). However, at the city level, emissions intensity was not accepted more widely until the 13th Five-Year Plan (2016-2020). Moreover, the Silk Road Economic Belt proposed in 2013 has been increasingly regarded as a future stimulus combining economic growth with probable environmental degradation (Cai et al., 2016; Li et al., 2017b).

Meantime, due to difficulties in data availability, there is a balance between spatial and temporal data for northwestern Chinese cities. To illustrate, the historical analysis of CO_2 emissions is conducted across 16 cities from 2010 to 2015, while the structural patterns of emissions are studied among 8 cities from 2006 to 2015[†]. These 8 cities are selected from the above 16 cities, and include all the capitals available.

3.2. Total emissions

Between 2010 and 2015, capital and industrial cities had remained the vital contributors to most cumulative emissions (Fig.1). But at the same time, the temporal changes in CO_2 emissions had been diverse across 16 cities. For instance, Lanzhou (the capital of Gansu), Weinan (an industrial city), Yulin (an industrial city), Yinchuan (the capital of Ningxia) and Shizuishan (an industrial city) had generated most cumulative emissions. However, Lanzhou and Shizuishan had experienced some fluctuations in total emissions. By contrast, Weinan and Yulin had witnessed an increase in total emissions. Therefore, based on these results, there is a need to establish a time-series CO_2 account at the city level.

Moreover, some capital cities (i.e. Xi'an, the capital of Shanaxi, and Xining, the capital of Qinghai), and relatively developed cities (i.e. Xianyang, Baoji, and Wuwei) experienced an emission peak in 2013 or 2014 based on the up-to-date results of this study. These, studying the historical trajectory of CO_2 emissions in these typical cities could be crucial because this process could help cities

[†] However, due to limited data availability, some city-scale data in a certain year (including Shangluo in 2013, Weinan in 2011, Yan'an in 2015, Shizuishan in 2010, and Wuwei in 2012) are not included in the case study of 16 cities (2010-2015). Neither are related data of Yan'an in 2015 and those of Xining in 2006 and 2007 in the case study of 8 cities (2006-2015). But to ensure the constant studies in 8 cities, data of Yulin in 2006 are supplemented by those in 2005.

struggling with tackling climate change to reduce emissions (Dhakal, 2009; Hoornweg et al., 2011; Wang et al., 2008; Yang and Meng, 2019).

