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An Empirical Study on the Relationship between Urban Spatial Form and CO_2 in Chinese Cities

Yanchun Yi [1], Sisi Ma [1], Weijun Guan [1] and Ke Li [2,*]

[1] School of Economics and Management, Hubei Normal University, Huangshi 435002, China; 13659864132@163.com (Y.Y.); Masisi931023@163.com (S.M.); guanwj@hbnu.edu.cn (W.G.)
[2] Key Laboratory of High Performance Computing and Stochastic Information Processing (HPCSIP) (Ministry of Education of China), College of Mathematics and Computer Science, Hunan Normal University, Changsha 410081, China
* Correspondence: likekent1208@163.com; Tel.: +86-731-8883-8057

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Abstract: Although several studies have explained the effect of urbanization on China's carbon emissions, most have focused on population urbanization, while ignoring the urban spatial form. This study investigates the impact of urban spatial form, measured by residential density, on the evolution of carbon emissions of 108 cities from 2003 to 2013 in China. The main results are as follows: (1) although urbanization significantly increases CO_2 emissions, urban spatial form measured by residential density produces a negative effect on CO_2 emissions in China.; (2) China has not become the "pollution haven" of foreign direct investment (FDI), instead, green FDI has reduced carbon emissions significantly; (3) the environmental dividends of low-carbon transformation have been observed in eastern and middle cities, but not in western ones. Therefore, establishing compact cities and traversing a low-carbon path is both feasible and necessary.

Keywords: urbanization; residential density; urban spatial form; carbon emissions; compact cities

1. Introduction

Scientists have reached a consensus that the main cause of global warming is greenhouse gas emissions induced by human activities. It is estimated that global carbon emissions increased from 3 million tons in 1751, to 9855 million tons in 2014. According to the Carbon Dioxide Information Analysis Center (CDIAC), China is the largest carbon dioxide (CO_2) emitter in the world, and accounted for 29% of the global emission in 2013. In 2015, China vowed to reduce its carbon dioxide emissions, and promised to reach the peak in 2030. Given its commitment to reduce carbon dioxide emissions, China aims to lower its carbon emissions per GDP in 2030 by 60–65%, compared to its 2005 level.

Carbon dioxide emission is mainly caused by human activities, especially energy consumption. Throughout history, a large amount of fossil fuels (such as coal, oil, natural gas, etc.) has been consumed to support human development, which releases a large amount of carbon dioxide and other greenhouse gases. As agglomerated areas of production and consumption, cities possess the highest energy consumption and carbon emissions. Although cities only occupy 2% of the world's entire area, they account for approximately 75% of the global greenhouse gas emissions (IPCC. Climate Change 2007: The Physical Science Basis [R] New York: Cambridge University Press, 2007:996).

Turning to China, since reforms and opening up of the country in 1978, the urbanization rate has surged from 18% in 1978, to 56% in 2015. It is predicted that the urbanization rate will reach 68% in 2030, and 80% in 2050. Correspondingly, China's energy consumption and CO_2 emission increased sharply. In 2015, energy consumption in China was 4.3 billion tons of standard coal equivalent (tce), and its CO_2 emissions soared accordingly. The feasibility and necessity of establishing a compact city to realize low-carbon development is an important topic for current Chinese scholars, and is this article's academic aim.

The distribution of urban form has great effects on low-carbon urbanization. Urban spatial form can be divided into two types: compact and distributed. Compact spatial form refers to the phenomenon in which a limited urban space possesses a high density of industries and population settlements. It is characterized by high density and a compact urban function to achieve the goal of resource conservation, and thus become environmentally-friendly [1,2]. Dispersed or distributed spatial form is characterized by a low population density. Urban overspreading often results in environmental deterioration. To realize the low-carbon urban spatial form, scholars recommend the compact space form [3–6]. They argue that compact cities can reduce carbon emissions from transportation and buildings, in order to realize low-carbon urbanization.

The contribution of this paper is threefold. Firstly, although several studies have investigated the effect of urbanization on China's carbon emissions, most of them focused solely on population urbanization. Only a few studies highlighted the urban spatial form. In this study, empirical analysis on the effects of urban spatial form on China's carbon emissions makes up the present qualitative study. Secondly, previous studies often used national and provincial CO_2 data, whereas carbon emissions data on the city level is seldom presented. Therefore, we use a panel data of 108 prefecture-level cities from 2003 to 2013 to present more detailed and specific results. Thirdly, based on empirical results, the effects of various control variables on urban carbon emissions are discussed. These include: (i) population size has a positive impact on CO_2 emissions; (ii) foreign direct investment (FDI) did not turn China into a "pollution haven"; and (iii) the green and low-carbon transformation effect gradually emerged in central and eastern cities.

