Applied Energy Symposium 2020: Low carbon cities and urban energy systems
October 10-17, 2020
Paper ID: CUE2020-D-083

Does urbanization lead to more carbon emissions? Evidence from China

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ABSTRACT

Although urbanization should be an integrated process of rural-to-urban transformation involving the interactions and mutual influences between population urbanization and land urbanization, its definition in such multi-dimensioned terms is as yet underexplored. This is an important issue for the relationship between urbanization and carbon emissions, as the fuzzy definition of urbanization may have contributed to the neglect of the mechanisms involved, with misleading low-carbon policy implications and misguidance for achieving 2030 carbon emission peak goals. This study is one of the first attempts to disaggregate the urbanization nexus and simultaneously explore the correlation between land urbanization and population urbanization, and carbon emissions across China.

The findings suggest that land urbanization and population urbanization both have an inverted U-shaped correlation with carbon emissions, and a U-shaped relationship with carbon productivity. These results support the environmental Kuznets curve, in that urbanization helps mitigate carbon dioxide emissions in the long run depending on urbanization performance. However, unlike western countries, the triple restrictions of land policy, fiscal and taxation policies, and the household registration system, as well as the disconnection between urbanization and industrial development in China will result in the asynchrony of land urbanization and population urbanization. The results also point to a considerable but differentiated potential for urbanization to reduce GHG emissions through effective urbanization management and policy adjustment, and that low-carbon policies and strategies need to be tailor-made based on regional differentiations.

Keywords: urbanization, carbon emissions, carbon productivity, low-carbon strategies

NONMENCLATURE

Abbreviations	
APEN	Applied Energy
Symbols	
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1. INTRODUCTION

The increase in greenhouse gas (GHG) emissions is a major threat to the environment worldwide, and international authorities have reached a consensus on the dynamic causal relationships with global climate change (Kenny and Gray, 2009). According to the United Intergovernmental Panel on Climate Change (IPCC) research report (Ren et al., 2015), urbanization – reflected by intensive human social and economic activities – leads to an increase in carbon emissions and, thus, an acceleration of global warming. The report further states that the average global temperature is forecasted to rise between 1.1 and 6.4°C in the next 100 years unless effective action is taken (Kasman and Duman, 2015). Indeed, according to the urbanization and carbon emissions curve, the two are highly consistent (Fig. 1). Accordingly, the correlation between urbanization and carbon emissions has received continued attention in academic circles and by policy makers. However, despite numerous in-depth studies linking these two at national and international scales, the debates continue, the existing evidence being divided

Selection and peer-review under responsibility of the scientific committee of CUE2020

into either *positive* correlation (e.g., Liddle and Lung, 2010), *negative* correlations (e.g., Fan et al., 2006), or *non-linear* correlations (e.g., Ehrhardt-Martinez et al., 2002).

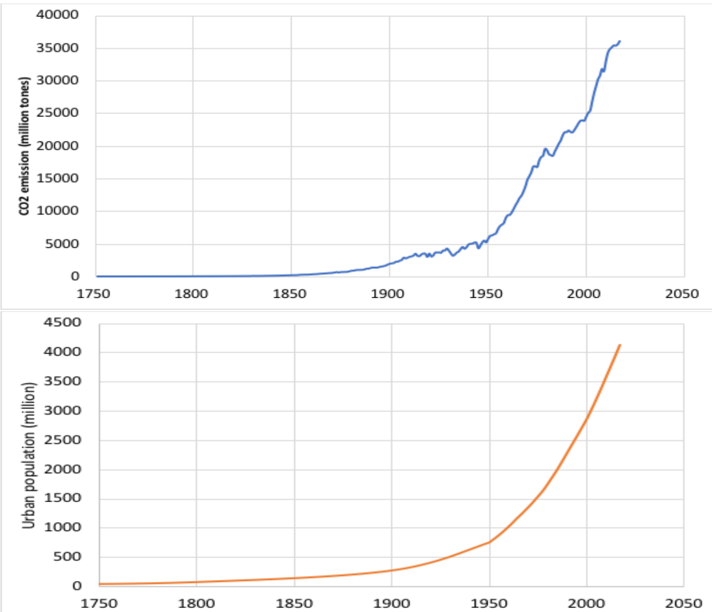

Fig 1 Global urbanization and carbon emissions

Central to this dispute is the definition of urbanization, with previous research largely concentrating on one aspect of urbanization, such as *population* urbanization – represented by the proportion of urban population to the total population. However, another irreversible phenomenon in the urbanization process is the transformation of the natural to human-dominated form of land use: this is an important carbon source, with the total annual greenhouse gas emissions generated in this way having reached a record high of 53.5 GtCO2e in 2017 – an increase of 0.7 GtCO2e compared with 2016 (IPCC 2018). Thus, simultaneously exploring the impact of land urbanization *and* population urbanization on carbon emissions – considering the urbanization process is a simultaneous process of urban population growth and urban expansion – as a disaggregated urbanization nexus should enhance the understanding of the mechanisms involved. This is particularly important for developing countries since they are expected to experience the greatest increase in urbanization in future.

China, as a country experiencing unprecedented industrialization and accelerating urbanization of economic development, consumes an enormous amount of energy and, as a result, releases a huge amount of GHGs. It has been pointed out that China has had the largest annual carbon emissions in the world since 2006 (Wu et al., 2018; Yao et al., 2018), emitting approximately one-quarter of the global production of GHG in 2017 (Fig. 2). To combat the intertwined challenges of global climate change and domestic air pollution, the Chinese government has adopted a low-carbon urbanization policy (Wang et al., 2019). However, China's urbanization has unique characteristics due to its land policy, fiscal and taxation policies, and household registration system, making its population urbanization and land urbanization independent and significantly unique. These substantial differences also have different effects on carbon emissions. Thus, there is an identified need to disaggregate urbanization to study the mechanisms by which population urbanization and land urbanization affect carbon emission and provide high-resolution low-carbon government policies and strategies. Considering the considerable pace and unique characteristics of the country's urbanization, as well as the prominent conflict between urbanization and environmental protection, such a need has been increasing because of its profound impact on not only China's but also global sustainable development.

