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Changing urban forms and carbon dioxide emissions in China: A case study of 30 provincial capital cities

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HIGHLIGHTS

- The relationship between urban form and CO_2 emissions is investigated.
- A panel data model is used, taking the period 1990–2010.
- The growth of urban areas correlates positively with CO_2 emissions.
- Increases in urban continuity has an inhibitory effect on CO_2 emissions.
- Increased urban shape complexity exhibits a positive influence in relation to CO_2 emissions.

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ABSTRACT

Urban form is increasingly being recognised by scientists for the potential role it might play in the coordination of sustainable urban development and the reduction of CO_2 emissions. However, despite increasing interest in the morphology of cities in climate change science, few quantitative estimates have been made of the effects of urban form on CO_2 emissions. The goal of this study is to quantify this relation, using panel data for China's 30 provincial capital cities from 1990 to 2010. In order to meet this aim, we first selected a series of urban form indicators, which we quantified by applying spatial metrics to remotely sensed data. We then estimated CO_2 emission levels using a unified standard method recommended by the IPCC Guidelines, and subsequently performed a panel data analysis. The results of the study demonstrated a positive correlation between the growth of urban areas and CO_2 emission levels. Further, it was also found that increased "urban continuity" led to reductions in CO_2 emissions and that, conversely, increased "urban shape complexity" exerted a positive influence in relation to CO_2 emissions. The findings of this study indicate that measures to make existing cities in China more compact may in fact help to reduce levels of CO_2 emissions, just as increasing fragmentation or increased irregularity with respect to urban form may contribute to increased CO_2 emissions. If serious about achieving meaningful reductions in CO_2 emissions, decision makers and planners should take urban form into consideration when developing low-carbon cities in China.

1. Introduction

Carbon dioxide (CO_2) is the greatest known contributor to climate change, and the global warming we are currently witnessing is a result of rising CO_2 levels in the Earth's atmosphere [1]. Human emissions of the gas, which have been increasing globally since at least the Industrial Revolution (that is, the late 18th century), have now reached levels not seen for at least three million years [2]. Concomitantly, the past century has also seen the gradual transition of the global population towards urban living, a shift which has resulted in spectacular levels of urbanisation, with the global urbanisation level rising from 10% in 1900 to 52.6% in 2011 [3,4]. Linking these two developments, current scientific research indicates that human activities in urban areas now constitute the primary source of anthropogenic CO_2 emissions [4], and cities, whilst covering less than 3% of the Earth's surface, consume 75% of the

Abbreviations: CE, CO_2 emissions; *E*, fossil fuels; *F*, CO_2 emissions coefficient; *TA*, total area; *LPI*, largest patch index; *AWMSI*, area weighted mean shape index; *AWMPFD*, area weighted mean patch fractal dimension; *PARA_MN*, mean perimeter area ratio; *PLADJ*, percentage of like adjacencies; *COHESION*, patch cohesion index; *AI*, aggregation index; *LSI*, landscape shape index; *CONTIG*, contiguity.

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world's energy and produce 80% of global greenhouse gas emissions [5]. At the same time, cities and towns can also promote global economic growth and improve living standards. Whilst city administrations and national governments struggle to support economic development, they therefore also face increasing pressure to address the impacts of climate change associated with such growth. Curbing fossil-energy use and emissions in urban areas while concurrently continuing to maintain urban development therefore constitutes a key challenge for governments internationally [6–9]. In the context of this complex issue, decision makers and urban planners concerned with sustainable development are required to pay great attention to the formulation of measures that can effectively reduce CO_2 emissions and mitigate climate change. In addition to traditional emission reduction measures that rely on technology and policy solutions, it is recognised that urban form (that is, the spatial patterns and structural features of urban land use) is implicated in urban CO_2 emission levels [9,10]. Despite this recognition, only a limited number of studies have empirically evaluated the direct impacts of different urban form patterns on CO_2 emissions. This deficiency in the current research motivates the present study and its aim to quantify the relationship between urban form and CO_2 emissions.