The remainder of this paper is organized as follows. Section 2 presents the literature review. Section 3 sets out the analytical framework and introduces the empirical approach. The empirical results are summarized and discussed in Sections 4 and 5, and Section 6 is the conclusion.

2. Literature Review

This section provides an overview of the theoretical and empirical state of research on the relationships between urban spatial structure and environmental pressures. First, we focus on definitions and measurements of urban spatial structure, and then move on to examine the possible causal links between urban spatial form and emissions.

A number of studies have explained definitions of urban spatial form. Horton and Reynolds [7] argued that spatial form was an abstract or general description of a geographically distributed form, while urban spatial form was the result of residential distribution and inter-spatial economic activities [8]. Urbanization has promoted the development of the agglomeration economy, and the city is the engine of economic growth [9]. The change of the role played by urban centers and surrounding areas can be used to describe the dynamic changes of human habitation in time and space. Some cities have a monocentric spatial distribution, and some are polycentric in distribution, therefore, the spatial form is different [10]. Although urban spatial form varies, most researchers divide urban spatial form into two types: scattered spatial form and polycentric spatial form [11,12].

Due to widespread use of private cars, the scattered spatial form city has begun to spread rapidly in North America since the mid-20th century. Commuting costs became cheaper, allowing more freedom of choice in residential location. People no longer needed to live close to their workplace or commercial activities, and started to relocate out from city cores. Cheap land prices also encouraged extensive land use around the new settlements. Similar dynamics appeared later in Europe and other areas, where urban growth has come together with urban sprawl in recent decades, especially in the most developed regions and cities with rapid economic growth. A large amount of literature on urban sprawl is available, but there is no agreement on the definition and measurement of it. Statistically, urban sprawl refers to the spatial distribution of economic activity as a large amount of land use [13].

Residential density is often used to measure the spread of urban indicators, it refers to the number of residents per unit area [14].

The European Union and European environmental agencies highlighted the impact of urbanization on the environment and climate change. This impact can be brought by urban spatial form [15–17].

The movement of population and goods between urban area is the main reason for urban greenhouse gas emissions [18,19]. The key to traffic demand is the distance between workplaces and dwellings, and the distance between them extended with the spread of urban sprawl. A large number of studies have proven that urban sprawl and traffic emissions are positively correlated. For example, Camagni et al. [10] indicated that urban sprawl and residential suburbanization have led to a surge in private cars, and hence a greater prevalence of car traffic and larger fossil energy consumption. Travisi et al. [14] analyzed the impact of transport on the environment of seven provinces of Italy, and found that in the most sprawling cities, there is a strong impact of traffic on the environment because of the mismatch between the place of work and the dwelling, together with the lack of competitive public transport. Kahn [20] predicted that typical household gasoline consumption is lowest in relatively compact cities such as New York and San Francisco, and highest in sprawling cities such as Atlanta and Houston. The environmental costs of sprawling cities are increasingly being studied in North America, and the theme is becoming more and more important in Europe. For example, during 1986–1996, Barcelona's travel distance per capita extended by 45%, and carbon emissions per capita tripled [21]. Other scholars [22–24] have also proved that urban spatial form affected traffic energy consumption.

The first channel of urban spatial form influenced by household emissions is the "urban heat island effect". In densely populated urban centers, energy demand rises in the summer and falls in the winter. The second channel, as Reid Ewing and Rong [25] suggested, of the urban spatial form influenced by household emissions is the size and variety of residential houses. In densely populated cities, where a large number of people live in smaller apartments, energy needs are smaller than those in separate, large house in the suburbs. The last channel is power transmission and distribution losses, which are higher in dispersed cities. However, due to the heterogeneity of geographical and climatic factors, it is difficult to obtain a unified conclusion on the impact of urban spatial form on household emissions. For example, Kahn [20] found no significant difference in energy use between the suburbs and the urban centers. Stone et al. [26] found that dispersed urban spatial forms emitted more greenhouse gases than compact cities.

The study of the relationship between urban spatial form and energy consumption of housing buildings has reached a consensus: larger and dispersed houses consumed more energy, while high-density dwellings consumed less energy [27]. Norway's study [28] found that connected houses consume 50% energy consumption less than decentralized houses. In the US, Ewing and Rong [25] found that the average household energy consumption in sprawling communities was 20% higher than for non-sprawling communities. The reason is that the scattered spatial form of the sprawling communities consumed more motor vehicle energy [29].