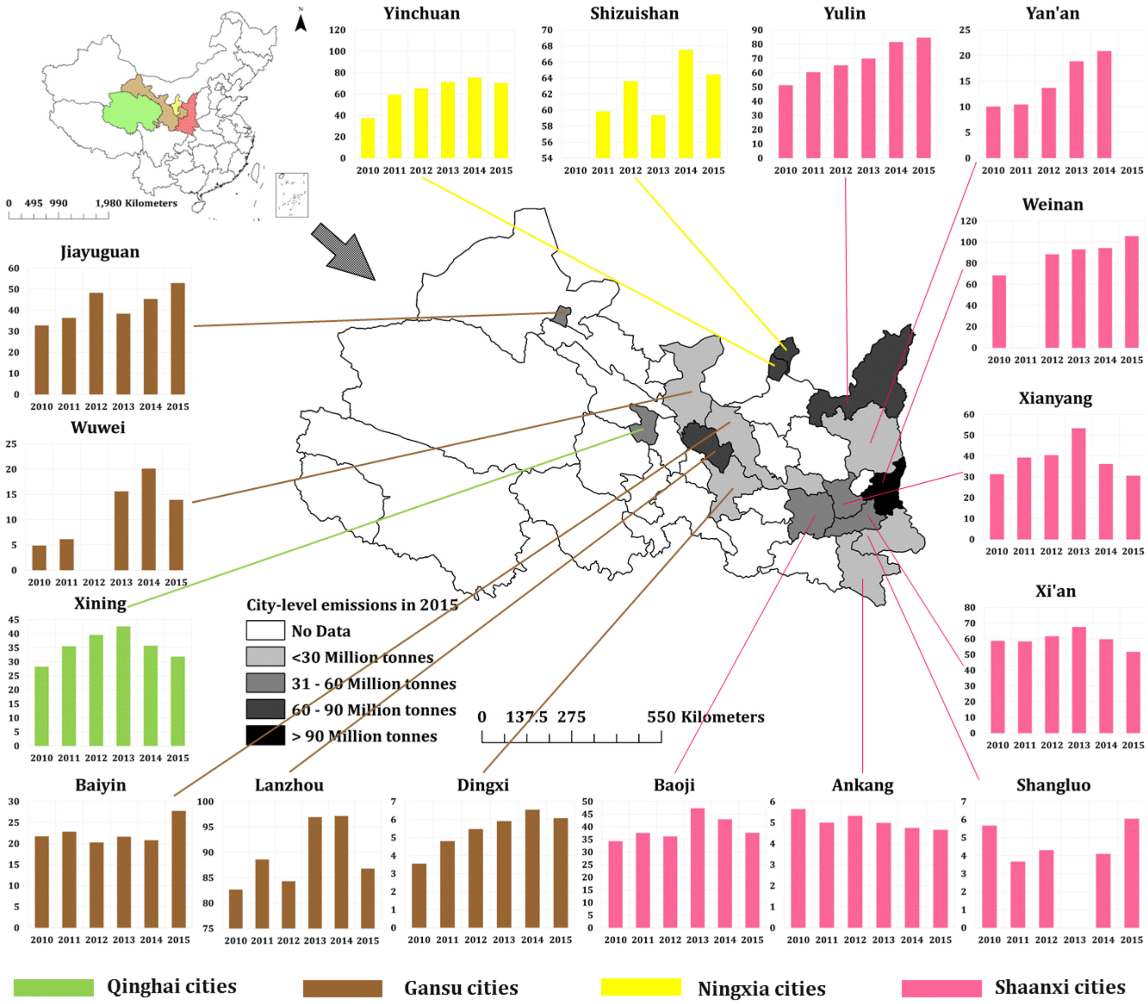


Fig. 1. CO_2 emissions of 16 northwestern Chinese cities over time.

3.3. Emissions by sectors and energy types

For most cities, energy production sectors (EP) and heavy manufacturing sectors (HM) persisted in contributing the most to emissions during11th and 12th Five-Year Plans (i.e., from 2006 to 2015) (Fig.2). This result supports that optimizing industrial structure (Guan et al., 2017) or promoting energy efficiency (Jiang et al., 2015; Wang and Wei, 2014) could be effective in CO_2 reduction for most cities. Also, developing circular economy has been recommended based on the reality of this area (Cheng et al., 2019). But it is also noted that, driven by the growing interregional trade, Northwest China has been the major contributor to embodied CO_2 transfers (Zhou et al., 2018). In this sense, to reduce CO_2 emissions, the final demand perspective (or a consumption-based perspective) will be highlighted when contributions of energy producers and users to emissions are clarified (Zhang et al., 2016).

When it comes to individual cities, if the production-based CO_2 responsibility is considered (Zhang, 2013), sectors could assume different responsibilities in Northwest China. According to Fig.2, for Xi'an and Yinchuan, the decarbonization of EP could be prioritized. For Lanzhou, Xianyang and Yulin, both EP and HM need decarbonization. For Jiayuguan, and Xining, decarbonizing HM is more significant. For Yan'an, although there were some fluctuations in sectoral shares of total emissions, EP and HM require further decarbonization based on the latest results in 2013 and 2014. However, other considerations concerning sectoral CO_2 responsibilities could be rethought (Mi et al., 2019; Zhang, 2013), partly because sectoral CO_2 accounting from multiple perspectives could promote efficient low-carbon policies (Li et al., 2018).

Then, energy mix had contributed stably to emissions from 2006 to 2015 (Fig.2). Generally, most cities were characterized by the largest share of emissions from coal, further hindering the decoupling process from economic growth in this area (Dong et al., 2016). Specifically, oil-related emissions in Lanzhou were the largest among those in these 8 cities, which were generated from petroleum processing and coking. Likewise, the process-related emissions in Jiayuguan were larger than those in other 7 cities, mainly consisting of emissions from ferrous and nonferrous metals smelting and pressing. Also, coal tends to be more carbon intensive than other fossil fuels like natural gas (Pan et al., 2013). Therefore, energy transition could be another feasible approach to alleviating emissions (Yang and Meng, 2019; Zhuang et al., 2010). However, during the energy transition process, some barriers could occur (Geng et al., 2016; Ren et al., 2015).