Thus motivated, this paper adopts China as an empirical study to answer two broad questions. First, what are the mechanisms driving carbon emissions from urbanization? Second, what are the opportunities for mitigating GHG emissions from cities and their effective governance and policies in the urbanization process? Specifically, this study investigates the relationship between urbanization and carbon emissions from panel data across provinces in China from 2000 to 2015 and explores the underlying mechanisms involved to extend knowledge of the urbanization and environment nexus. The paper's contribution to the related literature is two-fold. First, the research represents one of the first attempts to explore the correlation between urbanization and carbon emission simultaneously from both land urbanization and population urbanization perspectives within the framework of the environmental Kuznets curve (EKC), thus providing evidence for better understanding the mechanisms behind the impact of urbanization on carbon emissions. Second, this study identifies the aggregate potential of cities to mitigate climate change on a national scale, and provides new evidence that urbanization is not necessarily the culprit leading to carbon emissions, but the urbanization process can be harmonious with carbon emission abatement by suitable policies concerning the efficient resource allocation of land, capital, and labor.

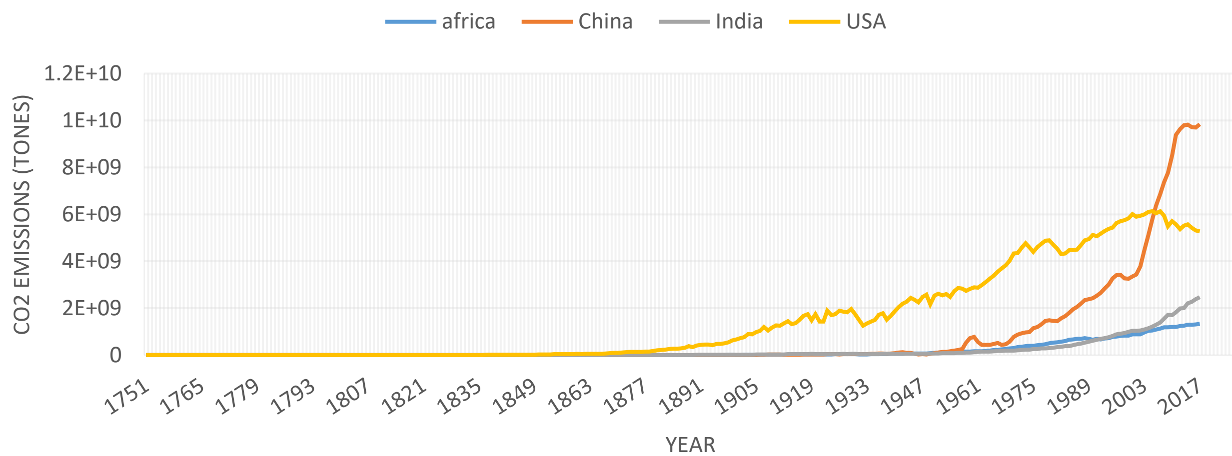

Fig. 2. Carbon emissions in China and other world regions
China has been experiencing a sharp acceleration in carbon emission in the 2000s.

The remainder of this paper proceeds as follows. Section 2 reviews the theoretical lens of urbanization and carbon emissions and establishes the research framework. Section 3 provides a brief description of the research data and specifies the methodology. Section 4 presents the empirical results and discusses the associated mechanisms and high-resolution policies involved. Section 5 contains concluding remarks and emergent policy implications.

2. Theoretical basis and framework

2.1 Research basis: urbanization and carbon emissions

2.1.1 Theoretical lens of urbanization on carbon emissions

Urbanization is an outcome of the agglomeration of people and resources, and leads to higher emissions/energy consumption through urbanization's association with industrialization. From a theoretical perspective, Poumanyvong and Kaneko (2010) summarize the effects of urbanization on environmental issues into three theories: ecological modernization, urban environmental transition, and compact city. *Ecological modernization* argues that the economy benefits from moves towards environmentalism, suggesting that economy and ecology can be favorably combined. The arguments of *urban environmental transition* theory focus on changes in environmental burdens as cities become wealthier. For low-income cities, environmental challenges are localized, immediate, and health threatening, while for wealthy cities, environmental burdens are global, delayed (intergenerational), and ecosystem threatening. The *compact city* is an urban planning concept that promotes a relatively high residential density with mixed land uses. It relies on efficient public transportation that encourages low energy consumption and reduced environmental pollution.

From an empirical view, the most frequently studied factors include demographic factors (Yu et al., 2018; O'Neill et al., 2010), economic factors (Jorgenson, 2014; Steinberger et al., 2012), energy consumption (Wang et al., 2017; Xu et al., 2014), industrial structure (Yu et al., 2018), land use change (Law et al., 2018), and lifestyle change (Whitmarsh et al., 2011). Studies considering *demographic factors* to explain the sources of air pollution have found a direct relationship between population change and carbon emissions (Shi, 2003). *Economic development*, along with the change of demographic factors, has also been suggested as having a significant positive impact on carbon emissions (Paul and Bhattacharya, 2004). Their arguments rely on the fact that human development depends on economic growth; national economic expansion in turn requires greater *energy use* and hence increased carbon emissions (Steinberger et al., 2012). At the same time, a growing body of literature now argues that urbanization holds the key to global sustainability since it is highly efficient at the local level: lowering the environmental costs of infrastructure, improving the efficiency of energy, and facilitating the innovation of low-carbon technologies, which is similar to the theory of ecological modernization.

Considering that consumption-based carbon emissions is significantly increasing, researchers have shifted their attention from production-based to consumption-based carbon emission studies. Particular attention has been paid to the effects of *land use*/cover change on carbon emissions, suggesting that such a process affects net global carbon emissions through the change of carbon source and carbon sink (Hansen et al., 2019; Mitchard, 2018; Tanaka and O'Neill, 2018). This is important because, even if carbon emissions could be reduced, the amount of carbon already stored in the atmosphere would lead to the occurrence of extreme thermal events for decades to come (Ortiz et al., 2014). In addition, the quality of land urbanization has also been verified to have a bidirectional causal relationship with CO2 emissions in China (Xu and Zhang, 2016). More recently, researchers have begun to relate carbon emissions to urban form, which determines consumption-based carbon emissions through patterns of energy consumption (Creutzig et al., 2015). Their arguments are similar to compact city theory in that compact urban forms with efficient transportation structures could reduce energy consumption, thus mitigating carbon emissions.