In contrast, Chinese researchers focused on the relationship between population urbanization and carbon emissions. It has basically been recognized by domestic theorists that spatial form has an impact on urban carbon, but most of this work is contained in literature reviews and qualitative research, whereas empirical research is relatively scarce. Gu et al. [30] affirmed the relationship between low-carbon development and urban scale, land use, energy planning, etc.

As can be seen, the relationship between urban spatial form and carbon emissions has become a popular issue in developed countries. However, firstly, researchers from China mainly focused on the relationship between population urbanization and carbon emissions. Empirical evidence on spatial form and carbon emissions in China is rare; secondly, current research is mostly in the form of case studies, thus it is difficult to draw general conclusions [31]; thirdly, most studies considered only bivariate relationships, without including socioeconomic influences on carbon emissions [32];

fourthly, some studies were in favor of compact cities, while some scholars questioned the merits of compact cities.

3. Methods and Materials

3.1. Model and Variable

In order to investigate the effects of urban spatial form on carbon emissions in China, the following model was constructed,

$$LNCO_{2it} = \beta_0 + \beta_1 LN(CITYSTRU)_{it} + \beta_2 LN(CITYSIZE)_{it} + \beta_i CONTR_{it} + \gamma_t + \eta_i + \varepsilon_i \quad (1)$$

where LN is the logarithm, CITYSTRU is the urban spatial form, CITYSIZE is the scale of a city, and CONTR denotes the other control variables. Subscript i denotes city, and t refers to the year. β_0 and ε_i reflect the differences between cities and residuals. In regard to control variables, Dietz and Rosa proposed a stochastic IPAT model, which indicates that population, GDP per capita, and technology are the three major factors to the environment. Grossman and Krueger [33] introduced scale, structural, and technical effects from pollution decomposition formula. Therefore, the control variables included the following: scale of population and economy, affluence (GDP per capita), technology (carbon intensity), and economic structures. To test the hypothesis of "pollution haven", FDI is also considered. Considering the influence of infrastructure level on environment, infrastructure level is adopted as a control variable. All variables are explained below.

(1) Carbon emissions: China currently has no official city-level carbon emission data. It is emitted from fossil fuel usage, and can be estimated by the following model introduced by IPCC (2007), namely

$$CO_2 = \Sigma E \times CF \times CC \times COF \times (44/12) \quad (2)$$

where CO_2 is the estimated CO_2 emissions caused by fossil-fuels consumption, and E is the energy consumption data. The energy consumption statistics of urban levels in China are mainly distributed in the following data sources: (i) raw coal, fuel coal, and fuel oil data from China Environment Yearbook; and (ii) urban natural gas, artificial gas, and liquefied petroleum gas data from China Economic Network Statistics Database. CF is the net calorific value, CC is the carbon emission coefficient, COF is a carbon oxidation factor, 44 is CO_2 molecular weight, 12 is the amount of carbon atoms, and (44/12) refers to the coefficient of the mass transfer of carbon atoms to CO_2 molecular weight. The conversion coefficient of CO_2 emission is shown in Table 1, as follows.

Table 1. CO_2 Emission Estimation Coefficient.

Energy	Average Low Calorific Value		Standard Coal Coefficient		CO_2 Emission Coefficient	
	Numerical Value	Unit	Numerical Value	Unit	Numerical Value	Unit
Fuel coal	5000	kcal/kg	0.714	kg/kg	1.98	kg/kg
Raw coal	6300	kcal/kg	0.9000	kg/kg	2.495	kg/kg
fuel oil	10,000	kcal/kg	1.429	kg/kg	3.239	kg/kg
Coal gas	4000	kcal/m^3	5.714	kg/m^3	0.743	kg/m^3
Liquefied petroleum gas	12,000	kcal/kg	1.714	kg/m^3	3.169	kg/kg
Electric power	860	kcal/kWh	0.123	kcal/kWh	–	

(2) Urban spatial form: Urban spatial form is generally characterized by two types of forms: high density and compact; and low density and dispersible. Population density and residential density were often used to measure urban spatial form. This paper used residential density (e.g., [14,18]) as the proxy variable for space form. Residential density refers to the average population per living area; a city with high density is a compact city. A compact city shortened the commuting distance, decreased energy use and carbon emissions. Therefore, residential density is expected to have a negative impact on carbon emissions.