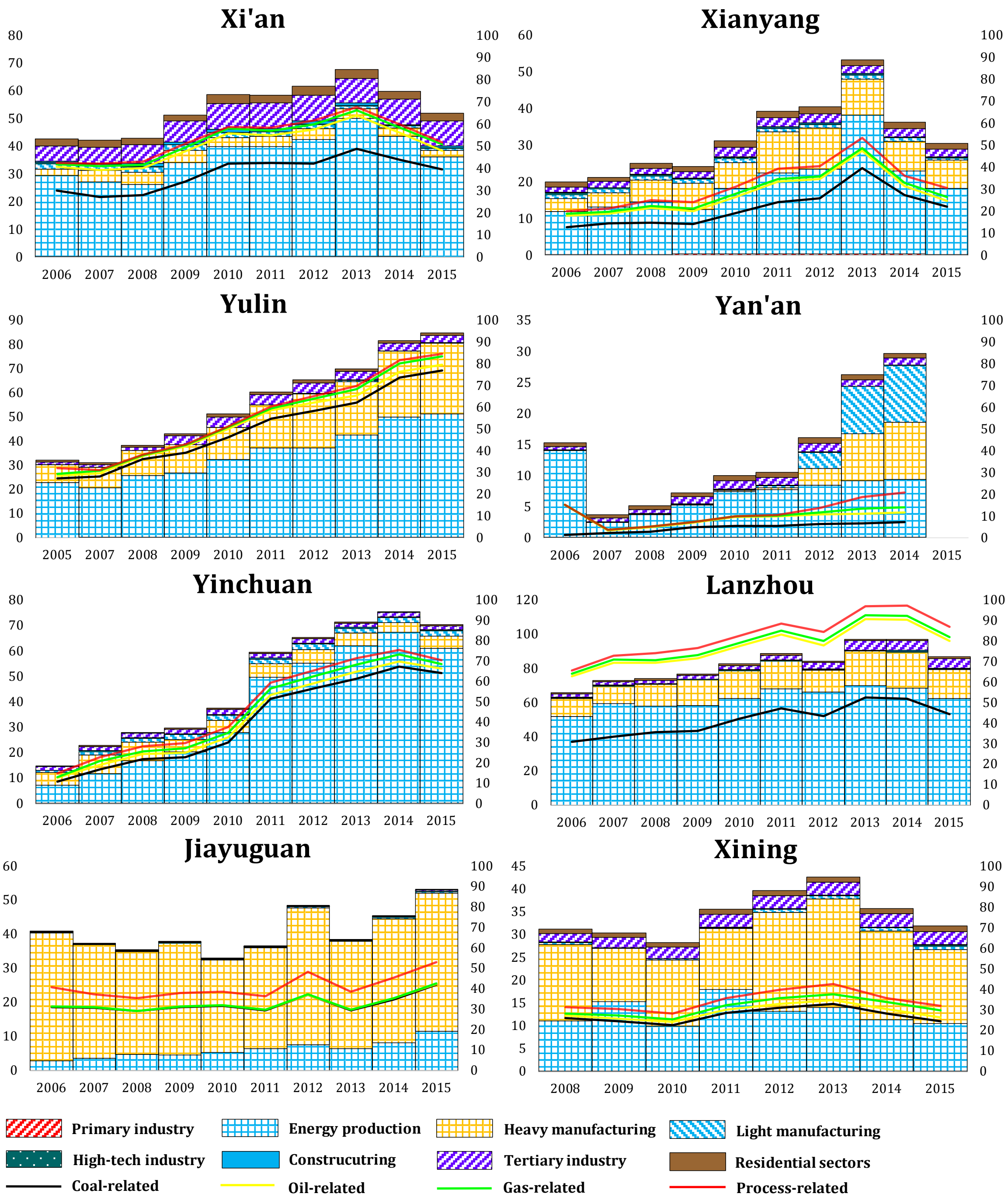


Fig. 2. CO_2 emissions by sector and energy type in 8 northwestern Chinese cities over time (Unit: $MtCO_2e$). Notes: For each subfigure, all the solid lines refer to the y-axis on the right while all the bar graphs refer to the y-axis on the left.

However, for each city, the interconnection between industrial structure and energy mix had exerted temporally varying impacts on CO_2 emissions from EP and HM (Fig.3). For example, in Xi'an and Lanzhou, the ratios of coal-related emissions from EP to total emissions (i.e., the sum of emissions from EP and HM across 8 cities) decreased obviously. In Xi'an, Yan'an and Lanzhou, the proportions of oil-related emissions from EP to total emissions achieved an obvious decline.

