Urbanization's short-and long-term effects on CO₂ emissions: evidence from China

Zhimin Zhou
Lingnan (University) College, Sun Yat-Sen University, Guangzhou, China
Email: st.zhimin@outlook.com

Abstract. It is necessary to investigate the nexus of China’s urbanization and carbon emissions, in order to better understand China’s carbon emissions abatement target. Urbanization’s impact on carbon dioxide (CO₂) emissions has hysteretic effects, it takes time to fully materialize. Knowing this is helpful for policymakers to better coordinate CO₂ mitigation and development. To this end, this study takes the panel data of 30 provinces/cities in China from 1995 to 2015 and applies the dynamic spatial panel data model to empirically analyze the short- and long-term effects of urbanization on CO₂ emissions. The application of the novel approach brings some new discoveries: there exist spatial and time lag effects in China, in terms of CO₂ emissions; urbanization progress has beneficial spatial spillover effects on CO₂ abatement in both the short and long run; energy intensity also exerts significant short- and long-term direct as well as spillover effects on CO₂ emissions; on the contrary, FDI and industrial structure have no significant impacts on CO₂ emissions in China.

1. Introduction
As the primary greenhouse gas, carbon dioxide (CO₂) has been extensively recognized to be a common cause of global environmental issues [1]. China started to promote its industrialization and urbanization since 1978. The rapid urbanization, however, is considered to have increased the CO₂ emissions largely in China. The Chinese government has set an ambitious target of reducing carbon intensity by 40–45% by 2020 compared to the level of 2005.

Although China has been the second largest economy and maintained the highest developing rate for a long time, compared with developed countries, its urbanization level has lagged behind. So the Chinese government has implanted a series of policies to promote the urbanization. The urbanization also raised concerns in academia. Studies on the relationship between urbanization and environmental quality have not reached an agreement. Some scholars argue that urbanization progress would inevitably cause more energy consumption and pollution emissions [2]. Although urban expansion is related to serious environmental issues on a certain extent, other researchers hold the view that the economic activities’ agglomeration and scale effects can reduce environmental pollution. This is because the rise in density of production would make the economic activities, utilization of public transportation and infrastructure more efficient [3]. Ecological modernization theory and urban environmental transition theory suggest that at different development stages, urbanization have different environmental effects since the energy structure and urban public service vary as the urban continuously spread [4]. Some other studies also suggest that in less developed areas without good infrastructure, it is too early for the urbanization to have scale effects. Rather, local industrial upgrading and modernization accompanied by the urbanization can have beneficially environmental effects [5].
Recent studies have investigated the air pollution-urbanization nexus at home and abroad. Zhou, et al. [6] found China’s urbanization progress at the provincial level has beneficial spillover effects for sulfur dioxide (SO2) reduction through spatial panel data approach. Zhou, et al. [7] concluded an inversely N-shaped relationship between the nitrogen oxide (NOx) emissions and urbanization within the Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) framework [8]. Shahbaz, et al. [9] also adopted STIRPAT model to explore the impact of urbanization on CO2 emissions and found that urbanization reduces CO2 emissions at the early stage and then increases the emission level in Malaysia.

This study aims to explore the relationship between urbanization and CO2 emissions through the panel data of 30 areas in China. Past studies on the similar subject fail to simultaneously incorporate both spatial and dynamic effects in the econometric models, which can lead to biased results [10, 11]. Since the novel application of the dynamic spatial econometric approach, the urbanization’s spatial spillover effects on CO2 in both short- and long-term are empirically detected for the first time. The remaining of the study is organized as follow: section two introduces the theoretical foundation, data, and variables; section three introduce the empirical model and then conduct the analysis; the final section makes conclusions and policy suggestions.

2. Data and variables

2.1. Variables selection and data resources

According to the subject, environmental Kuznets curve (EKC) theory [12], and the accessibility of the data, this research takes the following extended STIRPAT model as the benchmark of the empirical analysis:

\[
\ln I = \alpha + b_1 \ln \text{urb} + b_2 \ln \text{fdi} + b_3 \ln \text{stru} + b_4 \ln P + b_5 \ln T + b_6 \ln GDP + b_7 (\ln GDP)^2 + \epsilon
\]  

(1)

where urb, fdi, stru refers to urbanization level, foreign capital inflow, and industrial structure respectively. GDP, the quadratic term of GDP, P, and T refers to the effects of economic growth, population, and technology on the environment. The dependent variable I generally indicates the environmental impact, it refers to the CO2 emissions in this paper. \(\epsilon\) is the error term.