(3) Size of the city: City size involves population size, economy scale, and space scale. The present study used urban population to measure city size. Energy consumption in urban areas is usually higher than rural areas. Migration from country to town leads to higher energy consumption and carbon emissions. Most studies have confirmed that population urbanization increases carbon emissions.

(4) Level of urban economic development: Measured by GDP per capita, this represents the level of urban economic development and economic growth. Economic growth consumed more energy, and more green-house gases were released. Therefore, GDP per capita is expected to have a positive effect on carbon emissions.

(5) Technology: Carbon intensity, namely, carbon emissions per GDP, indicates technology. With economic growth, much energy is consumed, and carbon intensity increases. When energy efficiency decreases, carbon intensity increases. The more advanced technology is, the lower the carbon intensity. Therefore, a positive correlation exists between carbon intensity and the dependent variable.

(6) Economic structure: The structural effect is a key factor in impacting the environment. In the early stages of industrialization, the structural effect on the environment was negative. When industrialization shifted to a higher stage, the industry structure was upgraded from pollution intensive to resource saving. The proportion of the second industry value of GDP was used to measure the structural effect.

(7) Economic openness: FDI is also an important factor that affects carbon emissions. The influence of FDI on carbon emissions can be decomposed into scale, structural, and technical effects [33]. The relationship between FDI and the environment is explained by the "pollution haven" hypothesis [34]. This hypothesis argues that environmental regulations in less-developed countries are weaker than those in developed countries. Thus, pollution-intensive industries move into developing countries and turn developing countries into a "pollution haven". In this study, the proportion of FDI of GDP was used to represent openness.

(8) Infrastructure: Infrastructure plays an important role in urban carbon emissions. On the one hand, infrastructure improvement can improve traffic conditions and reduce urban energy consumption and carbon emissions. On the other hand, excessive investment in infrastructure may cause a waste of spatial resources. The number of buses per million people and road area per capita were used to measure the level of infrastructure.

3.2. Data and Descriptive Statistics

Energy consumption data were obtained from China Environment Yearbook and China Economic Network Statistics Database. Residential density, population, GDP, GDP per capita, proportion of the secondary industry value of GDP, proportion of the FDI of GDP, number of buses, and road area per capita were obtained from the China Economic Network Statistics Database, China Urban Construction Statistics Yearbook, and China Urban Statistics Yearbook. FDI was measured in Renminbi (RMB) at the current exchange rate. GDP was measured with the previous year's rate. The samples include 108 cites at the prefecture level and above, from 2003 to 2013 (Appendix A). The descriptive statistics of the variables are shown in Table 2.

Table 2. Variable Statistical Description.

Variable	Definition	Unit	Mean Value	Maximum Value	Minimum Value	Standard Deviation
CO_2	Carbon emission	Million tons	2837.13	16,003.06	5.53	2460.26
iden	Residential density	Million/square kilometer	4.734	78.6274	0.5667	3.4574
pop	Population	Ten thousand people	212.68	1770.6	36.18	212.68
gdp	GDP	Million Yuan	102,943.5	1,673,585.54	2875.24	140,715.49
pgdp	GDP per capita	Yuan	44,717.76	200,791.5	5556	26,829.58
T	Carbon intensity	Million tons/ million Yuan	0.00075	0.00049	6.37×10^{-5}	0.001001

Table 2. *Cont.*

Variable	Definition	Unit	Mean Value	Maximum Value	Minimum Value	Standard Deviation
manu	Proportion of manufacturing sector of GDP	%	51.869	88.760	17.710	11.171
fdigdp	Proportion of FDI of GDP	%	0.0351	0.3758	0.0001	0.0378
bus	Number of buses per capital		9.493	115	0.91	7.869
pave	Road area per capita	Square meter	11.14	47.29	1.96	5.75

4. Results

Model (1) in Table 3 shows the basic result. The regression coefficient of residential density is −0.387, at 1% significance level. This implies that when the density of living increases by 10%, urban carbon emissions will decrease by 3.87%. On the contrary, when the urban spatial form is scattered, urban residential density decreases and CO_2 emissions increase, suggesting that improvement of residential density reduces urban greenhouse gas emissions. In other words, the compact city is a low-carbon form city. Furthermore, Models (2)–(7) support the above result.