2.1.2 Continuous debates on the correlation between urbanization and carbon emissions

Research into the relationship between urbanization and carbon emissions has received considerable attention in the social sciences (Wang et al., 2015). However, as mentioned earlier, results are inconsistent and can be divided into three categories of positive, negative, and non-linear correlations. Of those who support *positive correlations*, Parikh and Shukla (1995), for instance, find greenhouse gas emissions to be positively correlated with urbanization level in a number of developed and developing countries. Zhang et al. (2014) also suggest there is a significant one-way causality between urbanization and carbon intensity (carbon emissions/GDP) through a panel study in China. Sharma (2011), with Sharma (2011), however, finding urbanization to have a *negative correlation* with carbon emissions in high, middle, and low-income counties. Similarly, Fan et al. (2006) locate a negative relationship between urbanization and carbon emissions in developing countries. Researchers who support this view believe that cities, because of their density of demand, can take advantage of a wide array of technology and policy options to increase energy efficiency and reduce per-capita consumption of fossil fuels (Parshall et al., 2010), thus helping to mitigate carbon emissions.

Regarding *non-linear correlations*, one of the most influential hypotheses is the Environmental Kuznets Curve (EKC), the traditional hypothesis holding that there is an inverted U-shaped curve relationship between environmental and economic development − first tested by Gross and Krueger (1991). This has been followed by a substantial number of studies attempting to extend the hypothesis to examine the relationship between urbanization and carbon emissions. Of the considerable amount of empirical work suggesting an EKC hypothesis between demographic factors and environmental quality, Xu and Lin (2015) provide evidence in support of an inverted U-shaped relationship by examining the relationship between urbanization and carbon emissions in the eastern region of China; Chikaraishi et al. (2015) finding that the urbanization process can actually make countries more environmentally friendly through the latent class mode; and Martnez-Zarzoso and Maruotti (2011) finding that urbanization has a long run negative relationship with carbon emissions in developing countries.

Regardless the continuing debate on the correlation between urbanization and carbon emissions, urbanization presents a huge challenge to sustainable development since it introduces multiple tradeoffs. Thus, it is crucial that economic growth and carbon emission abatement are harmonious and, as Kaya and Yokobori (1993) propose, carbon productivity (GDP/carbon emissions) provides a possible way to engender their coordination (Li and Wang, 2019). However, despite studies identifying the significance of the carbon efficiency concept, it is still under-researched. Of the limited work done to date, it is suggested that urbanization with respect to economic growth (Lu et al., 2015), energy structure (Lu et al., 2015), and technological innovation (Hu and Liu, 2016) will help improve carbon productivity. However, the evidence is not influential.

Although these studies make a great effort to obtain an in-depth understanding of the relationship between urbanization and carbon emissions, their lack of a comprehensive definition of urbanization could be leading to a misunderstanding of the mechanism involved and hence the lack of a consensus on whether there is a similar inverted U-shaped relationship between urbanization and carbon emissions (Li et al., 2015). Urbanization encompasses the influence of land urbanization and population urbanization, and these different aspects of urbanization may have different impacts on carbon emissions (Xu et al., 2018). While urbanization defaults to the ratio of population living in urban areas to the total population in most literature (e.g., Dong et al., 2016), others prefer aggregated urbanization indicators (e.g., Xu et al., 2018) so that describing urbanization and analyzing its effects on carbon emissions provide neither consistent conclusions nor effective plans for low-carbon development. Simultaneously studying the correlation between urbanization and carbon emissions from multiple aspects should not only provide an accurate understanding of the effects of urbanization on carbon emissions but also improve knowledge of the mechanism involved. In addition, the correlation between urbanization and carbon productivity is underexplored, and there is limited evidence relating to how urbanization impacts on carbon emissions. Thus, limited guidance is available to address the tradeoffs between economic growth and carbon emissions. Furthermore, although dozens of empirical studies of urbanization and the environment have been conducted regarding cities, urban agglomerations, and regions, it is evidence at the national scale that is the most influential. Studies of carbon emissions and carbon productivity nationally can help in obtaining and improved understanding of the relationships involved, thus informing and identifying tailor-made strategies across all of China.

Bridging these knowledge gaps has two practical implications. First, it provides a comprehensive understanding of the impact of different aspects of urbanization on the carbon dynamics of urban ecosystems and the potential to address climate change. Thus, the mechanisms involved could be evaluated, along with the development of the most cost-effective and high-resolution strategies for carbon mitigation. Second, a comprehensive analysis of cities nationwide would help identify the aggregate potential for cities in mitigating climate change, especially evidence from the largest carbon emitter in the world, something that is not possible with individual case studies.

2.2 Research framework

From the perspective of demography, Wilson (1941) views urbanization as a process where rural residents transform into urban citizens. As Clark (1988) acknowledges, urbanization is characterized by the flow of rural surplus labor to the non-agricultural sector. In contrast, geographers describe urbanization from a spatial perspective, where massive rural-to-urban migration results in the spatial expansion of urban areas, reflecting the transformation of land use type from ecological to built-up land. However, although each discipline provides specific and unique insights into the characteristics of urbanization, a more comprehensive and systematic conceptual framework is still needed for a better understanding of the urbanization process.

Here we consider urbanization as an integrated process of rural-to-urban transformation, involving the interactions and mutual influences between population urbanization and land urbanization (Sun et al., 2012; Henderson et al., 2009), in which people are the central and inherent actors, while urban land as the carrier supplies the life and development space of citizens. In this sense, a comprehensive and systematic evaluation of urbanization needs to pay more attention to the interaction and coordination between these two urbanization sub-processes as defined as Fig. 3.

