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Evaluating the effect of compact urban form on air quality in Korea

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Abstract

Air quality is affected by the interplay between emission sources and urban planning factors such as land use, built environment, development pattern, and transportation. Few empirical studies have been conducted to determine the influence of urban form characteristics on air quality in Korea. Thus, the purpose of this research is to examine the relationship between urban form and air pollution, focusing on ozone pollution in Korea. The characteristics of urban form include density, concentration, clustering, and land use mix. In this study, those characteristics were measured by population density, the Theil index, Moran's I index, G-statistic values, and an entropy index using statistical methods and a geographic information system. We employed a spatial regression model to consider the spatial effects of ozone concentrations. We found that the degree of urban land use mix, clustering, and concentration of development are significantly associated with better air quality by using a spatial lag model, which was found to be the best fit for the data used in this study. However, an increase in population density was found to be associated with exacerbated ozone concentrations. Communities with higher daily temperatures, a large number of cars, and polluting facilities exhibited poor air quality, while those with a larger percentage of residential land use tended to have lower ozone pollution. These findings suggest that, to properly address concerns over air quality, mixed-land use and compact urban form need to be more seriously considered in sustainable urban planning.

Keywords

Compact urban form, mixed land use, ozone pollution, spatial regression model, Korea

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Introduction

An increase in greenhouse gas emissions causes not only an increase in temperature, extreme weather events, and a rise in sea levels, but also the deterioration of air quality in urban areas, a phenomenon that threatens human health and quality of life. In Korea, the Ministry of Environment is mainly responsible for air quality control policies. It has focused on pollutant source management since the 1980s, when Korea experienced rapid industrialization, urbanization, and a dramatic increase in the number of private cars. Such was the dominant policy approach until recently, and it has significantly contributed to improving air quality in urban areas; however, some air pollutants, such as ozone and PM10 have continuously increased during the 2005–2010 period, due to climate change (Korea Environment Institute (KEI), 2012, 2013).

Concerns about the increase of ozone concentration are global in scale. Most countries have ozone pollution regulations and monitor their ground-level ozone concentration. Ozone is a harmful pollutant that can lead to breathing problems and exacerbate illnesses in vulnerable individuals. While the main sources of ozone pollutants include manufacturing plants and automobiles, climate change is also known to worsen ozone pollution, because ozone concentration is temperature dependent (Union of Concerned Scientists, 2011).

Recently, Korean national policy on pollutant source management has been criticized due to its failure to influence pollution behavior above a specific level, even if the policy is generally considered effective. Air quality is affected by the interplay between emission sources (manufacturing plants, automobiles) and urban planning factors such as land use, built environment, development pattern, and transportation (Frank, 2000; Frank et al., 2006). For example, in a high-density area where travel destinations are proximate and public transit is readily available, residents might exhibit a decreased reliance on motor vehicles, resulting in less vehicle emissions and, consequently, less air pollution. On the other hand, high-density development with a larger population but inadequate provision of public transit can create congestion, pollution, or heat waves that worsen ozone concentrations. Understanding the relationship between air quality and urban spatial structures is necessary for developing effective spatial policies coupled with air quality management.

In the Unites States and Europe, a growing number of academic research have demonstrated the positive relationship between urban sprawl characteristics such as low density, leapfrog development, and poor air quality (Ewing et al., 2002; Frank et al., 2006; Nam et al., 2012; Stone, 2008; Stone et al., 2007). The findings of such studies support the new paradigm of urban planning: smart growth and new urbanism stressing compact urban forms and development patterns. As Korea has a different geophysical environment and urban development history, characterized by rapid urbanization and high population density as compared to western countries, the impact of compact urban forms on air quality needs more study before Korea adopts policies followed by western countries. Few empirical studies have been conducted to identify the influence of compact urban form characteristics on air quality in Korea. Addressing that gap, this study examines the relationship between characteristics of compact urban form and air pollution, with a particular focus on ozone, in order to suggest policy implications relevant to the situation in Korea. This study provides the opportunity to test whether compact urban forms are valid and effective for controlling air quality in Asian countries that have very high population density and are undergoing rapid industrialization.

Literature review

Urban form and air quality

Since the United Nations Conference on Sustainable Development in 1992, sustainable development has emerged as a paradigm both in society and in the field of urban planning. The concept of sustainable development is based on a consideration of environmental capacity while enhancing health and quality of life in a community (Beatley, 2009). Planners have considered what constitutes a sustainable, ideal urban form and development pattern, with the idea of a "compact city" or "compact urban form" emerging as a key component. Compact urban form describes efforts to decrease the negative impacts of urban sprawl, a development pattern characterized by low-density, scattered, and highly segregated land use.