This research uses urbanization rate, foreign direct investment (FDI) ratio, industrial adjustment index, real per capita gross domestic product (GDP) in 1995 constant price, population size, energy intensity as the indicator of urbanization level, foreign capital inflow, industrial structure, economic growth, population, and technological progress respectively. We multiply the urbanization rate, industrial adjustment index (the ratio of the tertiary to the secondary industry), and FDI ratio by 100, and take the logarithm of rest indicators. In this case, the estimates of coefficients \(b_1-b_7\) denote the ecological elasticity [8]. lnGDP, P, and T are the pivot variables in the STIRPAT specification, and urb, according to the research purpose, is the core explanatory variable, stru as well as fdi, are the control variables.

A majority of the researches measure the CO2 emissions of China through the method (Equation 2) provided by the Intergovernmental Panel on Climate Change (IPCC):

\[
\text{CO}_2 = \frac{44}{12} \sum_i \text{EF}_i \cdot \text{Cons}_i \cdot \text{Conv}_i
\]  

(2)

where \(\text{EF}_i\) denotes the carbon emission factor of \(i\)-th energy, \(\text{Cons}_i\) is the consumption of \(i\)-th energy that needs to be converted to standard coal equivalent by multiplication of conversion coefficient (\(\text{Conv}_i\)). The 44/12 is the molar ratio of CO2 to carbon. Table 1 lists all the carbon emission factors and the conversion coefficients for \(i\)-th energy.
Table 1. CO2 emission factors and standard coal equivalent conversion coefficients.

| Energy type     | Raw coal | coke | fuel oil | diesel | kerosene | gasoline | electricity |
|-----------------|----------|------|---------|--------|----------|----------|------------|
| Emission factor | 0.756    | 0.855| 0.619   | 0.592  | 0.571    | 0.554    | 0.272      |
| Conversion      | 0.714    | 0.971| 1.429   | 1.457  | 1.471    | 1.471    | -          |

Note: The unit of CO2 emission factor of electricity is 10000 tC/kWh.

Energy consumptions and the standard coal consumptions (kg of coal equivalent) were obtained from the China Energy Statistical Yearbook. FDI, secondary industry and tertiary output were collected from China City Statistical Yearbook in EPS data bank. GDP, the urban and total population were obtained from the China Statistical Yearbook. Table 2 lists the descriptive statistics of all variables.

Table 2. Definitions and descriptive statistics of the variables.

| Variables | Definition                                                                 | Mean  | Std.Dev. | Min  | Max  |
|-----------|---------------------------------------------------------------------------|-------|----------|------|------|
| lnCO2     | CO2 emissions (10000 tons) in logarithm                                    | 10.02 | 0.918    | 6.791| 11.99|
| urb       | proportion of urban population (%)                                        | 46.40 | 16.04    | 20.39| 89.60|
| fdi       | ratio of FDI to GDP (%)                                                   | 2.986 | 3.181    | 0.001| 21.19|
| stru      | the ratio of the tertiary to the secondary industry (%)                    | 95.36 | 42.40    | 403.79| 49.70|
| lnGDP     | real per capita GDP (100 Yuan) in logarithm                               | 4.867 | 0.855    | 2.905| 7.170|
| lnPOP     | population size (10 thousand) in logarithm                                | 8.127 | 0.770    | 6.176| 9.292|
| lnEI       | energy intensity (tons of coal equivalent/billion yuan) in logarithm       | 9.715 | 0.511    | 8.706| 11.27|

Note: Yuan is the unit of Renminbi (RMB), the official currency in China. urb, fdi and stru are with their actual values.

2.2. CO2 emissions distribution

The Global Moran’s I statistics [13] measures the spatial autocorrelation, if the distribution pattern of a spatial index is clustered, random, or dispersed. The formula can be seen as

\[ I = \frac{1}{N} \sum_{i=1}^{N} \sum_{j=1}^{N} w_{ij} (x_i - \bar{x})(x_j - \bar{x}) / \left( \sum_{i=1}^{N} x_i - \bar{x} \right)^2 \sum_{i=1}^{N} \sum_{j=1}^{N} w_{ij}, \quad -1 \leq I \leq 1, \]

where \( \bar{x} = \frac{1}{N} \sum_{i=1}^{N} x_i \); \( x \) indicates the index of interest which is lnCO2; \( w_{ij} \) is the value on the \( i \)-th row and \( j \)-th column on \( W \), the spatial weight matrix. In the study, \( N \) (the number of regions) equals 30, \( W \) adopts the first order Rook Adjacency specification, which is widely utilized. \( w_i \) and \( w_j \) are the sum of the \( i \)-th row and \( j \)-th column of \( W \) respectively. The significance of Moran’s I statistics is verified by the z-value (the comparison of Moran’s I and its expectation: \[ Z = [I - EI] / \sqrt{Var(I)}, \] here \( EI = (n-1)^{-1} \), \( Var(I) = \left( n^2 w_i + n w^2 + 3 w^2 \right) - E^2(I), \)

\[ w_{ij} = \frac{n}{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij}}, \quad w_i = \frac{1}{2} \sum_{i=1}^{n} \sum_{j=1}^{n} (w_{ij} + w_{ji}), \quad w_j = \sum_{i=1}^{n} \sum_{j=1}^{n} (w_{ij} + w_{ji}). \]

If \( I \leq 0 \) significantly, the regions of the index with high/low values generally cluster together; if \( 0 \leq I \) significantly, the regions of the index with higher values tend to locate near the regions of the index with low values.