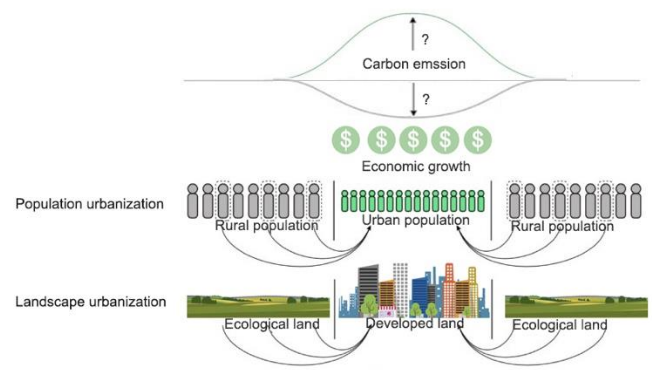

Fig. 3. Research framework of urbanization and carbon emissions

First, population urbanization is primarily characterized by the increase in size and density of the urban population, as well as the population in non-agricultural sectors (Zhu and Peng, 2012; Yang et al., 2015; Kang et al., 2020). Second, land urbanization mainly concerns the increase in the physical scale of cities and change in the urban landscape, which can be described as urban expansion (Newell and Vos, 2012; He et al., 2016; Zhang and Xu, 2017). Table 1 shows the indicators used in previous studies.

Table 1. Indicators used in previous studies

Variable	Definition	Indicator	Source
Population urbanization	Increase in urban population	Proportion of urban population or non-agricultural population; population density in the urban area	Zhu and Peng, 2012; Yang et al., 2015; Kang et al., 2020
Land urbanization	Urban land expansion	Area of built-up land; growth rate of built-up land	Newell and Vos, 2012; He et al., 2016; Zhang and Xu, 2017

3. Data and methodology

3.1 Study area

Our work focuses on regional carbon emissions and their decomposition effects for 31 provinces in China from 2004 to 2015 (Fig. 4). Due to the lack of data in Tibet (missing data) and the particularity of Shanghai (outlier), we take panel data of the remaining 29 provinces as the sample.

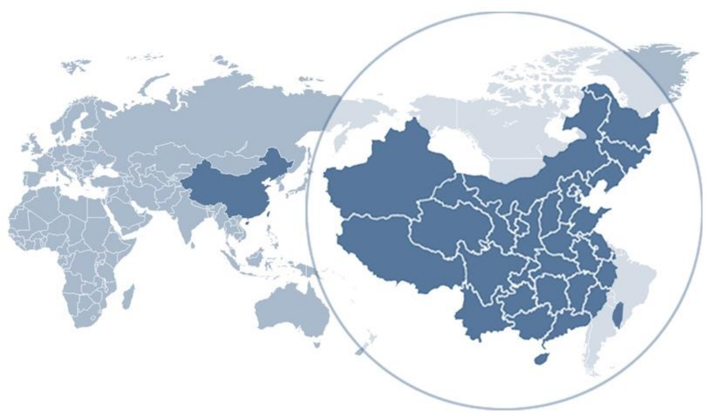

Fig. 4. Study area

3.2 Data

To analyze urbanization attributes related to carbon emissions, a comprehensive set of variables describing the multidimensional aspects of urbanization are required, including land urbanization and population urbanization. Other variables are set as control variables. The data for the total carbon emissions measured in 10,000 tons and energy mix, developed land, and population density are from the China Statistical Yearbook. Population urbanization, GDP, and industrial structure are from the China compendium of statistics 1949-2008 (National Bureau of Statistics).

3.3 Empirical models

3.3.1 Relationship between urbanization and carbon emissions

Based on the two forms of urbanization – population urbanization and land urbanization – a comprehensive analysis of the relationship between carbon emissions and urbanization is conducted. First examined is whether there is an inverted U-shape relationship between urbanization and carbon emissions in China. The empirical specification is

$$
\begin{aligned}
Carbon_{i,t} = \ & \beta_0 + \beta_1 GDP_{it} + \beta_2 (GDP_{it})^2 \\
& + \beta_3 Ur_{it} + \beta_4 (Ur_{it})^2 \\
& + \beta_5 Dev_{it} + \beta_6 (Dev_{it})^2 \\
& + \beta_7 Energy_{it} + \beta_8 Industry_{it} \\
& + \beta_9 Pop\_density_{it} + \gamma_i + \delta_t \\
& + \varepsilon_{it}
\end{aligned} \quad (1)
$$

where i and t indicate province and year, respectively; $Carbon$ represents carbon emissions; proportion of the urban population (Ur) and proportion of built-up land in the urban area (Dev) represent population urbanization and land urbanization, respectively. The control variables comprise economic development (GDP_{it}) measured by GDP per capita, energy structure ($Energy$) represented by the proportion of coal, industrial structure ($Industry$) denoted by the proportion of industrial output value, and population density ($Pop\_density$); γ_i and δ_t are the province fixed effects and the year fixed effect respectively, and ε_{it} is the error term.

3.3.2 Relationship between urbanization and carbon productivity

To achieve cost-effective low-carbon development for an individual province, more attention needs to be paid to carbon productivity with the consideration of both economic efficiency and environmental quality. For this purpose, the relationship between urbanization and carbon productivity in China is explored, and whether there is a U-shaped relationship further inspected. The specific model is

where $Productivity$ indicates carbon productivity, measured by GDP per unit of carbon emission. The explanatory variables and control variables are similar to equation (1).

4. Empirical results

4.1 Spatial distribution of carbon emissions and urbanization

As shown in Fig. 5, the total carbon emissions show a strong growth trend from 2004 to 2011, but much milder from 2011 to 2015. Shandong province has the largest carbon emissions, followed by Jiangsu and Guangdong, while Hainan has the smallest.