Multiple studies (Ewing et al., 2002; Frank et al., 2006; Nam et al., 2012; Stone, 2008; Stone et al., 2007) have found that urban sprawl affects quality of life by increasing automobile dependence, travel distance, and energy use, which directly impacts air quality. Ewing et al. (2002) found that urban sprawl was significantly correlated to a higher ozone level in cities, and Bereitschaft and Debbage (2013) reported similar results, determining a positive relationship between a sprawl index and ozone levels for 86 U.S. metropolitan areas. Frank et al. (2006) argued that more compact neighborhoods were associated with less driving, shorter trips taken, and thus, lower levels of pollution. These findings suggest that an urban form with more compact, mixed-use, and transit-oriented urban areas results in less driving and greater energy efficiency. Furthermore, expansive open spaces that are located throughout highly compact developments are helpful in diluting air pollution. Thus, urban form that is more compact, employs mixed-land use, is public transit-oriented, and is a primarily pedestrian-friendly urban area is a central tenet of smart growth and new urbanism.

However, the impacts of compact urban form on air quality are debatable, and depend on the measurement of compactness, unit of analysis, and study area. Compact urban form can be measured in several different ways. Population density is one measurement. Stone et al. (2007) found that a 10% increase in population density in a metropolitan area caused a 3.5% reduction in household vehicle use and emissions. Levinson and Kumar (1997) suggested that the relationship between density and travel behavior related to automobiles is ambiguous because higher-density areas can allow for shortened travel time, but can also result in lower speeds and more congestion. Banzhaf and Walsh (2008), using Californian cities as case studies, found that high-density development caused traffic congestion and pollution that exacerbates poor air quality, and suggested that high-density development needs to be accompanied by environmental policies aimed to reduce air pollution. Clark et al. (2011) found that while population density was related to higher ozone and fine particulate levels, population centrality and transit supply were associated with lower ozone and fine particulate levels. In Korea, Kim and Jun (2014) found that population and level of employment are positively related to a comprehensive air-quality index (CAI) in the Seoul metropolitan area. Thus, there is need to carefully understand the different effects that the characteristics of compact urban form have on air quality. There is need to understand the interplay of land use mix, high density, large open spaces, and public transit on the measurement of compactness.

While various studies have been conducted in the United States and Europe, a relatively limited number of studies have been done in Korea regarding the relationship between urban form and environmental impact, including air quality. Some researchers have examined the relationship between the characteristics of urban development and air pollution. For example, using multiple regression models, Kim and Jun (2014) found that population density and the number of manufacturers were positively associated with air pollution levels in the Seoul metropolitan area. Lee et al. (2011) suggested that the number of facilities and buildings positively influenced the air pollution index in Seoul. Choi et al. (2007) found that construction activity had a positive relation, but that the financial resources of a local jurisdiction had a negative impact on SO_2 levels. Using panel models for 22 case cities in Korea, Choi et al. (2007) also found that urban density positively influenced NO_2 levels.

Other characteristics of urban development, such as land use and urban facilities, were investigated to determine their relationship to air pollution in Korea (Choi et al., 2007; Kim and Jun, 2014; Lee et al., 2011), but few empirical studies have examined urban form characteristics. Most studies in Korea employed statistical models to examine these relationships; however, they did not consider the spatial effect of air pollution in empirical models. Our study addresses this critical gap in urban planning research by evaluating the impacts of urban form measurements and employing spatial regression models to reflect spatial autocorrelation of air pollution.

Measurement of compact urban form

The quantitative measurement of urban form is critical, yet it is still considerably ambiguous, despite the increasing amount of literature on the topic. Before measuring urban form, it is necessary to define and identify its characteristics. Urban form can be differentiated by type, pattern, and intensity of development compared to non-urban areas (Burton, 2001; Clifton et al., 2008). Anderson et al. (1996) suggested that urban form is determined by density, diversity, and spatial pattern. Increasing concerns over the negative impacts of urban sprawl have informed numerous studies on urban measurements, and advances in geographic information system (GIS) technology have enabled substantial progress in analyzing spatial data focusing on urban areas. Furthermore, researchers across disciplinary fields, including those from landscape ecology, transportation planning, community design, and planning, have conducted empirical studies to measure urban form and assess the relationships between urban form and other issues that have accelerated the debate over urban sprawl (Clifton et al., 2008).

In U.S. literature regarding urban form, many studies employ the sprawl index developed by Ewing et al. (2003) for analysis of 448 U.S. counties. The sprawl index combines six characteristics of urban form: gross population density, suburban density, urban density, Natural Resources Inventory net density, average block size, and proportion of blocks. This index was used in various studies to assess the impact of urban form on human behavior, human health, environmental quality, and energy use. Nam et al. (2012) included urban size, density, distribution, and clustering as further characteristics of urban form. They analyzed the effects of urban form on travel behavior and found that, contrary to results generally found in other countries, a large, high-density, unequally distributed, and dispersed pattern is associated with less vehicle kilometers traveled. Galster et al. (2001) measured urban form using eight dimensions: density, continuity, concentration, clustering, centrality, nuclearity, mixed use, and proximity.

As mentioned earlier, compact urban form is closely related to high density development. Urban density has been measured based on population (Nam et al., 2012) or on residential units per square mile (Galster et al., 2001). In growth management, compact development means development close to or radiating from an urban core, while simple high-density development that considers population per unit area primarily refers to the concentration of development, regardless of distance from an urban center or core (Kamal-Chaoui and Robert, 2009). Thus, while we utilize simple high density for this study—and important measurement of urban form—other measurements also need to be considered to correctly evaluate the impact of urban form on air quality.