Figure 1 shows the global Moran’s I statistics of CO2 emissions at the provincial level. The agglomeration effects of CO2 are significant at 5% level in most years. The Moran’s I statistics and its p-value were calculated by ArcGIS 10.2 and the rest of the empirical results were carried out by STATA 15.
Figure 2 intuitively depicts the spatial clustering pattern of CO₂ emissions (1995, 2005, and 2015) at the provincial level: the regions with similar emission levels generally cluster together. The regions with higher emission levels are mainly distributed in the central and eastern coastal areas which are economically developed, while the low emission level regions are mainly located in the poor western areas.
Table 3 lists the time series correlation coefficients. One can clearly see that the provincial CO₂ emission level is highly dependent on prior levels and the dependence only decreases slightly with the increase of the year interval. Fail to control for the spatial effects can lead to biased estimates [10], and the urbanization's impact on CO₂ emissions could be overestimated without the incorporation of the dynamic effects [11]. Therefore, it is reasonable to control for both the spatial and time series autocorrelation of the dependent variable (CO₂) in the empirical framework by applying the dynamic spatial econometric models.

**Figure 2.** CO₂ emissions distribution at the provincial level.
The empirical analysis is based on the extended STIRPAT model (Equation 1) and applies the dynamic spatial panel data model to test the effects of urbanization and other factors on CO₂ emissions. The most dimensional unit vector.

where \( V_t = \mathbf{c} + \mathbf{X}_t \mathbf{c} + \mathbf{W}_t \mathbf{V}_{t-1} + \mathbf{W}_t \mathbf{V}_t + \mathbf{e}_t \) and \( \mathbf{c} = \kappa \mathbf{W}_t \mathbf{c} + \zeta \)

3. Empirical model and results

3.1. Dynamic spatial panel data model

The empirical analysis is based on the extended STIRPAT model (Equation 1) and applies the dynamic spatial panel data model to test the effects of urbanization and other factors on CO₂ emissions. The most general spatial panel data model can be seen as:

\[
y_t = \gamma_0 y_{t-1} + \lambda_0 W_{yt} + \rho_0 W_{yt-1} + X_t \beta_0 + WX_t \beta_1 + X_{t-1} \beta_2 + WX_{t-1} \beta_3 + V_t
\]

Table 3. Correlation coefficients of annual CO₂ emissions.