Models (2)–(7) show that the coefficients of urban population size are significantly positive (1.143–1.025). When population size increases by 1%, urban carbon emissions increase by 1.025–1.143%. These results are consistent with the conclusions of previous literature due to characteristics of high-energy consumption during urbanization. Models (3)–(7) prove that the coefficients of GDP per capita are significantly positive, meaning that urban carbon emissions increase with prosperity. The coefficient of GDP per capita decreases with the increase in the number of control variables. Models (3)–(7) show that the coefficients of carbon intensity are significantly positive, a result that is consistent with theoretical expectations. A decrease in energy efficiency results in increased carbon intensity. Models (4)–(7) indicate that the variable that reflects the structural effects (manu) is significantly negative with a very small value (−0.0092~−0.0055), showing that the structure change effect has been felt. The manufacturing industry is shifting from high pollution, energy consumption and high emission, to a resource-saving and environmentally-friendly development mode. Models (5)–(7) indicate that the coefficients of FDI are significantly negative. FDI did not turn China into a "pollution haven" host country. On the contrary, the growth of FDI effectively reduced urban carbon emissions, owing to the outcome of China's FDI adjustment policy. In Models (6) and (7), public infrastructure variables (Lnbus and Lnpave) have opposite impacts on carbon emissions. The coefficient of Lnbus is significantly negative, whereas the coefficient of Lnpave is positive.

China is vast in territory, and its regions show large differences in development stages, spatial forms, etc. In order to test the stability of present empirical conclusions, we further study the relationship between spatial form and carbon emissions in eastern, central, and western cities respectively. The whole sample of 108 cities can be divided into three sub-samples of 52 eastern cities, 30 central cities and 26 western ones.

The empirical results of eastern, central, and western cities are shown in Tables 4–6, respectively. Among all the models, the coefficients of residential density are significantly negative. This result means that an increase in residential density significantly reduces urban greenhouse gas emissions. Similarly, the coefficients of urban population size are significantly positive, meaning the growth of population size increases carbon emissions in eastern, central, and western cities. In the models of western and central cities, population size elasticity coefficients are more than 1, compared to those of no more than 1 in the east. Thus, urban population expansion in the mid and west regions causes more carbon emissions than in the eastern cities.

Table 3. Regression Results of the Total Sample.

Explanatory Variable	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)	Model (6)	Model (7)
LNiden	−0.387 *** (−14.28)	−0.324 *** (−13.275)	−0.301 *** (−13.67)	−0.297 *** (−13.70)	−0.288 *** (14.257)	−0.234 *** (−11.388)	−0.178 *** (−9.15)
LNpop		1.06 *** (16.63)	1.14 *** (20.74)	1.117 *** (20.703)	1.042 *** (19.49)	1.143 *** (23.11)	1.025 *** (22.826)
LNpgdp			0.642 *** (17.804)	0.689 *** (19.066)	0.667 *** (18.00)	0.583 *** (16.905)	0.484 *** (14.91)
LNT (carbon intensity)			0.443 *** (15.98)	0.474 *** (17.16)	0.456 *** (16.30)	0.522 *** (20.095)	0.591 *** (24.216)
manu				−0.0092 ** (−6.383)	−0.0071 *** (−4.691)	−0.006 *** (−4.41)	−0.0055 *** (−4.283)
fdigdp					−1.516 *** (−5.413)	−1.039 *** (−4.022)	−1.37 *** (−5.791)
LNbus						−0.344 *** (−13.96)	
LNpave							0.503 *** (20.106)
Constant term	8.49 *** (215.39)	3.074 *** (9.38)	0.77 ** (2.002)	1.20 *** (3.131)	1.549 *** (3.965)	1.369 *** (3.814)	2.753 *** (8.261)
R^2	0.9196	0.9367	0.9565	0.958	0.960	0.966	0.972
F	110.05 (0.00)	140.48 (0.00)	203.71 (0.00)	209.72 (0.00)	210.36 (0.00)	249.25 (0.00)	298.30 (0.00)
Hausman	0.306 (0.58)	7.91 (0.02)	193.48 (0.00)	221.77 (0.00)	203.97 (0.00)	255.66 (0.00)	170.05 (0.00)
Model	Random effects	Random effects	Fixed effect	Fixed effect	Fixed effect	Fixed effect	Fixed effect
Sample number	1148	1148	1130	1129	1076	1073	1066
Number of cities	108	108	107	107	105	105	104

Note: ***, **, and * respectively represent the significance levels of 1%, 5%, and 10%. The value of the system is T, and the explanatory variables are LN CO_2. Number of cities varied due to missing data.

Table 4. Regression Results of Eastern Urban Samples.