However, in Yinchuan and Yulin, the shares of coal-related emissions from EP in total emissions increased apparently. Thus, regarding this phenomenon, one possible explanation is that interregional CO_2 flows may occur more evidently, but to explore the exact CO_2 flows, establishing a multi-region input-output table across regions is necessary (Meng et al., 2018; Zheng et al., 2019).

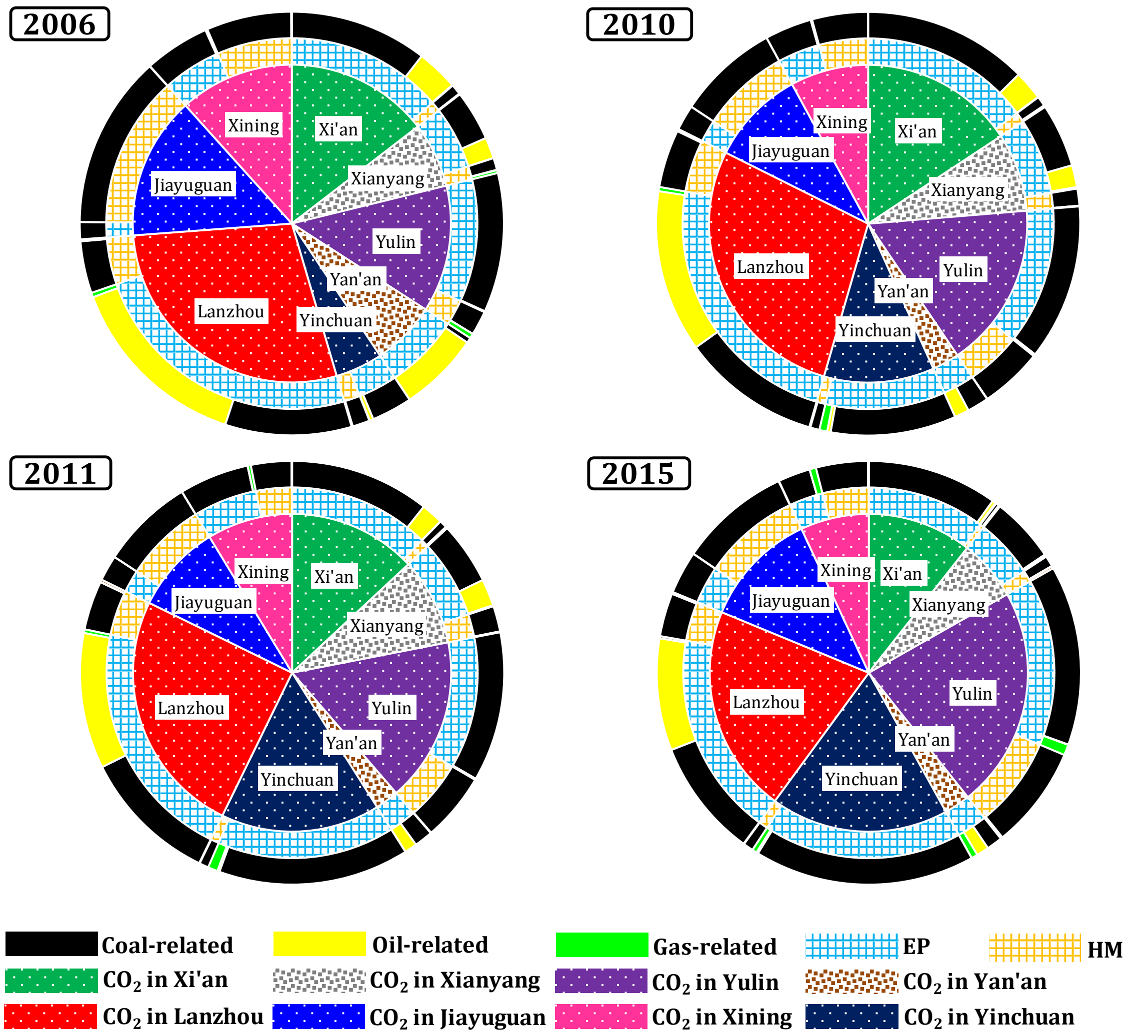


Fig. 3. Contributions of energy types to CO_2 emissions from EP and HM in 8 northwestern Chinese cities in 2006, 2010, 2011, and 2015, respectively (Unit: $MtCO_2e$)