Spatial concentration of development has been referred to as the degree to which population or development is disproportionately distributed within a study area, as opposed to being spread equally throughout. The Theil entropy index has been suggested as a reliable indicator for measuring the level of distribution or concentration in an urban area (Gordon and Richardson, 1997; Im et al., 2006; Nam et al., 2012). In order to assess land use mix, given that it is an important strategy for creating a sustainable compact urban form, the entropy index is proposed because it considers the relative percentage of two or more land use types within an area (Nam et al., 2012; Song et al., 2013; Yeh and Xia, 2001). Clustering is the degree to which development or population has been compactly grouped together (Galster et al., 2001; Nam et al., 2012). The degree of spatial autocorrelation measured by global Moran's I index can be a reliable indicator of clustering.

Multiple studies (Ewing et al., 2003; Fulton and Pendall, 2001; Nam et al., 2012) have analyzed urban form at the metropolitan region or city level. Advances in GIS technology have enabled research measuring urban form at the neighborhood level as well. Neighborhood-level analysis can include more detailed data, such as land use mix (land use intensity, single family lot size, single family flood size, land use pattern), street network (street network design), residential proximity to commercial uses, and pedestrian access to commercial areas (Knaap et al., 2007; Song and Knaap, 2004).

Overall, researchers have tended to consider highly dense development, clustering, concentration, and land use mix to be characteristics of a compact urban form. Thus, it is necessary to accurately measure these characteristics. Despite the usefulness of one index describing the overall characteristics of sprawl or compactness, the particular components that comprise compactness need to be examined individually to understand the impact that each has on air quality.

Methods

Study area and unit of analysis

This study was a cross-sectional analysis of 225 jurisdictions in Korea and based on available data. Research on urban form can be conducted at various scales, from the city level to the neighborhood one. For complete urban form research, analyses at both a macro- and micro-scale are needed. Given that there has been little comprehensive empirical research that addresses urban form at all levels in Korea, we began with an attempt to analyze the relationship between urban form characteristics and ozone concentration at the local government level. The unit of analysis is the local jurisdiction, which is referred to as *si/gun/gu* in Korea. A *si* and a *gun* are subdivisions of a province, called a *do* (Figure 1). A *gun*'s population is less than 150,000 and a jurisdiction with a population greater than 150,000 is a *si*. A *gu* is a district of a metropolitan city. The *si/gun/gu* is the basic unit of a local jurisdiction, as well as an administrative unit in Korea. As the local government is also responsible for urban planning decisions such as land use, development pattern, type, and density, which determine urban form, it is the ideal unit for analyzing the impact of urban form on air quality at the macro level.

Figure 1. Administrative map of Korea (2010).

In order to calculate urban form, we employed a *dong*, which is the smallest administrative region in Korea and similar in size to a census tract in the United States, as a sub-zone unit. All collected data is from 2010.

Data measurement

The main goal of this study was to investigate the impact of urban form on air quality as measured by several different variables. Ozone was used as a representative for air pollutants because it has become problematic in Korea, and its concentration is continuously increasing because of climate change (KEI, 2011, 2012), despite ongoing efforts to mitigate air pollution. Researchers generally consider the amount of ozone collected from monitoring stations. However, while the total amount of ozone is important for understanding its impact on human health, of even greater importance is the number of days that an area surpasses its ozone threshold levels (KEI, 2012; Schweitzer and Zhou, 2010). Generally, 100 ppb of ozone per hour is considered the critical threshold above which concentrations will cause serious human health problems. We collected data on the number of days exceeding 100 ppb of ozone per hour at the jurisdiction level in Korea from the Korea Environment Institute (KEI), as shown in Table 1 (KEI, 2011, 2012; Lee et al., 2011). Table 1 explains the overall variables with names, operations, types, and data sources.

The main independent variables were the urban form measurement variables. Based on the literature review, urban form should consider density, diversity, and spatial pattern of development or population. As shown in Table 2, four characteristics of urban form were chosen in this study: density, diversity, concentration, and clustering.

Population density was measured as the number of inhabitants per square meter. We assumed that higher population density is associated with increases in economic activity, traffic, and road congestion, possibly causing poor air quality, based on literature review

Table 1. Constructs, variables, operational measurements, and their sources.

Concept	Variable name	Variable operation	Type	Data source
Air quality	Ozone concentration	Days of higher than 100 ppb ozone per hour	Dependent	Korea Environment Institute (KEI)
Urban form factor	Population density	Population density (person/sq km)	Independent	Calculated
	Land use mix	Land use mix index	Independent	Calculated
	Concentration	Theil's entropy index	Independent	Calculated
	Clustering	Global Moran's I index	Independent	Calculated
		Getis and Ord's G statistic	Independent	Calculated
Climate factor	Temperature	Daily maximum temperature	Independent	National Weather Service (NWS)
	Precipitation	Total precipitation	Independent	NWS
Polluter factor	Number of cars	Number of registered cars	Independent	National statistical office (NSO)
	Pollution causing facilities	Pollution causing facilities	Independent	NSO
Land use factor	Green space	% of green space (artificial green area + forest area)	Independent	KEI
	Residential land use	% of residential area	Independent	Ministry of Land, Infrastructure and Transport (MOLIT)
	Commercial land use	% of commercial area	Independent	MOLIT
	Industrial land use	% of industrial area	Independent	MOLIT

Table 2. Urban form measurement variables.