| Year | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 |
|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| 1995 | 1.00 |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 1996 | 0.998 | 1.000 |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 1997 | 0.982 | 0.984 | 1.000 |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 1998 | 0.978 | 0.981 | 0.997 | 1.000 |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 1999 | 0.961 | 0.964 | 0.991 | 0.994 | 1.000 |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 2000 | 0.950 | 0.954 | 0.982 | 0.988 | 0.997 | 1.000 |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 2001 | 0.951 | 0.955 | 0.982 | 0.988 | 0.994 | 0.995 | 1.000 |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 2002 | 0.946 | 0.953 | 0.976 | 0.984 | 0.986 | 0.986 | 0.996 | 1.000 |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 2003 | 0.939 | 0.948 | 0.969 | 0.976 | 0.978 | 0.979 | 0.991 | 0.997 | 1.000 |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 2004 | 0.926 | 0.935 | 0.957 | 0.963 | 0.969 | 0.969 | 0.984 | 0.988 | 0.993 | 1.000 |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 2005 | 0.902 | 0.911 | 0.939 | 0.941 | 0.952 | 0.948 | 0.967 | 0.969 | 0.976 | 0.992 | 1.000 |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 2006 | 0.892 | 0.902 | 0.930 | 0.932 | 0.943 | 0.939 | 0.959 | 0.963 | 0.971 | 0.990 | 0.999 | 1.000 |      |      |      |      |      |      |      |      |      |      |      |      |
| 2007 | 0.879 | 0.889 | 0.919 | 0.932 | 0.929 | 0.950 | 0.953 | 0.963 | 0.984 | 0.997 | 0.999 | 1.000 |      |      |      |      |      |      |      |      |      |      |      |
| 2008 | 0.864 | 0.874 | 0.905 | 0.902 | 0.918 | 0.914 | 0.936 | 0.937 | 0.948 | 0.974 | 0.991 | 0.994 | 0.998 | 1.000 |      |      |      |      |      |      |      |      |
| 2009 | 0.857 | 0.868 | 0.896 | 0.893 | 0.909 | 0.905 | 0.926 | 0.926 | 0.938 | 0.966 | 0.985 | 0.989 | 0.994 | 0.998 | 1.000 |      |      |      |      |      |      |      |
| 2010 | 0.848 | 0.858 | 0.889 | 0.886 | 0.904 | 0.900 | 0.920 | 0.920 | 0.932 | 0.961 | 0.983 | 0.987 | 0.992 | 0.998 | 0.999 | 1.000 |      |      |      |      |      |      |      |
| 2011 | 0.826 | 0.837 | 0.870 | 0.866 | 0.886 | 0.882 | 0.902 | 0.903 | 0.917 | 0.949 | 0.971 | 0.977 | 0.984 | 0.992 | 0.995 | 0.997 | 1.000 |      |      |      |      |      |      |
| 2012 | 0.820 | 0.832 | 0.865 | 0.860 | 0.877 | 0.872 | 0.893 | 0.896 | 0.910 | 0.941 | 0.964 | 0.971 | 0.978 | 0.987 | 0.991 | 0.993 | 0.998 | 1.000 |      |      |      |      |      |      |
| 2013 | 0.814 | 0.827 | 0.856 | 0.852 | 0.869 | 0.865 | 0.887 | 0.891 | 0.906 | 0.936 | 0.958 | 0.965 | 0.971 | 0.980 | 0.985 | 0.987 | 0.993 | 0.997 | 1.000 |      |      |      |      |      |      |
| 2014 | 0.798 | 0.812 | 0.841 | 0.837 | 0.853 | 0.850 | 0.873 | 0.878 | 0.884 | 0.924 | 0.948 | 0.956 | 0.963 | 0.974 | 0.979 | 0.982 | 0.988 | 0.995 | 0.998 | 1.000 |      |      |      |      |
| 2015 | 0.776 | 0.790 | 0.821 | 0.816 | 0.833 | 0.828 | 0.855 | 0.859 | 0.875 | 0.908 | 0.937 | 0.946 | 0.955 | 0.967 | 0.972 | 0.976 | 0.981 | 0.989 | 0.992 | 0.997 | 1.000 |      |      |      |

Note: the result has been rounded up.
the difficulties of parameter estimations, the commonly used dynamic spatial econometric models in empirical studies are reduced form of Equation 3.

If \( \beta_2 = \beta_3 = \phi = \phi = k = 0 \) in Equation 3, the Dynamic Spatial Durbin Model (DSDM) can be derived:

\[
y_t = \gamma_0 y_{t-1} + \lambda_0 y_{t-1} + \rho_0 W y_{t-1} + X_t \beta_0 + WX_{2t} \beta_1 + c + \alpha + V_t
\]  

(4)

Since the provincial data is not randomly sampled from a population, and the samples of observations are relatively small (N=30), thus the fixed individual effects should be adopted in the panel data analysis [10, 14]. If \( \gamma_0 = 0 \), Equation 4 can be further simplified:

\[
y_t = \lambda_0 W y_{t-1} + \rho_0 W y_{t-1} + X_t \beta_0 + WX_{2t} \beta_1 + c + \alpha + V_t
\]  

(5)

Furthermore, if \( \rho_0 = 0 \), Equation 6 can be derived:

\[
y_t = \gamma_0 y_{t-1} + \lambda_0 W y_{t-1} + X_t \beta_0 + WX_{2t} \beta_1 + c + \alpha + V_t
\]  

(6)

Due to the inclusion of the quadratic term of \( \ln\text{GDP} \) (Equation 1), the coefficients of \( \ln\text{GDP} \) and its quadratic term are meaningless in terms of economics. Therefore, \( \ln\text{GDP} \) and its quadratic term are only included in \( X \), not in \( WX \). Then \( y_t = (\ln\text{CO}_2_{1t}, \ln\text{CO}_2_{2t}, \ldots, \ln\text{CO}_2_{Nt}) \) in Equation 4-Equation 6.

3.2. Empirical results and analysis

| Variables | Fixed effects | Random effects | Variables | Fixed effects | Random effects |
|-----------|---------------|----------------|-----------|---------------|----------------|
| \( urb \) | 0.002 | 0.005*** | \( (\ln\text{GDP})^2 \) | -0.003 | -0.036*** |
| \( fdi \) | -0.003 | 0.001 | \( \ln\text{POP} \) | -0.164* | 0.854*** |
| \( stru \) | -0.001** | -0.002*** | \( \ln\text{EI} \) | 0.994*** | 0.885*** |
| \( \ln\text{GDP} \) | 1.050*** | 1.246*** | constant | -3.382*** | -10.763*** |

\[ R^2 = 0.975 \]

Hausman (\( \chi^2 \)) = 142.09***

Observations = 630

Note: t-statistics in parentheses, * p<0.10, ** p<0.05, *** p<0.010. \( \ln\text{CO}_2 \) is the dependent variable. The model specification is based around Equation 1.