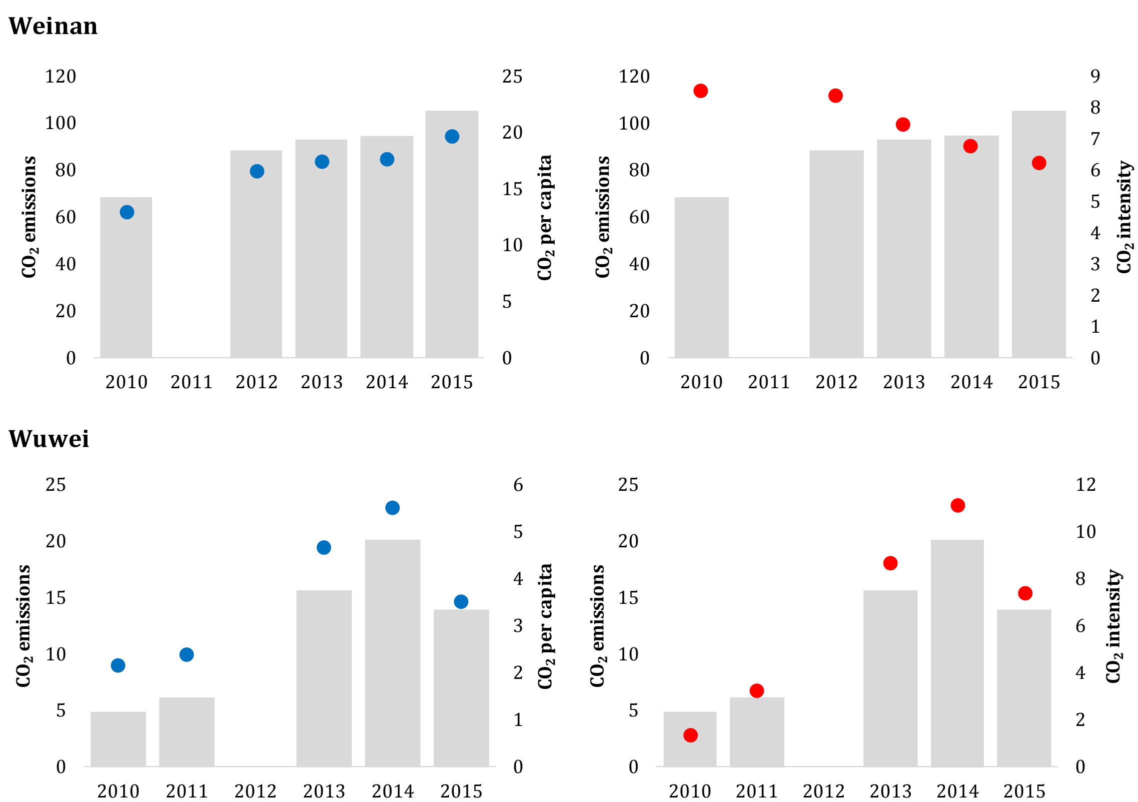
4. Emission-socioeconomic indictors of northwestern Chinese cities

4.1 Joint analysis of total emissions, intensity, and per capita emissions

For most cities, CO_2 emissions were not compatible with CO_2 intensity, but consistent with CO_2 per capita, which is similar to the results in developed cities in China (Liu et al., 2015a). This phenomenon supports three points. First, for most cities, the drivers of CO_2 emissions appeared to be diverse, not limited to variations in CO_2 intensity, which aligns with (Guan et al., 2017). Second, experience and lessons from Chinese developed cites could be learnt by cities in this area in the field of CO_2 alleviation (Khanna et al., 2014). Finally, CO_2 emissions and CO_2 intensity could be advocated simultaneously in the policymaking process.