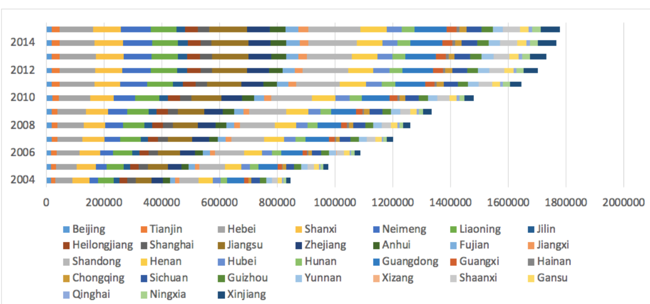

Fig. 5. Provincial carbon emissions from 2004 to 2015

To understand the spatial distribution of the characteristics of urbanization across China, a multi-temporal (years of 2005, 2010, and 2015 used to show the change in multi-dimension urbanization over time) analysis is performed (Fig. 6). Despite the large differences in urbanization performances between these regions, the spatial pattern of population urbanization is largely dominated by coastal and large cities, while land urbanization is high from Shandong and Jiangsu provinces to the West, including Hubei, Chongqing, Sichuan, Qinghai, and Xinjiang provinces.

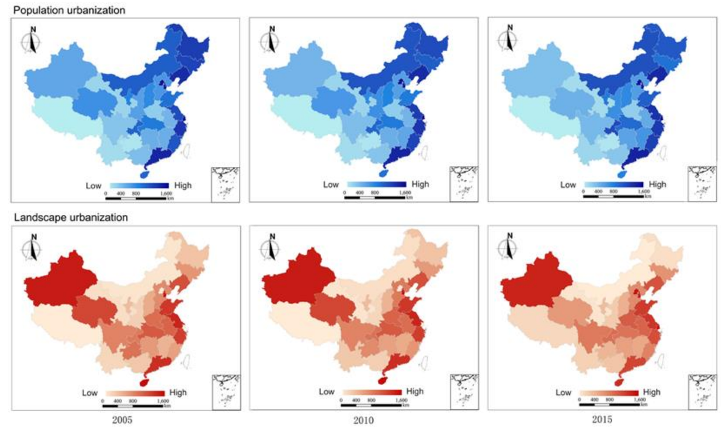

Fig. 6. Urbanization performance in 2005, 2010, and 2015

The broad regional patterns of carbon emissions and carbon productivity from 2004 to 2015 are shown in Fig. 7 in aggregate, and for total energy consumption at the provincial level. The coastal areas, along with the Beijing-Tianjin-Hebei agglomeration, and Shaanxi, Henan, have particularly high carbon emissions, indicating highly developed regions (e.g., Bohai Rim, the Yangtze River Delta, and Pearl River Delta) are the dominant emission contributors, while the entire West and North regions of the country show relatively low carbon emissions.

Similarly, the spatial distribution of carbon productivity shows a significant distribution pattern that is highly correlated with carbon emissions. The southeastern regions have an obviously higher carbon productivity than the Central and West areas. Beijing, Tianjin, and Chongqing are particularly prominent. It is worth noticing that Jiangxi, Anhui, Hubei, Hunan, and Chongqing have low carbon emissions but high carbon productivity, while Shandong, Hebei, and Shanxi have high carbon emissions but low carbon productivity.

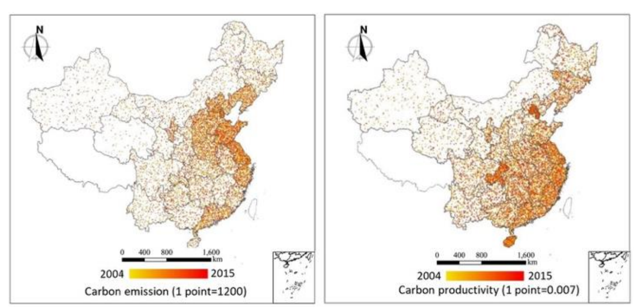

Fig. 7. Spatial patterns of carbon emissions and carbon productivity from 2004 to 2015

4.2 Correlations urbanization and carbon emissions

Our analysis (Table 3) shows that land urbanization correlates more strongly with carbon emissions than population urbanization, and is the most important factor in GHG emissions across all datasets, although population urbanization is also significant.

According to these results, the relationship between both forms of urbanization and carbon emissions is a non-linear quadratic function. The coefficient of the square term of the quadratic function is less than 0, thus the parabola opens down, and then there is an inverted U-shaped correlation (Fig. 8). The maximum value is obtained at the axis of symmetry ($-U/2U^2$). Therefore, the turning point of the two inverted U-shaped curves is 0.56859 (population urbanization), and 0.03548 (land urbanization), respectively.

Table 2 Relationship between carbon emissions and urbanization

Fixed-effect regression results, 2004-2015

Variables	(1)	(2)	(3)	(4)
$GDP\ pc$	13826.03***	13472.01***	14963.08***	11892.66***
	(2459.72)	(2464.20)	(2485.88)	(2605.03)
$(GDP\ pc)^2$	-439.25***	-412.80***	-500.67***	-310.92**
	(150.06)	(150.65)	(151.75)	(159.27)
UR	1138.35***	1123.74***	1276.85***	1340.67***
	(293.39)	(292.84)	(293.85)	(289.40)
$(UR)^2$	-12.61***	-12.65***	-14.42***	-15.48***
	(3.47)	(3.47)	(3.48)	(3.43)
Dev	11052.98***	11399.73***	11091.11***	20170.91***
	(2305.70)	(2310.78)	(2284.34)	(3491.29)
$(Dev)^2$	-1081.45***	-1137.94***	-1110.02***	-1682.47***
	(252.31)	(254.28)	(251.28)	(299.00)
$Energy$		-127.62	-153.65*	-139.23**
		(81.53)	(80.99)	(79.72)
$Industry$			-331.74**	-301.61***
			(113.04)	(111.44)
$Pop\_density$				-86.90***
				(25.59)
constant	-77500.21***	-70536.85***	-66358.2***	-25591.61***
	(12256.64)	(13011.22)	(12927.32)	(17479.22)
R^2	0.7640	0.7659	0.7725	0.7810

Note: *indicates significant at 10% level; **indicates significant at 5% level; ***indicates significant at 1% level. Standard error in parentheses.