In order to avoid the occurrence of serious multiple-collinearity of explanatory variables, the Variance Inflation Factor (VIF) of each independent variable was calculated. All the variables’ VIF values are less than 10 (\( urb 6.06, \ln\text{GDP} 6.01, \ln\text{EI} 2.86, fdi 1.81, \ln\text{POP} 1.75, \text{stru} 1.54 \)), which implies that no special treatment is needed for the multiple-collinearity issue in the regression analysis. Table 4 reports the results of the traditional non-spatial panel data model based on Equation 1, which serves as the baseline. The coefficients of fixed and random individual effects specifications were estimated and the Hausman test shows that the fixed effects should be considered rather than the random effects. The urbanization seems to have no impacts on the \( \text{CO}_2 \) emissions according. However, this is only the
preliminary result and the negligence of the spatial effects could lead to biased results [10]. Further empirical analysis control for spatial and dynamic effects is necessary.

Table 5 lists the coefficients estimates (Maximum Likelihood Estimation [15]) of Equation 4-Equation 6. None estimates of $\rho_0$ (coefficient of $W\ln CO_2 t-1$) in Equation 4 and Equation 5 are statistically significant. Besides, coefficients of determination ($R^2$) of Equation 4 and Equation 6 are the same which means the inclusion of $W\ln CO_2 t-1$ in the model does not enhance the explanatory power. $\lambda_0$ is not significant alone in all three models, whereas the spatial dependence of CO2 is significant (Figure 1), and in China, there exist a strong sense of cooperation and competition among adjacent provinces in terms of economic development. Neighbor provinces tend to imitate each other’s industrial structure layout and developing patterns, indicating that energy consumption and CO2 emissions are usually affected by neighbors [7]. Therefore, it is still better off to control for the spatial CO2 term, $W\ln CO_2 t$, in the empirical model. To conclude, Equation 6 is the most appropriate model specification and the estimation of explanatory variables’ short- and long-term effects on CO2 will base on coefficients of Equation 6 in Table 5.

Table 5. Coefficients estimates of the dynamic spatial panel data model.

| Variables       | Equation 4 | Equation 5 | Equation 6 |
|-----------------|------------|------------|------------|
| $\ln CO_2 t-1 (\gamma_0)$ | 0.758***   | 0.758***   |            |
|                  | (34.02)    | (34.04)    |            |
| $W\ln CO_2 t-1 (\rho_0)$ | 0.037      | 0.104      |            |
|                  | (0.61)     | (1.26)     |            |
| $urb$            | -0.002*    | -0.044**   | -0.002*    |
|                  | (-1.85)    | (-2.04)    | (-1.90)    |
| $fdi$            | 0.001      | 0.003      | 0.004      |
|                  | (0.52)     | (1.30)     | (0.98)     |
| $stru$           | -0.0002    | 0.0001     | 0.0003     |
|                  | (-0.19)    | (0.41)     | (-0.62)    |
| $\ln GDP$       | 0.402***   | 1.358***   | 0.396***   |
|                  | (4.91)     | (10.78)    | (4.86)     |
| $(\ln GDP)^2$   | -0.012**   | -0.030***  | -0.012**   |
|                  | (-2.22)    | (-3.38)    | (-2.17)    |
| $\ln POP$       | -0.031     | 0.104      | -0.147     |
|                  | (-0.51)    | (1.11)     | (-0.96)    |
| $\ln EI$        | 0.310***   | 0.077      | 0.119      |
|                  | (10.62)    | (30.81)    | (10.61)    |
| $W\ln CO_2 t (\lambda_0)$ | 0.016      | 0.055      | 0.042      |
|                  | (0.28)     | (0.78)     | (1.17)     |

| Observations    | 600        | 600        | 600        |
| Log-likelihood  | 851.280    | 634.966    | 825.312    |
| $R^2$           | 0.956      | 0.182      | 0.956      |
| N               | 30         | 30         | 30         |

Note: z-statistics in parentheses, *** p<0.01, ** p<0.05, * p<0.1. $\ln CO_2$ is the dependent variable.