For individual cities, Weinan, one industrial city in Shaanxi, stood for the city where the decline in CO_2 intensity continued accompanying the increase in CO_2 emissions (Fig.4a). On the contrary, there are another two types of cities. First, Wuwei represented the city where the development pathway between CO_2 emissions and CO_2 intensity remained consistent (Fig. 4b). The situation in Wuwei was also similar to that in Shangluo. Second, in Lanzhou, the interconnection between CO_2 emissions and CO_2 intensity was inconsistent in several years (Fig. 4c). Most cities experienced this similar situation, including Ankang, Baoji, Xi'an, Yulin, Xianyang, Yan'an, Shizuishan, Yinchuan, Xining, Jiayuguan, Baiyin, and Dingxi.

Moreover, in practice, some provinces in Northwest China, such as Shaanxi (The People's Government of Shaanxi Province, 2018) and Gansu (The People's Government of Gansu Province, 2017), have emphasized the role of emissions intensity and absolute emissions being considered simultaneously in climate change mitigation. Thus, these provinces have selected pilot cities, expecting these cities' pragmatic experience will be applied to others. Despite this, since the interconnection between CO_2 emissions and CO_2 intensity across most cities were slightly or largely different, these cities could critically and carefully learn from others succeeding in climate change mitigation and adaptation.



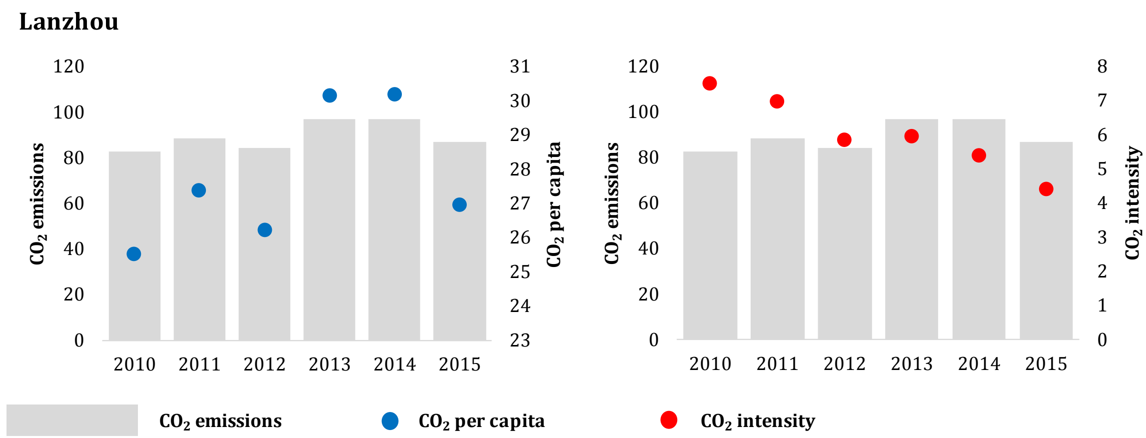


Fig. 4. CO_2 emissions, CO_2 intensity (Unit: tCO_2e per one thousand yuan in constant 2010 price), and CO_2 per capita (Unit: tCO_2e per capita) across time at the city level.

4.2. Emissions in related to household energy consumption

Generally, urban gas consumption and rural coal use were the major contributors to HCE and HCE per capita (Fig.5). This result helps make reducing rural coal-related emissions the vital task of reducing emissions from rural household consumption. Then, some measures could be implemented, such as upgrading and greening energy consumption patterns (Jiang, 2016; Niu et al., 2011), encouraging sustainable consumption patterns and lifestyles (Li et al., 2016; Liu et al., 2011), and making full use of the importance of income and education levels to CO_2 reduction (Guan et al., 2017; Xing et al., 2017).

Then, when HCE and HCE per capita were decomposed by energy type, they developed an inconsistent development pathway across cities in terms of the rural-urban disparity (Fig.5). In light of HCE, in Xi'an, Xianyang, Yulin, Yan'an, Yinchuan and Xining, the urban-rural divide in gas-related HCE maintained the largest. In Jiayuguan, the urban-rural disparity in HCE by all energy types was smaller. In Lanzhou, between 2013 and 2015, the urban-rural divergence in HCE caused by oil was larger. Then, with respect to HCE per capita, in Xi'an, Xianyang, Yulin and Yan'an, the urban-rural divide continued being centered in gas; in Lanzhou, Jiayuguan and Yinchuan, this divide kept focusing on coal; and in Xining, this divide had the stable focus on coal and gas. So there are further explorations in the region-specific factors influencing the urban-rural disparities in HCE by energy type and HCE per capita by energy type, which is in line with the results exploring the factors affecting HCE and HCE per capita in Northwest China (Guan et al., 2017; Li et al., 2016).