Explanatory Variable	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)	Model (6)	Model (7)
LNiden	−0.503 *** (−13.409)	−0.414 *** (−11.971)	−0.369 *** (−10.647)	−0.364 *** (−10.790)	−0.315 *** (−9.328)	−0.250 *** (−7.844)	−0.215 *** (−7.137)
LNpop		0.845 *** (12.286)	0.855 *** (11.068)	0.759 *** (9.823)	0.711 *** (9.455)	0.844 *** (12.001)	0.778 *** (12.076)
LNpgdp			0.525 *** (9.268)	0.58 *** (10.342)	0.496 *** (8.790)	0.449 *** (8.600)	0.365 *** (7.377)
LNT (carbon intensity)			0.201 *** (4.204)	0.293 *** (5.915)	0.284 *** (5.892)	0.369 *** (8.187)	0.451 *** (10.50)
manu				−0.0134 *** (−5.344)	−0.012 *** (−4.803)	−0.0099 *** (−4.407)	−0.0089 *** (−4.175)
fdigdp					−1.935 *** (−5.571)	−1.167 *** (−3.556)	−1.681 *** (−5.616)
LNbus						−0.314 *** (−9.513)	
LNpave							0.470 *** (13.162)
Constant term	8.865 *** (66.21)	4.342 *** (9.910)	1.389 *** (2.1920)	2.834 *** (4.209)	3.641 *** (5.466)	3.115 *** (5.061)	4.239 *** (7.407)

Table 4. *Cont.*

Explanatory Variable	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)	Model (6)	Model (7)
R^2	0.250	0.409	0.957	0.960	0.963	0.968	0.973
F	180.01 (0.00)	186.49 (0.00)	196.43 (0.00)	204.00 (0.00)	214.34 (0.00)	248.13 (0.00)	290.81 (0.00)
Hausman	0.179 (0.673)	0.188 (0.910)	138.91 (0.00)	165.96 (0.00)	161.73 (0.00)	163.04 (0.00)	121.36 (0.00)
Model	Random effects	Random effects	Fixed effect	Fixed effect	Fixed effect	Fixed effect	Fixed effect
Sample number	541	541	526	525	523	521	513
Number of cities	52	52	51	51	51	51	50

Note: ***, **, and * respectively represent the significance levels of 1%, 5%, and 10%. The explained variable is LN CO_2. Number of cities varied due to missing data.

Table 5. Regression Results of Central City Samples.

Explanatory Variable	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)	Model (6)	Model (7)
LNiden	−0.275 *** (−5.635)	−0.265 *** (−6.203)	−0.284 *** (−6.988)	−0.284 *** (−7.122)	−0.28 *** (−7.014)	−0.253 *** (−6.758)	−0.108 *** (−3.235)
LNpop		1.031 *** (9.672)	1.209 *** (11.85)	1.233 *** (12.30)	1.214 *** (12.108)	1.296 *** (13.758)	1.191 *** (15.406)
LNpgdp			0.628 *** (9.577)	0.971 *** (10.255)	0.675 *** (10.237)	0.647 *** (10.514)	0.415 *** (7.644)
LNT (carbon intensity)			0.492 *** (10.301)	0.515 *** (10.897)	0.536 *** (11.218)	0.606 *** (13.251)	0.610 *** (16.40)
manu				−0.0095 *** (−3.552)	−0.0096 *** (−3.559)	−0.011 *** (−4.295)	−0.0038 * (−1.809)
fdigdp					−1.148 ** (−2.123)	−1.724 *** (−3.375)	−0.913 ** (−2.19)
LNbus						−0.310 *** (−6.609)	
LNpave							0.573 *** (13.82)
Constant term	8.259 *** (48.119)	3.195 *** (5.853)	0.941 (1.461)	1.151 * (1.814)	1.389 ** (2.163)	1.131 * (1.888)	2.32 *** (4.646)
R^2	0.09	0.296	0.959	0.96	0.961	0.967	0.977
F	31.83 (0.00)	66.96 (0.00)	203.3)4 (0.00)	205.69 (0.00)	198.20 (0.00)	223.49 (0.00)	329.70 (0.00)
Hausman	0.029 (0.865)	4.014 (0.134)	83.81 (0.000	100.51 (0.00)	89.01 (0.000	109.53 (0.00)	111.79 (0.00)
Model	Random effects	Random effects	Fixed effect	Fixed effect	Fixed effect	Fixed effect	Fixed effect
Sample number	322	322	322	322	314	314	314
Number of cities	30	30	30	30	30	30	30

Note: ***, **, and * respectively represent the significance level of 1%, 5%, and 10%. The explained variable is LN CO_2.