Variable name	Purpose	Variable operation	Formula
Density	To describe density	The index of population density (person/sq meters)	$\mathit{Index\ of\ PopDen}_i = \frac{Pop_i}{UA_i}$ Pop_i: *number of population of i jurisdiction* UA_i : *urban area of i jurisdiction*
Land use mix	To show the degree of mixed land use	Index of land use mix based on entropy index	$\mathit{Index\ of\ LandUseMix} = -\frac{\sum_{i=1}^{n}(P_i)\ln(P_i)}{\ln(S)}$ P_i : ratio of area per each land use S : number of land uses
Concentration	To show the degree to which population is disproportionately distributed	Theil's entropy index	$\text{Theil's entropy index}_i = \ln n - \sum_{k=1}^{n} PopR_{ik} \ln\left({}^{1}/_{PopR_{ik}}\right)$ $PopR_{ik}$: Population ratio of k-subzone of i jurisdiction
Clustering	To show the degree to which population has been grouped	Global Moran's I index	$\text{Global Moran's I index} = \frac{N\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\left(\sum_{i=1}^{n}\sum_{j=1}^{n}[w_{ij})\sum_{i=1}^{n}(x_i - \bar{x})^2]\right)}$ W_{ij} : weight of i, j subzones N : number of subzones X_i : population of i subzone X_j : population of j subzone $\bar{X}$: average population
		Getis and Ord's G-statistic	$G - \mathit{statistic} = \frac{\sum_{i=1}^{n}\sum_{j}^{n} W_{i,j}x_i x_j}{\sum_{i=1}^{n}\sum_{j=1}^{n} x_i x_j}$ x_i : population of i subzone x_j : population of j subzone $W_{i,j}$: weight of i, j subzones

focusing on Korean cases. The data regarding the population and area of each jurisdiction came from the National Statistical Office.

The degree of land use mix represents the diversity of urban development, an essential character of compact development. Land use mix is defined as the practice of accommodating more than one type of land use within a specific area. The land use types in this study include residential, commercial, industrial, and green area. We assume that people living in areas with mixed land uses do not need to travel far and thus would result in less automobile usage and less air pollution. Multiple studies (Cervero, 2001; Cervero and Kockelman, 1997; Knaap et al., 2005; Nam et al., 2012; Song et al., 2013; Yeh and Xia, 2001) have employed the concept of land use mix based on the entropy index. The entropy index has been used to present biodiversity, diversity of race, and diversity of industry, as well as land use mix. The original entropy index has a minimum value of 0 for single land use, and the maximum value depends on the number of uses. Cervero and Kockelman (1997) normalized the value in a range from 0 to 1 and applied it to measure land use mix. The land use mix index, shown in Table 2, makes it possible to present variations in a range from 0 to 1; the higher the value of the entropy index, the greater the land use mix (Song and Knaap, 2004). A value of 0 means single use, and a value of 1 indicates highly mixed use. The data of land uses in this research came from the Ministry of Land, Infrastructure and Transport (MOLIT) of Korea.

The degree of concentration of activities and population can be measured by the Theil entropy index (Im et al., 2006; Nam et al., 2012; Tsai, 2005). Derived from Shannon's information theory, the Theil index is a relative entropy index used for considering and comparing different numbers of subdivisions for particular jurisdictions. In the Theil index, the value 0 indicates an equal distribution of population in a study area. Thus, a concentrated urban form will have a high Theil entropy index value and an equally distributed urban form will have a lower index value. The high concentration of development will show relatively compact urban form as shown in Figure 2 and is supposed to shorten travel distance causing less ozone pollution. The data on population for each subdivision of the jurisdictions came from the National Statistical Office.

The high level of development clustering leads to compact urban structure as shown in Figure 3; thus, we assume that high development clustering is related to lesser days of high degrees of ozone concentration. Low level of clustering has different meanings from low level of concentration. While low level of concentration suggests equal distribution of development, low level of clustering shows random distribution of development. This study includes both clustering and concentration measures with complementary values to present the compact urban structure.

The degree of clustering can be measured using global Moran's I index and Getis and Ord's G statistic. Most previous studies employ global Moran's I index, which has a range of -1 to 1. On global Moran's I index, a value near -1 indicates rarely clustered areas of high-high or low-low population subzones, and a value near 1 indicates highly clustered areas of similar population levels (Lee and Rho, 2013; Park et al., 2008). However, there is a drawback in using global Moran's I index. As the index shows spatial autocorrelation of similar values, it is difficult to differentiate whether the clusters are high-value or low-value, because both clusters of large population sub-zones and those of small population areas present high index values. This study attempted to overcome this limitation by adding another index—Getis and Ord's (1992) G-statistics, in which larger values distinguish clustering of higher population sub-zones, and lower values represent small population clusters (Lee and Rho, 2013). A 0 value of G-statistics indicates that populations of subzones have rarely been grouped. This study compared two results using global Moran's I index and G-statistics to better understand the statistical outcomes. The method of calculation of G-statistics is given in Table 2.