The coefficients do not reflect the explanatory variables’ effects on the dependent variable in spatial models that incorporates spatial lag term of the dependent variable. The explanatory variables’ direct and spillover effects on the dependent variable need to be further calculated. By rewriting Equation 6:

$$y_t = (I - \lambda_0 W)^{-1} \gamma_0 y_{t-1} + (I - \lambda_0 W)^{-1} (X_t \beta_1 + WX_{2t} \beta_2) + (I - \lambda_0 W)^{-1} V_t$$  (7)
The matrix of partial derivatives of $y_t$’s expected value to the $k^{th}$ explanatory variable of $X$ from unit 1 to unit $N$ in time $t$ is

$$
\begin{bmatrix}
\frac{\partial E_y}{\partial x_{1k}} & \ldots & \frac{\partial E_y}{\partial x_{Nk}} \\
\vdots & \ddots & \vdots \\
\frac{\partial E_y}{\partial x_{1k}} & \ldots & \frac{\partial E_y}{\partial x_{Nk}}
\end{bmatrix}
= (I - \lambda_0 W)^{-1} [\beta_{1k} I + \beta_{2k} W]
$$

Equation 8

The $(I - \lambda_0 W)^{-1}$ term is calculated by $(I - \lambda_0 W)^{-1} = I + \lambda_0 W + \lambda_0^2 W^2 + \lambda_0^3 W^3 + \ldots$. The partial derivatives refer to the effect of an independent variable in a particular region on the dependent variable of all other regions in the short term [10]. The mathematical expectation of the diagonal elements in Equation 8 is defined as the short-term direct effects while the mathematical expectation of the off-diagonal elements is defined as the short-term spillover (or indirect in some literature) effects, total effects = direct effects + spillover effects. Similarly, the long-term effects are

$$
\begin{bmatrix}
\frac{\partial E_y}{\partial x_{1k}} & \ldots & \frac{\partial E_y}{\partial x_{Nk}} \\
\vdots & \ddots & \vdots \\
\frac{\partial E_y}{\partial x_{1k}} & \ldots & \frac{\partial E_y}{\partial x_{Nk}}
\end{bmatrix}
= [(I - \gamma_0 I - \lambda_0 W)^{-1} [\beta_{1k} I + \beta_{2k} W]
$$

Equation 9

The direct and spillover effects in the long-run are similarly defined by Equation 9. The necessary coefficients for Equation 8 and Equation 9 are already estimated and listed in Table 5. Table 6 illustrates the estimates of independent variables’ effects on CO2 emissions based on Equation 8 and Equation 9. It is worth noting that CO2 emissions reflect the overall pollution level instead of a particular pollution index, thus it is more difficult for a single factor to influence its’ emissions level. FDI, industrial structure and population show no significant impacts on CO2 emissions. On the other hand, the improvement of urbanization level has significant direct and spillover beneficial effects on CO2 abatement while energy intensity has beneficial effects on carbon reduction as well. In other words, the lower the energy intensity, the higher the level of technological progress, the higher the energy efficiency which lead to fewer carbon emissions.

In the short run, a 10% improvement of local urbanization level would lead to a 0.02% and 0.04% decreases of CO2 emissions in local and adjacent areas respectively, ceteris paribus. In the long run, this change in urbanization would decrease the local CO2 emissions by 0.08% and adjacent areas by 0.19%, ceteris paribus. The technological impacts (energy intensity) have similar direct and spillover effects on CO2 emissions.

**Table 6. Short- and long-term effects on CO2 emissions.**

| Variables | Direct effects (short term) | Spillover effects (short term) | Total effects (short term) | Direct effects (long term) | Spillover effects (long term) | Total effects (long term) |
|-----------|-----------------------------|--------------------------------|----------------------------|-----------------------------|-------------------------------|-----------------------------|
| urb       | -0.002*                     | -0.004**                       | -0.006***                  | -0.008**                    | -0.019*                       | -0.028**                    |
|           | (-1.94)                     | (-2.07)                        | (-2.95)                    | (-2.07)                     | (-1.93)                       | (-2.54)                     |
| fdi       | 0.001                       | 0.003                          | 0.004                      | 0.004                       | 0.016                         | 0.019                       |
|           | (0.62)                      | (1.25)                         | (1.51)                     | (0.71)                      | (1.26)                        | (1.46)                      |
| stru      | -0.0044                     | 0.0009                         | 0.0005                     | -0.0001                     | 0.0005                        | 0.0003                      |
|           | (-0.26)                     | (0.29)                         | (0.14)                     | (-0.22)                     | (0.31)                        | (0.18)                      |
| lnPOP     | -0.029                      | 0.115                          | 0.086                      | -0.107                      | 0.520                         | 0.413                       |
|           | (-0.50)                     | (1.30)                         | (0.85)                     | (-0.44)                     | (1.22)                        | (0.82)                      |
| lnEI      | 0.310***                    | 0.093*                         | 0.403***                   | 1.306***                    | 0.648*                        | 1.955***                    |
|           | (10.87)                     | (1.69)                         | (6.42)                     | (10.48)                     | (1.93)                        | (4.93)                      |

Note: z-statistics in parentheses, *** p<0.01, ** p<0.05, * p<0.1.
3.3. Robustness check
Statistical results could be sensitive to model specifications and, thus far, the DSDM model is still not widely applied in environmental economics research. Besides, policy suggestions heavily rely on the robustness of the empirical analysis. Therefore, this section conducts the robustness check by different DSDM specifications that incorporate no or partial control variables (stru and fdi), and the results are reported in Table 7.