Table 6. Regression Results of Western Urban Samples.

Explanatory Variable	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)	Model (6)	Model (7)
LNiden	−0.328 *** (−5.687)	−0.274 *** (−5.295)	−0.222 *** (−6.03)	−0.221 *** (−6.069)	−0.231 *** (−6.178)	−0.184 *** (−5.377)	−0.181 *** (−5.140)
LNpop		1.357 *** (8.729)	1.525 *** (14.031)	1.558 *** (14.387)	1.40 *** (12.841)	1.523 *** (15.341)	1.266 *** (12.495)
LNpgdp			0.815 *** (13.562)	0.847 *** (13.940)	0.926 *** (14.50)	0.694 *** (10.465)	0.782 *** (12.424)

Table 6. *Cont.*

Explanatory Variable	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)	Model (6)	Model (7)
LNT (carbon intensity)			0.64 *** (14.464)	0.650 *** (14.785)	0.634 *** (14.16)	0.684 *** (16.72)	0.718 *** (16.607)
manu				−0.0058 ** (−2.547)	0.0013 (0.479)	0.0019 (0.801)	−0.0011 (−0.439)
fdigdp					−2.175 (−1.642)	−1.534 (−1.267)	−2.325 * (−1.911)
LNbus						−0.439 *** (−7.129)	
LNpave							0.36 *** (6.299)
Constant term	8.123 *** (43.887)	1.468 * (1.914)	−1.139 * (−1.745)	−1.173 * (−1.816)	−1.444 ** (−2.188)	−0.88 (−1.453)	0.243 (0.714)
R^2	0.103	0.90	0.956	0.957	0.963	0.97	0.969
F	32.35 (0.00)	86.38 (0.00)	190.03 (0.00)	187.92 (0.00)	188.41 (0.00)	222.69 (0.00)	217.15 (0.00)
Hausman	0.988 (0.32)	11.25 (0.00)	49.156 (0.00)	57.27 (0.00)	34.93 (0.00)	70.47 (0.00)	24.86 (0.00)
Model	Random effects	Fixed effect	Fixed effect	Fixed effect	Fixed effect	Fixed effect	Fixed effect
Sample number	285	285	282	282	239	238	239
Number of cities	26	26	26	26	24	24	24

Note: ***, **, and * respectively represent the significance level of 1%, 5%, and 10%. The explained variable is LN CO_2. Number of cities varied due to missing data.

Tables 4–6 showed similar results with the total sample. The regression coefficient of GDP per capita is significantly positive in the east, central, and west samples. With the rise of urban prosperity, carbon emissions also increase. The elasticity of carbon intensity in the three samples are also significantly positive, which is consistent with previous theoretical expectations. Similarly, in three samples, the coefficients of openness are negative and less than 1; this result further confirms that FDI does not lead China into the "pollution haven". On the contrary, the inflow of green FDI significantly reduced carbon emissions. The infrastructure variables (Lnbus and Lnpave) showed contrary impacts on carbon emissions. The coefficients of Lnbus are significantly negative, whereas those of Lnpave are significantly positive.

The structural variables (manu) in three sample cities show different characteristics. In the samples of eastern and central cities, the elasticity coefficients of industrial structure are significantly negative with a very small value. However, the coefficients of structural variables are sometimes positive and sometimes negative, but not significant in the western cities.

5. Discussion

From the above empirical results, we derive several meaningful conclusions about the relationship between urban spatial form and carbon emissions.

First, residential density improvement can significantly decrease carbon emissions, and indicates a compact population distribution. The coefficients of residential density are significantly negative for all models. For different regions, if the residential density increases by 10%, the CO_2 emissions will decline by 2.15~5.03% in eastern cities, 1.08~2.84% in central cities, and 1.81~3.28% in western cities. According to previous literature, there is a positive relationship between sprawl and environmental pressures from transport. An increase in urban dispersion causes a shift towards private transport, and in turn, increases the use of private transport, fuel consumption and carbon emissions. Residential density improvement can significantly decrease carbon emissions owning to less private transport and intensive use of resources. The results show that in eastern cities, compact distribution of urban population achieved more external benefits, and used less resources than those in central and western cities.

Second, consistent with previous literature, the result indicates that the growth of population size increases carbon emissions. The coefficients of urban population size are significantly positive among all models. During the process of population urbanization, vast numbers of people move from the countryside to towns, and as a result, energy demand, energy consumption per capita, and carbon emissions increase rapidly. In western and central cities, population size elasticity is more than 1, compared with the elasticity of no more than 1 in the east. Thus, urban population expansion in the mid and west cities causes more carbon emissions than those in the eastern cities.