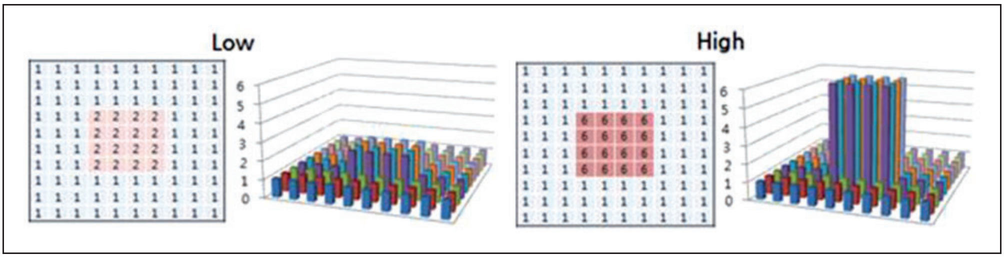

Figure 2. Spatial structure by the degree of concentration.
Source: Kim (2016).

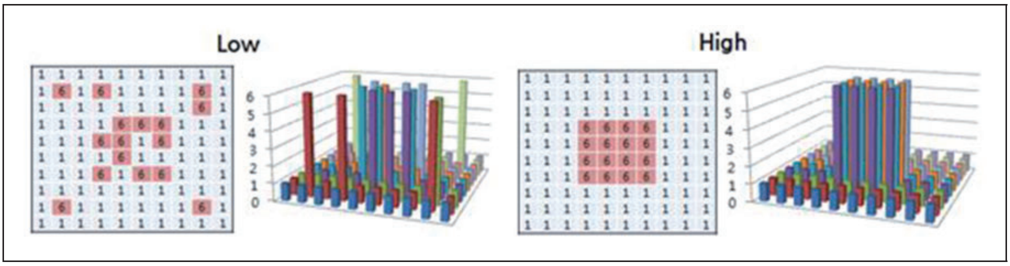

Figure 3. Spatial structure by the degree of clustering.
Source: Kim (2016).

Early in our research, we considered the idea that a large population and high road density might be associated with increased economic activity, and that an increase in traffic could cause poor air quality. To account for this, population size and road density were included in the early stage of the statistical model. However, these variables were later excluded because of multicollinearity with other variables. In Korea, population size and population density are closely related; bigger cities with larger populations tend to have larger population density.

Furthermore, we suggest that meteorological, polluter, and land use variables affect air quality, as measured by the number of days in which there was in excess of 100 ppb of ozone per hour. Climate factors such as daily maximum temperature and total precipitation affect the formation and dispersion of ozone (Clark et al., 2011; Schweitzer and Zhou, 2010; Stone, 2008). Ozone concentration is directly affected by pollutant sources such as industries and motor vehicles and therefore these sources must be considered in the statistical models. Characteristics of land use are closely related to air quality through interactions with other factors. In particular, green space, such as forests and trees, is relevant to air quality by mitigating ozone precursor emissions (McCarty and Kaza, 2015). The type of land use influences ozone formation (Choi et al., 2007; Taha, 2008), and industrial land use may be related to higher emissions from factories.

Spatial regression model

Generally, the impact of independent variables on a dependent variable is investigated using multivariate regression models, such as ordinary least squares (OLS), only when the relationship between them is linear and assumptions are observed. The assumptions of

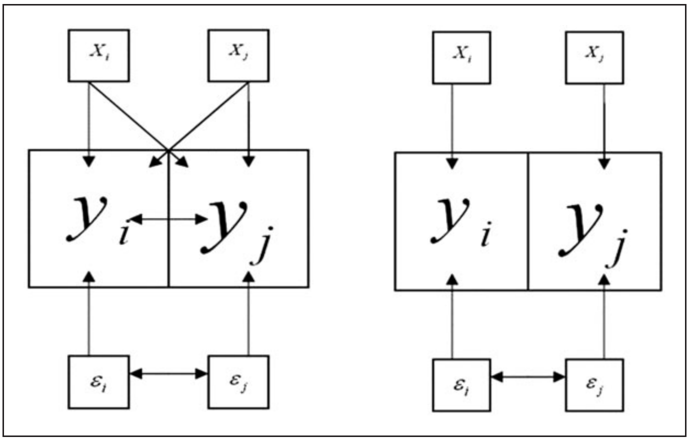

Figure 4. Spatial lag (left) and spatial error (right) models.
Source: Baller et al. (2001).

linear regression modeling include normality, independence, homoscedasticity of errors, exclusion of spatial autocorrelation, and multicollinearity.

As air quality data shows a spatial pattern, it can be highly affected by the first law of geography suggested by Tobler, which states, "everything is related to everything else, but near things are more related than distant things (1970: 236)." This is the concept of spatial autocorrelation. To examine spatial autocorrelation to a higher number of ozone exceedance days, this study employed a global Moran's I index. When air quality has spatial autocorrelation, we must consider spatial variables in the regression models—otherwise, the magnitude of the estimates and their significance could be erroneous.