Although many factors affect CO_2 emissions (for instance, industrial production, transportation, local climates and the burning of fossil fuels, to name but a few), the spatial evolution of urban sprawl is highlighted as a particularly important influencing factor [11–15]. Urban form can be defined as the spatial organisation and arrangement of human activities – it affects how cities grow and expand and how efficiently they are able to configure resources, land use, transport and infrastructure [10,12,16]. Previous studies have addressed a number of influencing factors which begin to explain the relation between urban form and CO_2 emissions [12,17–22], particularly in terms of the effects of urban form on urban infrastructure [23], urban transportation [24], urban heat inland effects [25], carbon taxes [26], the energy efficiency of buildings [11] and residential energy demand [27], in addition to local climatic conditions. Pursuant to these previous studies, the impact of urban form on CO_2 emissions appears to be both significant and profound. Taking this link as the basis for their work, a number of scholars have concluded that designing more compact and more complex cities could decrease CO_2 emissions. For instance, using Helsinki city as an example, Harmaajarvi et al. [28] found that a compact urban development pattern could save as much as 35% of the study district's 2010 total energy usage, through changes in urban transport and district heating. In their analysis of the relationship between the urban form patterns of China's fastest growing cities and CO_2 emissions, which used panel data analysis, Ou et al. [10] similarly found that compact, multiple-nuclei development patterns (rather than dispersed, single-nuclei development patterns) help to reduce CO_2 emissions. These results are supported by the findings of studies undertaken in relation to the U.K. by Banister [29], in Canada by Christen et al. [30], in Japan by Makidoa et al. [31] and in China by Wang et al. [22]. Using Beijing as an example, Ma et al. [32] investigated how urban form impact individual's daily travel behaviour and subsequent CO_2 emission from work and non-work trips, respectively. They found that residents living in neighbourhoods with higher job density emitted less CO_2 from work related trips, and people resident in neighbourhoods with higher retail density tended to travel shorter distance and emitted less CO_2 emission from non-work trips. From the viewpoint of energy consumption and CO_2 emissions to assess the sustainability of urban form, Ye et al. [33] found that urban sprawl aspects of compactness were positively correlated with urban household energy use CO_2 emissions. Using 125 largest urbanised areas in the U.S., Lee and Lee [34] examined how urban form influence an individual household's CO_2 emissions. They found that doubling population-weighted density was associated with a reduction in CO_2 emissions from household travel and residential energy consumption by 48% and 35%, respectively. They suggested that smart growth policies to build more compact cities were useful to mitigate CO_2 emissions. Similarly, using the Greater Dublin Region as an example, Liu and Sweeney [27] estimated the relationship between CO_2 emissions and urban form. They found that the energy-related CO_2 emissions could be significantly decreased by building compact cities.

These existing studies generally indicate that low-carbon energy solutions and energy conservation are important emission reduction measures. However, urban planning and spatial optimisation methods are also required to reduce CO_2 emissions [2]. Studies addressing the nature of the link between urban form and CO_2 emissions have, as a result, become increasingly important. As a factor associated with spatial urban planning, urban form could in fact constitute the basis for a new rationale in the coordination of urban sustainable development and the reduction of CO_2 emissions. It is therefore quite remarkable that such a limited number of studies have engaged in the task of quantitatively estimating spatiotemporal changes in urban form, or have quantified the impact of urban growth and sprawl on CO_2 emissions. Although some studies have attempted to quantify urban form patterns by calculating ratios between two related variables (for instance, through the use of compactness ratios, elongation ratios and urban population density measures) [21], such research denies the process-based character of urban sprawl – which in fact evolves spatially – and further, it neglects the fundamental role played by the basic statistical unit (in terms of landscape metrics). These omissions are evident in the study of CO_2 emissions in Beijing conducted by Qin and Shao [35], who, whilst presenting a new method based on questionnaire data in relation to building and travel (a method which enabled them to estimate the direct CO_2 emissions of the residents of a given community), did not consider the land-use patterns and characteristics of their study area. Although previous studies have certainly enriched our understanding of the relationships between CO_2 emissions and urban form, they have concurrently failed to provide systematic and explicit evidence in relation to how urban form affects those emissions.

The design of the present study attempts to address many of these deficiencies. As such, we first calculated energy-related CO_2 emissions using a unified standard method recommended by the IPCC Guidelines [36]. We then analysed and compared the urban form patterns of various cities using pre-existing sprawl indexes and spatial metrics based on remotely sensed land-use and land-cover data. Based on these calculations, and by employing a range of analysis techniques, we generated a number of quantitative measures in relation to the spatial and temporal characteristics of CO_2 emissions, of urban built-up areas and of various urban form patterns. Finally, we attempted to quantify the relationship between CO_2 emissions and urban form using a panel data analysis. The panel data model was chosen because of its many advantages over conventional cross-sectional or time series models [37,38]. China's 30 provincial capital cities (Beijing, Changchun, Changsha, Chengdu, Chongqing, Fuzhou, Guangzhou, Guiyang, Harbin, Haikou, Hangzhou, Hefei, Hohhot, Jinan, Kunming, Lanzhou, Nanchang, Nanjing, Nanning, Shanghai, Shenyang, Shijiazhuang, Taiyuan, Tianjin, Wuhan, Urumqi, Xi'an, Xining, Yinchuan, and Zhengzhou) constituted the study area in this research. As provincial capital cities, these cities suffer from a series of environmental problems and their CO_2 emissions continue to grow as a result of their rapid urban growth and sprawl. Addressing the panel of these 30 cities, the study attempted to explore the relationships between urban form and CO_2 emissions using time series data for the period 1990–2010. Our findings not only offer a scientific model for analysis, but also suggest a rational path