Third, the coefficients of FDI are significantly negative in the total samples, in eastern and central cities. Our findings argue that FDI did not turn China into a "pollution haven". However, we found that the growth of FDI in eastern and central cities effectively reduced urban carbon emissions. In the past few years, China mainly introduced clean and low-carbon FDI, thus realizing the technical effect of FDI [33], and alleviating carbon emissions. We also noticed that the coefficients of FDI are negative but insignificant in western urban area.

Fourth, the elasticity coefficients of manufacture structure vary among three sample cities. In central and eastern cities, coefficients of industrial structure are significantly negative with a very small value, indicating that the green and low-carbon transformation effect gradually emerged. However, in the west, the coefficients of structural variables are sometimes positive and sometimes negative, but not significant—a result that shows that development mode of low carbon has not been realized yet. On one hand, an obvious imbalance in regional development exists in China. Compared with eastern cities, western cities are at a comparative disadvantage in terms of talent, capital, entrepreneurship, innovative awareness, and other aspects. For many cities in the west, the crucial issue is to solve the problem of development, thus inheriting the high-pollution, high-emission mode of growth. On the other hand, environmental standards and labor costs in the east increased. Some high-carbon industries migrated from eastern cities to the west, and aggravated pollution.

Fifth, we find that public infrastructure variables (Lnbus and Lnpave) have opposite impacts on carbon emissions. A large road area per capita implies highly developed urban road traffic and a high level of suburbanization. Too much land for road traffic may cause blind expansion, and too much traffic increases carbon emissions. Therefore, the road area per capita coefficient is significantly positive. Public transportation can reduce the use of private cars and traffic carbon emissions. As a result, the number of public buses has a negative impact on CO_2 emissions.

6. Conclusions

This study investigated the effects of urban spatial form and other factors on the evolution of carbon emissions, by analyzing the data of 108 cities of China from 2003 to 2013. Based on the sample data's heterogeneity, the samples were divided into three groups (eastern, central, western cities). Residential density was used to measure the urban form. The results yielded the following conclusions. First, as a determinant of urban form, residential density plays an important role in carbon emissions. Residential density improvement can significantly decrease carbon emissions, and indicates a compact population distribution. Therefore, our findings support the theory of compact cities. Second, under the background of urbanization, the rapid expansion of urban populations profoundly affects carbon emissions. The growth of population size increases carbon emissions. Third, carbon emissions rise with increases in urban prosperity. Fourth, with the backdrop of globalization, China has not become a "pollution haven". On the contrary, the inflow of FDI reduced China's CO_2 emissions. In addition, the high-carbon growth mode has been gradually transformed into a green low-carbon development model in eastern and central cities. However, this environmental dividend did not occur significantly in the west. Further, the growth of urban public traffic resources helped decrease carbon emissions by replacing some private car travel.

Therefore, the target of establishing compact cities to realize low-carbon development is feasible and necessary. To reduce carbon emissions, the density of urban residences should be improved, and compact cities can be established. The increase in residential density can reduce commuting time, shorten commuting distances, and thus significantly reduce urban carbon emissions. Therefore, we advocate a resource-saving and environmentally-friendly means of living consumption: by improving the density of urban living, and establishing compact cities through reasonable housing allocation. Furthermore, local governments should improve the efficiency of public transport, increase the quantity of public transport, and replace or reduce private car travel, in order to decrease traffic carbon emissions.

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Abbreviations

The following abbreviations are used in this manuscript:

IPCC	Intergovernmental Panel on Climate Change
CDIAC	Carbon Dioxide Information Analysis Center
FDI	Foreign Direct Investment

Appendix A

We have divided the total sample into 3 sub-area samples of eastern, central, and western cities.Eastern cities are from eastern region including Jiangsu, Zhejiang, Fujian, Shandong, Hebei, Guang-dong, Hainan, Liaoning, Beijing, Tianjin, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Hebei, Guang-dong, Hainan, Liaoning, Beijing, Tianjin, Shanghai. Central region includes Shanxi, Anhui, Jiangxi, Henan, Hubei, Hunan, Jilin, Heilongjiang. And the western region includes Guangxi, Sichuan, Chongqing, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang, InnerMongolia. The classification by region is common in China, taking China's economic development level into account combined withthe geographic position.

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