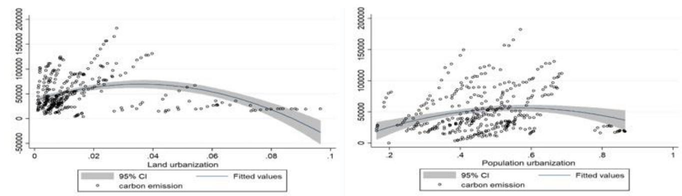

Fig. 8. Scatter plots of the urbanization-carbon emission nexus

Note: the blue curves represent fitted values for adjusted effects of the other explanatory variables in the model, and 95% confidence bands are indicated by shading.

The results indicate that urbanization does help reduce carbon emissions when counties/regions are highly urbanized. When population urbanization and land urbanization reach 56.86% and 0.35% respectively, the coefficients change to negative, suggesting the population urbanization and land urbanization facilitate the agglomeration effects and potentially reach the goal of the compact city.

4.3 Correlations of urbanization and carbon productivity

To explore the impact of urbanization on carbon dynamic characteristics in-depth, the regression of urbanization with carbon productivity (represented by GDP/carbon emission) is further conducted. As shown in Table 4, both population urbanization and land urbanization have a negative impact on carbon productivity, while the square of these two has a significant positive correlation with carbon productivity, suggesting that both population urbanization and land urbanization have a U-shaped relationship with carbon productivity.

Carbon productivity initially decreases with population urbanization and land urbanization then, after reaching the turning point of the U-shaped curve, carbon productivity increases with land expansion and population agglomeration. This can be explained in terms of agglomeration effects. Initially, the agglomeration effects of urban expansion in China are not significant due to the limited population migration from rural areas to cities, while the quickening speed of land expansion increases the input of land resources along with the urbanization process, leading to an inefficient pattern of urban development. The continuous growth in population density makes it possible to optimize the allocation of public infrastructures in urbanization agglomerations, as a result, improving the utilization of assets, and eventually reducing the intensity of energy consumption.

Table 3 Relationship between carbon productivity and urbanization

Fixed-effect regression results, 2004-2015

Variables	(5)	(6)	(7)	(8)
$\boldsymbol{UR}$	-0.498*** (0.164)	-0.467*** (0.163)	-0.520*** (0.166)	-0.610*** (0.158)
$(\boldsymbol{UR})^2$	0.607*** (0.178)	0.593*** (0.176)	0.654*** (0.180)	0.791*** (0.172)
$\boldsymbol{Dev}$	-5.467*** (1.523)	-5.687*** (1.510)	-5.763*** (1.507)	-14.945*** (2.086)
$(\boldsymbol{Dev})^2$	83.075*** (15.635)	87.132*** (15.559)	88.624*** (15.552)	137.568*** (16.800)
$\boldsymbol{Energy}$		0.153*** (0.058)	0.164*** (0.058)	0.138*** (0.055)
$\boldsymbol{Industry}$			0.124 (0.080)	0.123 (0.075)
$\boldsymbol{Pop\_density}$				0.001*** (0.0001)
constant	0.517* (0.069)	0.446*** (0.074)	0.413*** (0.077)	0.048*** (0.094)
$\boldsymbol{R^2}$	0.7232	0.7295	0.7316	0.7607

Note: same as Table 3.

These results point to a considerable but differentiated potential for urbanization to reduce GHG emissions in the long run. Although continued urban population growth and the associated development of urban areas combined with increases in GDP per capita can lead to an increase in carbon emissions and a decrease in carbon productivity in the early stage of urbanization, in the long-run, population agglomeration and the compactness of urban land, combined with efficient economic growth patterns, have the potential to mitigate carbon emissions and improve carbon productivity.

5. Discussion and policy implications

5.1 Unintended policy outcomes of the urbanization process

Our results point to an important result in that carbon emission performance depends on the stage of urbanization. As urbanization is a comprehensive concept, characterized by two sub-processes – population urbanization and land urbanization – its various characteristics determine that sub-systems of the urbanization policy system and well-managed urbanization relies on the coordination of various urbanization policies. This is particularly the case in China, where urbanization has occurred more as a result of government control than market forces. The migration of rural workers into urban areas is limited by the restrictions placed on their access to the benefits of increased social welfare brought by urbanization (Wu et al., 2016).

The household registration system, land policies, and fiscal and tax policies, along with the disconnect between urbanization and industrial development, has led to an asynchrony of land urbanization and population urbanization. First, the *household registration policy* leads to a lag in population urbanization. The employment and settlement of rural-to-urban migrants in cities is regarded as the primary task of urbanization. Historically, internal migration in China has been strictly regulated by the household registration policy increasing the cost of migration, which divides the population into 'Agricultural' and 'Non-agricultural' sectors and thus greatly shapes the country's urban-rural dual structure (Cai, 2007; Henderson et al., 2009). The restrictions placed on "the floating population", has meant that rural migrant workers fail to settle in cities and have to return to their home or commute between two homes (Zhan, 2011). Such duality problems have not only set the barriers to the flow of rural surplus labor to non-agricultural sectors, but also cause the prominent 'double-dipping' of land waste in both urban and rural areas, which forms the mismatch between labor and land, and a double environmental burden.

Second, *land policies* and *fiscal and tax policies* result in an inefficient land use pattern. The major concern for urbanization policy is how to regulate land allocations for a balance between public and private land use. As all land in China is publicly owned, land use planning by Chinese local governments plays an irreplaceable role in urban expansion. The country's rural land requisition and land transfer mechanisms enable local governments to gain a high land premium through the monopoly of land resources, and permits rent-seeking in the land market to reduce the fiscal pressure caused by fiscal decentralization and tax-sharing (Liu et al., 2018). In addition, as land is the carrier of economic activities, local officials assessed under a GDP-based performance system have a greater incentive to provide more land for energy-intensive industries, even at the expense of high carbon emissions (He et al., 2016; Tang et al., 2018). These two important institutional features of China's urban planning and development provide an explanation for urban spatial expansion and the resulting increase in industrial emissions.