Furthermore, although the relation between CO_2 emissions and CO_2 per capita across cities was consistent, the interplay between emissions and population could be changed when HCE by energy type and HCE per capita by energy type are further decomposed among rural and urban households. So some polices related to HCE could think seriously of this probable change, to promote the fairness among urban and rural households, in terms of CO_2 responsibility allocation (Gill and

Moeller, 2018; Qu et al., 2013; Roberts, 2010) and help address associated urban concerns (Wang et al., 2018; Wang et al., 2017).

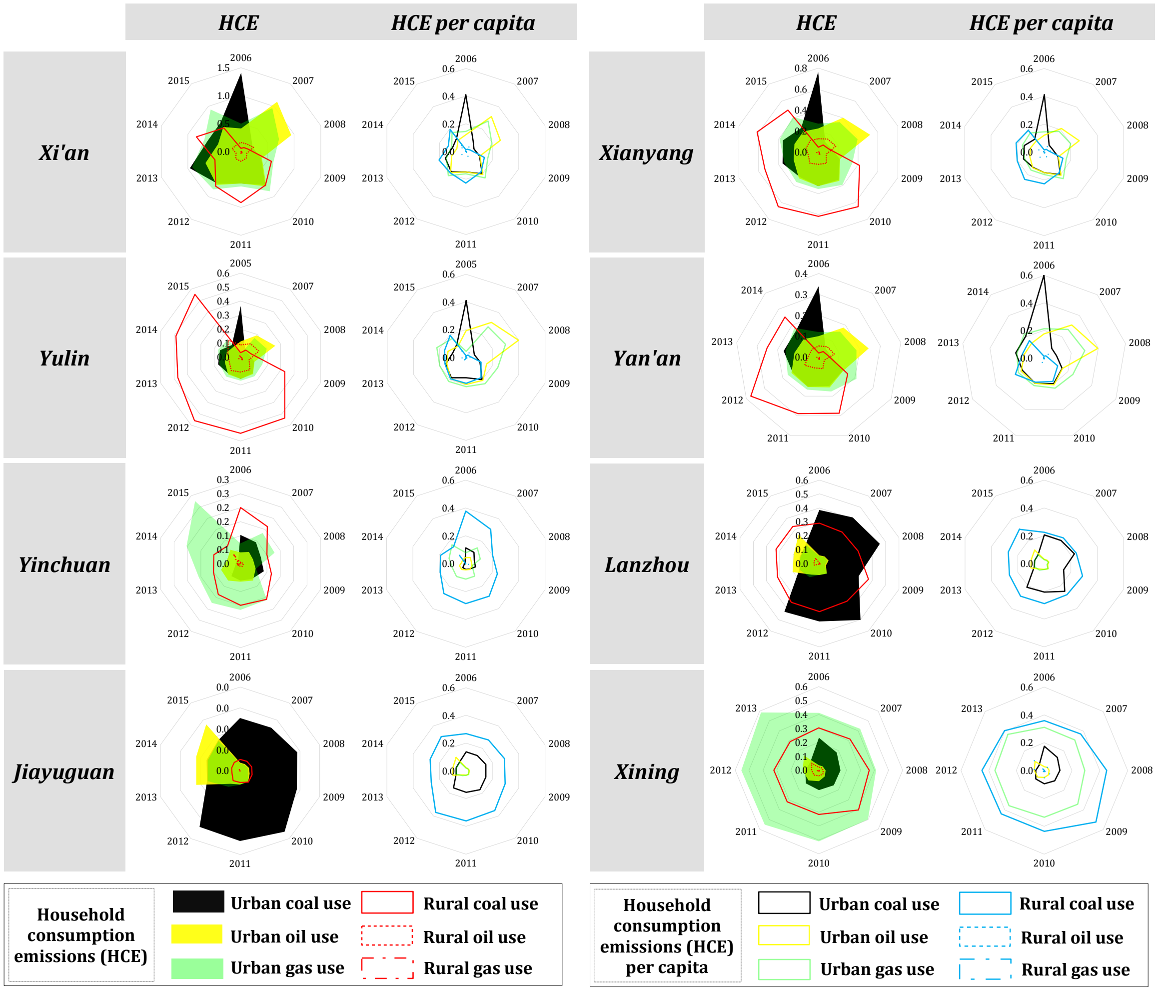


Fig. 5. HCE by energy type (Unit: $MtCO_2e$) and HCE per capita by energy type (Unit: tCO_2e per capita) in 8 northwestern Chinese cities across time.