**Table 7. Short-and long-term effects of different model specifications.**

| Variables | Direct effects (short term) | Spillover effects (short term) | Total effects (short term) | Direct effects (long term) | Spillover effects (long term) | Total effects (long term) |
|-----------|-----------------------------|-------------------------------|---------------------------|---------------------------|-------------------------------|---------------------------|
| Model specification: $\ln CO_2 = \alpha + \beta_{urb} + \beta_{fdi} + \beta_{ln POP} + h_{ln EI} + h_{ln GDP} + h_{(ln GDP)^2} + e$ |
| urb       | -0.002**                    | -0.004**                     | -0.006***                 | -0.009**                  | -0.019*                      | -0.028**                   |
|           | (-2.12)                     | (-2.02)                      | (-3.07)                   | (-2.26)                   | (-1.87)                      | (-2.54)                   |
| fdi       | 0.001                       | 0.003                        | 0.004*                    | 0.004                     | 0.017                        | 0.021                     |
|           | (0.73)                      | (1.38)                       | (1.66)                    | (0.82)                    | (1.40)                       | (1.60)                     |
| lnPOP     | -0.036                      | 0.135*                       | 0.099                     | -0.130                    | 0.630                        | 0.501                     |
|           | (-0.65)                     | (1.65)                       | (1.09)                    | (-0.56)                   | (1.54)                       | (1.04)                     |
| lnEI      | 0.312***                    | 0.093*                       | 0.404***                  | 1.316***                  | 0.669*                       | 1.986***                   |
|           | (11.21)                     | (1.79)                       | (7.21)                    | (10.82)                   | (2.10)                       | (5.38)                     |
| Model specification: $\ln CO_2 = \alpha + \beta_{urb} + \beta_{stru} + \beta_{ln POP} + h_{ln EI} + h_{ln GDP} + h_{(ln GDP)^2} + e$ |
| urb       | -0.002**                    | -0.004**                     | -0.006***                 | -0.009**                  | -0.023**                     | -0.032**                   |
|           | (-2.18)                     | (-2.22)                      | (-3.25)                   | (-2.36)                   | (-1.98)                      | (-2.54)                   |
| stru      | -0.000                      | 0.000                        | 0.000                     | 0.000                     | 0.001                        | 0.001                     |
|           | (-0.02)                     | (0.54)                       | (0.45)                    | (0.06)                    | (0.54)                       | (0.47)                     |
| lnPOP     | -0.037                      | 0.036                        | -0.001                    | -0.148                    | 0.139                        | -0.008                    |
|           | (-0.66)                     | (0.44)                       | (-0.01)                   | (-0.64)                   | (0.33)                       | (-0.02)                   |
| lnEI      | 0.312***                    | 0.086                        | 0.397***                  | 1.305***                  | 0.727*                       | 2.032***                   |
|           | (10.85)                     | (1.62)                       | (6.65)                    | (10.17)                   | (1.85)                       | (4.41)                     |
| Model specification: $\ln CO_2 = \alpha + \beta_{urb} + \beta_{ln POP} + h_{ln EI} + h_{ln GDP} + h_{(ln GDP)^2} + e$ |
| urb       | -0.002**                    | -0.004**                     | -0.006***                 | -0.009**                  | -0.020**                     | -0.029***                  |
|           | (-2.24)                     | (-2.08)                      | (-3.05)                   | (-2.39)                   | (-2.00)                      | (-2.66)                   |
| lnPOP     | -0.035                      | 0.058                        | 0.023                     | -0.137                    | 0.256                        | 0.120                     |
|           | (-0.63)                     | (0.78)                       | (0.28)                    | (-0.59)                   | (0.73)                       | (0.30)                     |
| lnEI      | 0.312***                    | 0.082                        | 0.394***                  | 1.297***                  | 0.626*                       | 1.923***                   |
|           | (11.26)                     | (1.63)                       | (6.85)                    | (10.80)                   | (2.11)                       | (5.39)                     |

Note: z-statistics in parentheses, *** p<0.01, ** p<0.05, * p<0.1.

Clearly, the urbanization’s beneficial effects remain significant in the short- and long-run, only the amounts of long-term spillover effects change slightly. Therefore, the empirical findings of urbanization’s effects on CO2 emissions in China are reliable.

3.4. Discussion
The empirical findings in the study provide evidence of urbanization’s spatial and dynamic effects on CO2 emissions at the provincial level in China.