To develop an effective regression model, we took the following steps. First, we conducted a multiple regression model and basic correlation analysis with variables selected based on a literature review. Next, we checked the model fit and other assumptions of normality, independence, homoscedasticity, and collinearity. A global Moran's I statistic was employed to further analyze the existence of spatial dependence. When the test confirmed the spatial autocorrelation of the dependent variable, spatial regression models were employed as an alternative to the OLS regression model. There are two spatial autoregressive models: the spatial lag model and the spatial error model. The spatial lag model can be used when the dependent variable Y_i is affected by the independent variables X_i and X_j, which at the same time are influenced by Y_j. The spatial error model is considered when the errors are correlated with each other (Figure 4).

The equations of the spatial lag and spatial error models are as follows:

Spatial lag model: $y = \rho W_y + X\beta + \varepsilon$

y : Dependent variable
X : Independent variable
β : Regression coefficient
ε : Random error term
ρ : Spatial autoregressive coefficient
W_y : Spatially lagged dependent variable

Spatial error model: $y = X\beta + \varepsilon, \quad \varepsilon = \lambda W_\varepsilon + \xi$
y : Dependent variable
X : Independent variable
β : Regression coefficient
ε : Random error term
λ : Autoregressive coefficient
W_ε : Spatial lag for the error
ξ : Normal distribution with mean 0 and variance $\sigma^2 I$

Next, we estimated the Lagrange multiplier (LM) as a criterion to select the proper spatial regression model. Based on the significance of LM-lag statistic and LM-error statistic, the best model was selected. When both statistics are significant, the robustness of the LM statistics needs to be tested to identify the best model fit for the data. The analyses in this study utilized SPSS, ArcGIS, and GeoDa software, which are designed particularly for spatial analysis.

For spatial regression analysis, neighborhoods can be defined in a number of ways. Contiguity based on common boundaries and distances is the most commonly used criteria to define neighborhood area. Contiguity-based neighbor matrix includes rook contiguity and queen contiguity methods. Rook contiguity has four neighbors at each central location in the cardinal directions, and queen contiguity has eight neighbors at each central location in all directions. In this study, the rook contiguity weight was used as the spatial weight matrix to define the spatial neighborhood indicating the best model fit.

Results

Hotspots of ozone concentration and descriptive analysis

This section first examines the hotspots of ozone concentration at the local level in Korea. We employed hot spot analysis in order to indicate a quick snapshot about ozone problematic areas. Hot spots and cool spots identified through the Local Index of Spatial Association (LISA) map can promote understandings about whether or not the levels of ozone are problematic and the areas where the concentration is severe in Korea.

As is shown in Figure 5, the LISA map lists four types of clusters, including high-high, high-low, low-high, and low-low clusters. Hot spots of high-high clusters are high ozone concentration areas in high-concentration neighborhoods, and cool spots are low-ozone concentration areas in low-concentration neighborhoods. The high-low clusters are high ozone concentration areas surrounded by comparatively low ozone neighborhood jurisdictions, while the low-high clusters have relatively lower ozone amounts, but its neighborhoods in adjacent jurisdictions suffer high ozone concentration.

While most hot spots are clustered in the Seoul metropolitan area, including Seoul and Gyeonggi-do, local jurisdictions in Jeollabuk-do and several cities in Jeollanam-do are clustered in cool spots. The Seoul metropolitan area is highly developed and approximately a third of the entire Korean population lives there, with 2.5 million elderly citizens (over 65 years of age) who are considered vulnerable due to higher levels of ozone concentration (National Statistical Office, 2015). The area requires special attention given to its air quality, in the form of active measures taken to mitigate air pollution.

Most local communities in Jeollabuk-do and Jeollanam-do are in relatively small rural jurisdictions that contain fewer ozone sources, such as industrial plants and cars. Gijang-gun, in the Busan Metropolitan area, located in the southeast part of the Korean Peninsula, includes large industrial areas, and Naju-si in Jeollanam-do contains an industrial complex.