5.2 Spatial characteristics of CO2 emission performance and regional collaborative governance

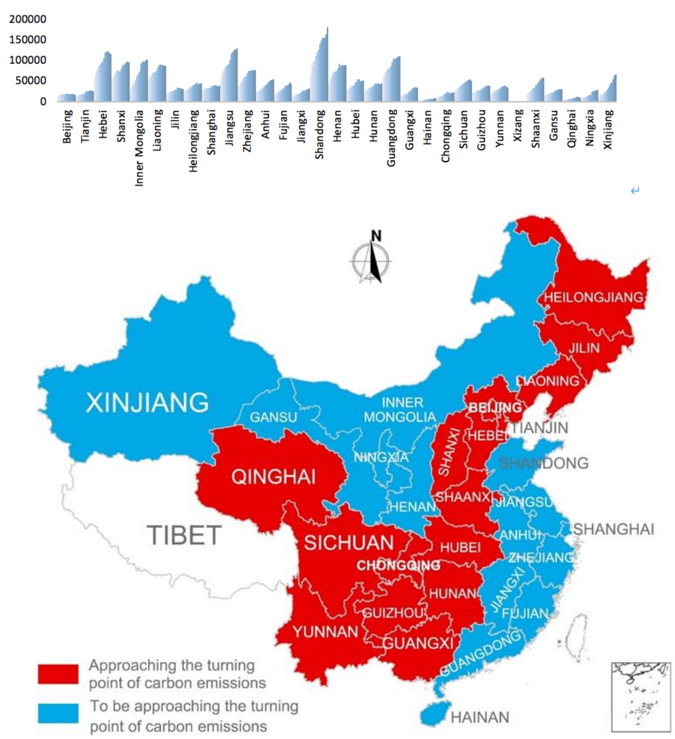

Fig. 9. Spatial characteristics of CO2 emission performance
Note: the red areas represent areas that are reaching the turning point of carbon emission, while blue areas are not.

We further classify the 29 provinces into two categories based on their carbon emission trends (Fig. 9). The areas in red represent areas where carbon emissions are approaching their carbon peak or turning point. The areas in blue refer to regions experiencing carbon emission increases (up to 2015). The patterns suggest that governments should not only pay attention to the universality of development but also consider the local heterogeneity of carbon emissions in the process of implementing a low-carbon economy transformation (Zhou et al., 2017).

Generally, the eastern regions are relatively higher urbanized than the mid-west regions. However, carbon emissions in the eastern regions are still increasing. The likely explanation is that as the main destination of migration – the rapid population growth in eastern regions – has led to the increase in emissions of the transportation and building sectors, which are closely related to living activities. In addition, in most eastern regions, there are various local controls on urban land use, slowing the rate of urban expansion and resulting in a high population density. In this regard, the eastern regions need to greater incentivize a low-carbon lifestyle and consumption patterns to mitigate carbon emissions.

In the northern regions, especially Inner Mongolia, Gansu, and Shaanxi, economic growth is highly dependent on heavy industries and industries that are the primary drivers of carbon emissions. However, due to the dilemma between economic growth and environmental regulation, the local governments of northern provinces have less incentive to reduce industrial emissions: the solution lies beyond regulatory measures. As one prominent benefit of urbanization, the technological improvements of some key industrial sectors may help reduce emissions while maintaining economic growth under the current industrial structure and energy systems. Thus, the local governments of the less urbanized northern regions need to pay more attention to industrial mitigation and sustain technological improvements by encouraging urbanization.

The carbon emissions of the central regions appear to have reached or approached their peak. However, the central region industries are still main drivers of carbon emissions, implying that these regions need to accelerate industrial transformation and upgrading for further mitigation of their carbon emissions. This requires for the joint application of urban development strategies for both land and economy.

The results also suggest that spatial dependence needs to be considered in policy making. The spatial effect supports Tobler's first law of geography, in that all attribute values on a geographic surface are related to each other and closer values are more strongly related than others. As Anselin and Lesage et al. point out, a local region would be more or less influenced by neighboring regions by, on the one hand, taking advantage of knowledge spillovers, technological innovation, and resource sharing to promote environmental innovation and energy efficiency. While, on the other, the environmental problems brought about by the urbanization of local regions could also be transferred to adjacent regions through a "pollution transfer effect" (Fan and Zhou, 2019).

5.3 Tailor-made governance for provinces at different urbanization levels

Since CO2 is one of the main contributors to global emissions, it is important to determine the effective policy implications in curbing CO2 emissions. Considering the high carbon emissions from cities, there are opportunities for climate change mitigation through effective strategies and governance. As urbanization is commonly recognized as a primary driver of CO2 emissions in most countries, mitigation strategies of urban development control may be effective in their reduction. Nevertheless, our results suggest that urbanization is the key to mitigating carbon emissions and improving carbon productivity in the long run, no matter from what dimensions (population or land). Thus, the carbon emissions of each province are closely related to its urbanization performance.

In order to characterize urbanization performance regarding carbon emissions and provide high-resolution low-carbon policies, the selected provinces and municipalities are subdivided into 4 categories by referring to the inflection point of the two forms of urbanization. As depicted in Table 5, Beijing, Tianjin, and Jiangsu are in the "pop+land" category, in that their population urbanization and land urbanization are all highly-urbanized. Inner Mongolia, Liaoning, Zhejiang, Fujian, Shandong, Guangdong, Heilongjiang, and Chongqing belong to the "pop" category in that they have a high population urbanization level but less land urbanization. Hainan and Xinjiang are in the "land" category in that they are at a high land urbanization level but low population urbanization level. The other 16 provinces are less urbanized with respect to both land and population urbanization.

Table 5.

	1	2	3	4
Description	pop+land	pop	land	none
# of provinces	3	8	2	16
Province	Beijing; Tianjin; Jiangsu	Inner Mongolia; Liaoning; Zhejiang; Fujian; Shandong; Guangdong; Heilongjiang; Chongqing	Hainan; Xinjiang	Hebei; Shanxi; Jilin; Anhui; Jiangxi; Henan; Hubei; Hunan; Guangxi; Sichuan; Guizhou; Yunnan; Shanxi; Shaanxi; Gansu; Qinghai; Ningxia

Note: "pop" and "land" respectively denote population urbanization or land urbanization that has approached the turning point of carbon emissions; "none" refers to neither population urbanization nor land urbanization having surpassed the threshold that makes carbon emissions reach a turning point.