5. Conclusion and policy implication

5.1. Conclusion

In Northwest China, the historical trajectory of CO_2 emissions is reflected in 16 cities from 2010 to 2015. Then, the structural patterns of emissions are grasped in 8 cities from 2006 to 2015 with respect to industrial structure, energy mix and urban-rural divides. Also, socioeconomic indicators in relation to CO_2 emissions and HCE are also analyzed. Besides, to validate these constructed CO_2 accounts, Monte Carlo analysis is applied to explore the uncertainties featuring the CO_2 accounting process.

For 16 cities (2010-2015), First, capital and industrial cities kept contributing the most to emissions. Then, Xi'an, Xining, Xianyang, Baoji, and Wuwei experienced an emission peak in 2013 or 2014 based on the updates in this study. Second, CO_2 emissions were mostly consistent with CO_2 per capita, but incompatible with CO_2 intensity.

For 8 cities (2006-2015), first, EP, HM, and coal contributed the most to emissions. Further, the interconnections between industrial structure and energy mix exerted temporally varying impacts on CO_2 emissions from EP and HM. Second, urban gas consumption and rural coal use were the major contributors to HCE and HCE per capita. Third, when HCE and HCE per capita were decomposed by energy type, they developed an inconsistent development pathway across cities in terms of the rural-urban disparity. Finally, the interplay between emissions and population could be changed when HCE by energy type and HCE per capita by energy type are further decomposed among urban and rural households.

Uncertainty analysis results show that the overall uncertainty of emissions fall in the reasonable range for non-OECD countries. When it comes to city-scale contributions to the uncertainty (2010~2015), Lanzhou contributed the most while Weinan experienced the opposite. For corresponding contributions from 2006 to 2015, Lanzhou remained the major player but Jiayuguan is responsible for the smallest share. Additionally, coal mining and dressing sector accounts for the most to the uncertainty of total emissions.

5.2. Policy implication

For 16 cities (2010-2015), first, establishing a time-series CO_2 account is necessary on the city scale. Moreover, studying the historical trajectory of CO_2 emissions in typical cities could help cities struggling with tackling climate change to reduce emissions. Second, it is meaningful to explore city-specific drivers of CO_2 emissions, dissimilate experience and lessons from Chinese developed cites to cities in this area in the field of CO_2 alleviation, and support the simultaneous but critical thinking of CO_2 emissions and CO_2 intensity in the policymaking process.

For 8 cities (2006-2015), first, optimizing industrial structure, promoting energy efficiency, and developing circular economy could be effective in CO_2 reduction. Additionally, a consumption-based perspective could be highlighted when contributions of energy producers and users to emissions are clarified. Second. energy transition could be another feasible approach to alleviating emissions. Third, to explore the CO_2 flows within the interregional network informing industrial structure and energy mix, establishing a multi-region input-output table across regions is recommended. Forth, to reduce rural coal-related HCE, some countermeasures could be taken into account, including upgrading and greening energy consumption patterns, encouraging sustainable consumption patterns and lifestyles, and making full use of the importance of income and education levels to CO_2 reduction. Fifth, further explorations are encouraged in the field of region-specific factors influencing the urban-rural disparities in HCE by energy type and HCE per capita by energy type. Finally, some polices related to HCE could detail the relation between emissions and population to cope with CO_2 reduction and associated urban concerns.

5.3. Future work

Although the up-to-date data collected in this study are those that we can ever find, it could be more informative when more spatiotemporal data are involved. Also, as the socioeconomic data are sometimes supplementary to the required but missing energy data, uncertainties could exist. In this sense, collecting and compiling more data related to this area could be one direction of our future work. The second direction is to combine the methodology with other methods such as input-output models and econometric methods. For instance, it is useful to establish a MRIO to identify the role that interregional trade has played in the field of economy and environment. A third direction is to combine this top down thinking with a bottom up one to compile CO_2 emissions inventories for northwestern Chinese cities. For instance, some household surveys have been conducted for cities in this area (Li et al., 2016; Qu et al., 2013), although the relevant uncertainty analyses need further explorations.

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