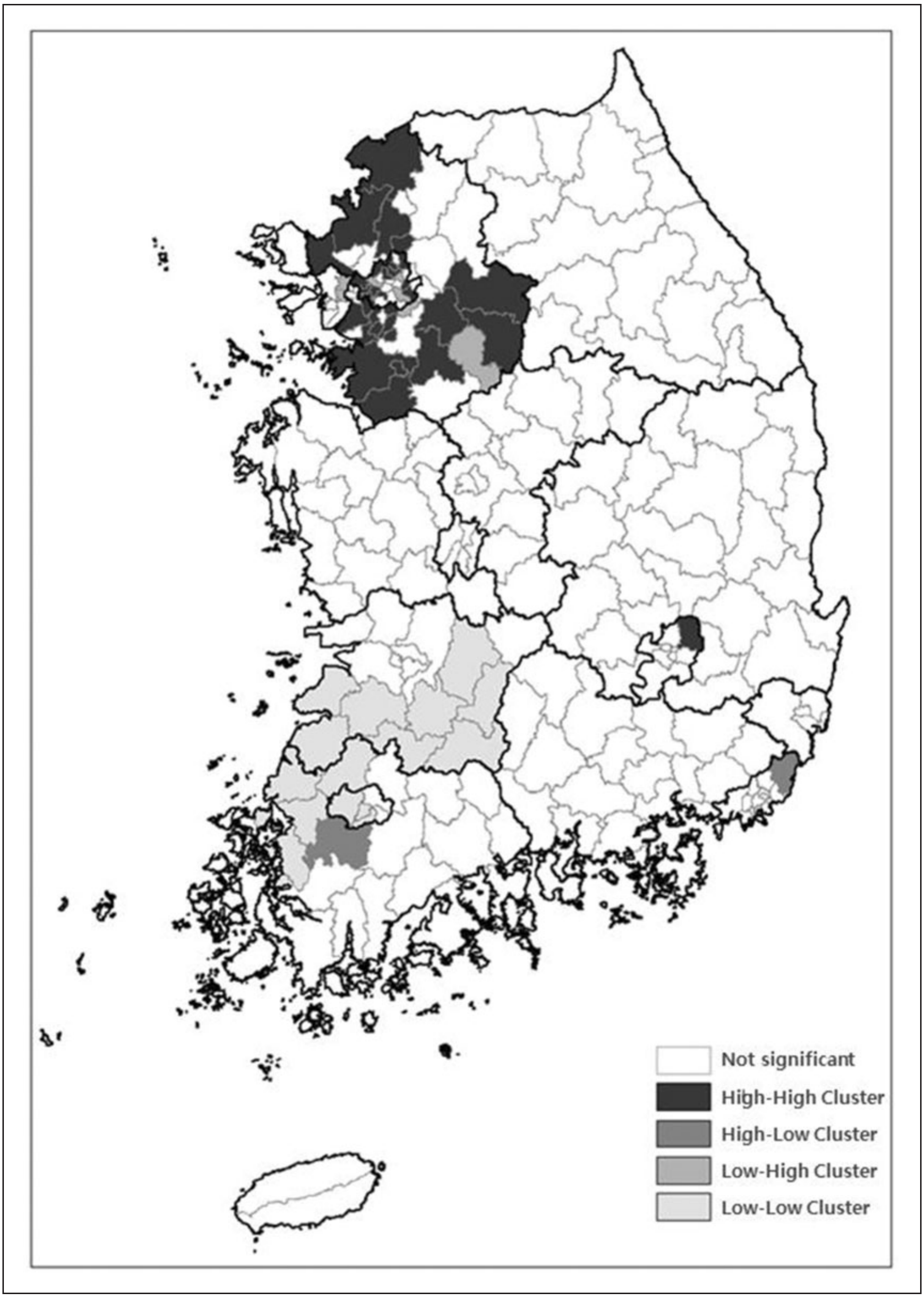

Figure 5. Hotspots of ozone concentrations.

Both are transition areas with high-low clusters, meaning that they have high-ozone concentrations and are neighboring low-ozone concentration jurisdictions.

Table 3 presents the descriptive statistics for each variable. Each jurisdiction experienced an annual average of 3.59 days exceeding 100 ppb ozone per hour, with a standard deviation

Table 3. Descriptive statistics of variables.

Concept	Variable	Measurement	Mean	SD	Min	Max	N
Air quality	Days of higher 100 ppb ozone per hour	Days of higher than 100 ppb ozone per hour	3.59	3.03	0	19	225
Urban form factor	Population density (person/sq km)	Population density	3900	6,100	18	26,310	225
	Land use mix (Entropy index)	Entropy index	0.53	0.17	0.18	0.99	225
	Concentration (Theil's entropy index)	Theil's entropy index	2.8	0.17	1.69	3.82	225
	Clustering	Moran's I index	−0.0257	0.2485	−1.53	0.75	225
		G-statistic	0.000149	0.000122	0	0.000595	225
Climate factor	Temperature	Daily maximum temperature	34.27	0.75	31.02	35.65	225
	Precipitation	Total precipitation	1489.33	312.21	885	2820	225
Polluter factor	Number of cars	Number of registered cars	72959.51	57095.08	7617	302,779	225
	Pollution causing facilities	Pollution causing facilities	162.24	257.48	0	1750	225
Land use factor	Green space	% of green space	43.48	17.82	0.15	74.53	225
	Residential land use	% of residential area	15.02	22.04	0.11	129.32	225
	Commercial land use	% of commercial area	2.37	6.37	0.02	62.63	225
	Industrial land use	% of industrial area	3.49	7.26	0	42.12	225

of 3.03 in a 0–19.00 range. The mean population density in this study was 3900 person/km^2 with a range of 18 person/km^2~26,310 person/km^2. The percentage of green space was 43.48%, which was relatively large because we included both natural green spaces, such as forests, and man-made green spaces, such as parks. Residential land use shows a standard deviation of 22.04 with a mean of 15.02%, and industrial land use in the entire study area averaged 3.49%.

The influence of urban form on air quality

In the preliminary steps of our research, we used multiple regression analysis to test whether variables indicating urban form influenced ozone concentration, while controlling for climate, polluter, and land-use variables. We compared the analysis results using global Moran's I index for measuring the degree of development clustering based on population data (Table 4) with the statistical outcome of G-statistic variables (Table 5).