Beijing, Tianjin, and Jiangsu are highly urbanized in terms of population agglomeration and urban land development. For these regions, stricter environmental protection policies (e.g., increasing tax, low-carbon subsidy policies) should be introduced, which could increase the operating costs of enterprises, encourage the development of low-carbon production technologies, speed up industry structure updates, and improve the industry competition, which would result in an improvement in carbon productivity and facilitate technological innovation.

Inner Mongolia, Liaoning, Zhejiang, Fujian, Shandong, Guangdong, Heilongjiang, and Chongqing are high-population urbanized, but less land urbanized. Because each province has its own indicators for protecting arable land, urban construction land indicators in coastal areas are significantly scarce. Given these regions have difficulty in urban expansion, the enhancement of land-use efficiency can contribute to the reduction of carbon emissions and improvement in carbon productivity.

Generally, land is regulated through three stages in China: 1) regulations concerning the *land acquisition stage*, in which landownership must be converted from collective communes to the state prior to any urban construction (Ding, 2007); 2) regulations concerning the *urban land supply stage*, in which local governments determine the amount of industrial land, residential land, transportation land, and public service land for each year (Yan, 2018) – this could appropriately control urban growth in a free market; and 3) regulations concerning the *land development stage*, in which the urban form and land-use patterns are determined, usually by urban planning institutions, through a series of plans (e.g., Land Use Plan, Master Plan) to specify land use patterns, the allocation of space, etc., thus determining the quality of urban land.

Since the eastern regions have a limited construction land index, local governments there need to pay more attention to land use efficiency through rationally planning infrastructure construction and invigorating existing public facilities to encourage low-carbon living patterns of residents. It is a public endeavor to change consumption behaviors to reduce consumption-based carbon emissions in the long run through a shift from environmentally damaging behaviors to green behaviors (Zheng et al., 2020).

For less-urbanized regions (category 4), local governments need to continuously encourage urbanization to reach an advanced level to facilitate agglomeration effects while also encouraging the low-carbon transformation of economic growth. This strives to achieve long-term, high-quality development by optimizing the economic structure and transforming the drivers of economic growth. The low-carbon transformation of the energy system is also needed to improve energy efficiency and optimize the energy structure, particularly in industrial-driven development regions. Compared to developed economies, China still lags behind in energy efficiency, which could be enhanced by technological improvement and industrial structure optimization (Zheng et al., 2020). In addition, considering these areas are expected to continuously experience rapid urbanization, it is critical for local governments to pay particular attention to land management regarding the land regulation stage concerning land supply, since the construction land indicators in Mid-west China are much more abundant than in coastal areas. This has crucial policy implications because once cities are built their urban form and land-use patterns lock in patterns of energy consumption for generations (Creutzig et al., 2015). In the long run, when these regions reach an advanced stage of urbanization, the focus on the top-down low-carbon transformation of economic growth could shift to policy inventions on low-carbon behavior from the bottom-up. Further, these areas could instead exploit their vast land areas for solar and wind farms to keep up (Liu et al., 2015).

Considering the 2030 CO2 emissions peak target and the responsibility for helping the world achieve the Paris climate targets, the next decade will be critical for China to reach its carbon emission peak. Thus, adjusting a transition toward a low-carbon economy from the top-down and encouraging low-carbon behavior from the bottom-up is not only the main way China can harmonize economic growth and environmental protection but also a key policy for achieving its carbon emission goals. This includes purposeful low-carbon urbanization development through the establishment of low-carbon urbanization policy standards and strategies to emphasize China's land-use conditions to achieve the sustainable development of urbanization (Zhang and Xu, 2017). Moreover, since China has a vast territory and great regional disparities, differentiated regional development strategies need to be considered based on inter-regional urbanization levels, industrial structure, and natural resource endowments.

6. Conclusion

A sizable literature examines the impact of urbanization on carbon dioxide emissions. However, their explanation of urbanization is unclear, which may have misled low-carbon policy makers. A major contribution of this study is to present a comprehensive and reliable estimate of the correlation between urbanization and carbon emissions through the disaggregation of urbanization into population urbanization and land urbanization. This helps explain the underlying mechanism involved in the dynamic process, and puts right misunderstanding of the impacts of urbanization on carbon emission as well as carbon productivity in China. This study extends several lines of scientific inquiry.

First, this research involves high-resolution multi-perspective urbanization: population and land, based on which, correlations between urbanization and carbon emissions and carbon productivity are studied. This involves two stages.

(1) The study provides empirical evidence of the inverted U-shaped relations between population urbanization and land urbanization with carbon emissions, suggesting that urbanization potentially helps *mitigate* climate change in the long run. This is unlike previous studies, which reveal that urbanization, economic growth, and land use *increase* carbon emissions. The findings also indicate that the considerable but differentiated potential of effective urbanization management could help cities reach their carbon peak and achieve their carbon emissions goal in 2030.
(2) This research reports a U-shaped correlation between population urbanization, land urbanization, and carbon productivity.

Second, this study provides a detailed discussion of the mechanisms analysis and high-resolution low-carbon policy implications for Chinese cities.

(1) We suggest that the triple restrictions of land policy, fiscal and taxation policies, and the household registration system, as well as the disconnection between urbanization and industrial development, lead to the asynchrony of land urbanization and population urbanization in China.
(2) We emphasize that carbon emission mitigation policies should differentiate between areas according to their situation and weaknesses to realize the most cost-effective and tailor-made low-carbon strategies and governance.
(3) The research indicates that a key to achieving China's 2030 carbon emission peak goals is by adjusting the transition toward a low-carbon economy from the top-down to encourage low-carbon behavior from the bottom-up. This includes purposeful low-carbon urbanization development through the establishment of low-carbon urbanization policy standards.

These results indicate that there is a need to reframe the urbanization nexus and revisit the correlation between urbanization and carbon emissions in CO2 reduction policy discussions. In the future, therefore, there is a need to explore the relationship between more diverse case studies from the viewpoint of different policy discourses worldwide to yield more concrete policy discussions.

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