Benefits of urbanization progress on CO2 reduction in China is consistent with both ecological modernization and urban environmental transition theories. Namely, the urbanization progress can promote economic scale effects, provide more sanitation and environmental protection facilities, and enhance energy efficiency, all these changes can drive the local carbon emissions decrease [3]. The environmental spillover effects of urbanization could be explained by the population migration and industrial transfer to neighbor regions. Apparently, the results of DSDM is different from the results of traditional non-spatial panel data (Table 4). The inadequate negligence of spatial lag and time lag effects can contribute to such differences [10, 11]. The urbanization’s direct and indirect (spillover) environmental-beneficial effects are similar to the findings from Chen, et al. [3] and Zhou, et al. [6]
respectively. However, the results of long-term environmental urbanization’s impact in this study contradict Sheng and Guo [11] who states positive long-term effects of urbanization on CO₂ emissions. One reason for the difference could be that they failed to control for the spatial effects of emissions. The other reason might be that Sheng and Guo [11] investigated the data ranging from 1990-2010, and urbanization’s environmental impacts can vary at the different developing stage [4, 9].

4. Conclusion
This study uses the extended STIRPAT model and the dynamic spatial econometric tool to investigate the nexus of urbanization and CO₂ emissions in China. The results reveal that in 1995-2015, FDI and adjustment of the industrial structure have no impacts on CO₂ emissions. The improvement in the urbanization level, in the short and long run, is helpful for CO₂ abatement in local as well as adjacent provinces. Energy intensity has similar effects. The Chinese government and environmental protection department are expected to implement effective measurements to take full advantages of urbanization progress and efficient energy utilization to eventually achieve energy conservation and carbon emission reduction. The greater magnitude of spillover effects of urbanization implies that policymakers should consider the influence on/from the neighbor regions. Local governments can break administrative boundaries and cooperate for the enhancement of CO₂ abatement and urbanization. The central government needs to make national wide plans on carbon mitigation and define well-directed reduction goals for prefecture administrators. And the greater magnitude of urbanization's long-term environmental effects suggests that policymakers need to track urbanization's impacts over a long time to evaluate its' full environmental influence.

Acknowledgments
I want to thank the editor and three anonymous referees for their review, comments, and valuable suggestions.

References
[1] Karl T R and Trenberth K E 2003 Modern Global Climate Change Science, vol. 302, no. 5651, pp. 1719-1723
[2] York R 2007 Demographic trends and energy consumption in European Union Nations, 1960–2025 Social Science Research, vol. 36, no. 3, pp. 855-872
[3] Chen H, Jia B and Lau S S Y 2008 Sustainable urban form for Chinese compact cities: Challenges of a rapid urbanized economy Habitat International, vol. 32, no. 1, pp. 28-40
[4] Poumanyvong P and Kaneko S 2010 Does urbanization lead to less energy use and lower CO₂ emissions? A cross-country analysis Ecological Economics, vol. 70, no. 2, pp. 434-444
[5] Pachauri S and Jiang L 2008 The household energy transition in India and China Energy Policy, vol. 36, no. 11, pp. 4022-4035
[6] Zhou Z, Ye X and Ge X 2017 The Impacts of Technical Progress on Sulfur Dioxide Kuznets Curve in China: A Spatial Panel Data Approach Sustainability, vol. 9, no. 4, Apr 2017, Art. no. 674
[7] Zhou Z, Zhou Y and Ge X 2018 Nitrogen Oxide Emission, Economic Growth and Urbanization in China: a Spatial Econometric Analysis in Materials Science & Engineering Conference Series
[8] York R, Rosa E A and Dietz T 2003 STIRPAT, IPAT and ImPACT: analytic tools for unpacking the driving forces of environmental impacts Ecological Economics, vol. 46, no. 3, pp. 351-365
[9] Shahbaz M, Loganathan N, Muzaffar A T, Ahmed K and Jabran M A 2016 How urbanization affects CO₂ emissions in Malaysia? The application of STIRPAT model Renewable & Sustainable Energy Reviews, vol. 57, pp. 83-93
[10] Elhorst J P 2014 Spatial Econometrics From Cross-Sectional Data to Spatial Panels. Heidelberg, Germany: Springer
[11] Sheng P and Guo X 2016 The Long-run and Short-run Impacts of Urbanization on Carbon
Dioxide Emissions *Economic Modelling*, vol. 53, pp. 208-215

[12] Grossman G M and Krueger A B 1995 Economic Growth and the Environment *Nber Working Papers*, vol. 110, no. 2, pp. 353-377

[13] Moran P A 1950 A test for the serial independence of residuals *Biometrika*, vol. 37, no. 1/2, pp. 178-181

[14] Baltagi B 2008 *Econometric analysis of panel data*. John Wiley & Sons

[15] Yu J, de Jong R and Lee L.-f 2012 Estimation for spatial dynamic panel data with fixed effects: The case of spatial cointegration *Journal of Econometrics*, vol. 167, no. 1, pp. 16-37