The OLS regression model explained 23% of the variance in the ozone concentration, as shown in Table 4. However, the Jarque-Bera test confirmed the non-normal distribution of the error terms, and the Breusch–Pagan test showed strong heteroscedasticity and spatial dependence. In addition, diffusion of air pollutants in the atmosphere is highly possible due to spatial dependence. Because a spatial autocorrelation test showed strong spatial autocorrelation (Moran's I: 0.3416, $p < 0.01$) in the dependent variable, a spatial regression model that can consider spatial autocorrelation was required instead of an OLS regression.

Table 4. Impact of urban form on ozone (variable of clustering: global Moran's I index).

		OLS model (B)	Spatial lag model	Spatial error model
Spatial effect	ρ (rho)		0.362***	
	λ (Lambda)			0.386***
	constant	−13.67	−9.492	−17.042
Urban form factor	Population density	2.54E−002***	2.25E−002***	2.19E−002***
	Land use mix (Entropy index)	−3.028**	−2.649**	−2.486*
	Concentration (Theil's entropy index)	−1.781***	−1.341**	−1.233**
	Clustering (global Moran's I index)	1.421*	1.275*	1.221*
Climate factor	Temperature	0.622**	0.45	0.697*
	Precipitation	0.001	0	0.001
Polluter factor	Number of cars	7.862E−006*	4.603E−006	3.445E−006
	Pollution causing facilities	0.003***	0.002***	0.002***
Land use factor	Green space	−0.005	−0.009	−0.018
	Residential land use	−0.040**	−0.046***	−0.043***
	Commercial land use	−0.048	−0.032	−0.036
	Industrial land use	0.008	0.019	0.012
	R^2	0.23	0.32	0.32
	Log likelihood	−539.85	−528.143	−529.398
	AIC	1105.7	1084.29	1084.8
	SC	1150.11	1132.11	1129.21
	Jarque-Bera	32.44***	71.39***	72.189***
	Breusch–Pagan	42.01**		
	Kosenker–Bassett	26.49**		
	White	138.20**		
Spatial dependence	Likelihood ratio		23.413***	20.903***
LM-Lag		27.795***		
Robust LM-Lag		4.173**		
LM-Error		23.657***		
Robust LM-Error		0.035		

*<0.01 level.

**<0.05 level.

***<0.01 level.

We conducted diagnostic tests to determine whether a spatial lag model or a spatial error model was a better fit for our dataset. The results favored the spatial lag model based on the significantly robust LM-lag (4.173) at the 0.05 level.

The spatial lag model, shown in Table 3, increased from 23% to 32% the ability to explain the variance of serious ozone concentration days by integrating a statistically significant spatial effect ($\rho = 0.362$, $p < 0.01$), while the log likelihood of the model developed from −539.85 to −528.143. Even if introducing the spatial lag model improved the model fit,

Table 5. Impact of urban form on ozone (variable of clustering: G-statistic).

		OLS model (B)	Spatial lag model	Spatial error model
Spatial effect	ρ (rho)		0.367***	
	λ (Lambda)			0.395***
	constant	−15.877	−11.618	−20.326
Urban form factor	Population density	2.40E−002***	2.09E−002***	2.04E−002***
	Land use mix (Entropy index)	−3.144**	−2.765**	−2.505*
	Concentration (Theil's entropy index)	−1.476**	−1.027*	−0.883
	Clustering (G-statistic)	−303.14	−872.687	−1301.61
Climate factor	Temperature	0.663**	0.488*	0.764**
	Precipitation	0.001	0.001	0.001
Polluter factor	Number of cars	8.508E−006*	5.38E−06	4.01E−06
	Pollution causing facilities	0.003***	0.002**	0.002***
Land use factor	Green space	−0.005	−0.009	
	Residential land use	−0.037*	−0.041**	
	Commercial land use	−0.039	−0.023	−0.025
	Industrial land use	0.009	0.023	0.019
	R^2	0.22	0.32	−0.017
	Log likelihood	−541.429	−529.494	−0.038**
	AIC	1108.86	1086.99	1087.04
	SC	1153.27	1134.81	1131.45
	Jarque-Bera	42.299***		
	Breusch–Pagan	45.963***	78.638***	82.700***
	Kosenker–Bassett	26.471***		
	White			
Spatial dependence	Likelihood ratio		23.871***	21.815***
LM-Lag		28.208***		
Robust LM-Lag		3.982**		
LM-Error		24.368***		
Robust LM-Error		0.05		

*<0.01 level.
**<0.05 level.
***<0.01 level.

heteroscedasticity and spatial dependence still existed. Based on the performance parameter and diagnostic tests, the spatial lag model was determined to be the best.

The results of the spatial lag regression model indicated that ozone concentration was associated with characteristics of compact urban form, even though the directions to ozone were inconsistent. Controlling for other variables, an increase in population density led to a degradation of air quality caused by the ozone concentration. This result suggests the likelihood that a larger population in a specific area measured by simple population density would result in more congestion and a greater travel distance and, therefore, lower air quality. This result is consistent with the findings of some research conducted in

Korea (Kim and Jun, 2014; Nam et al., 2012). However, when considering ozone concentrations, other variables of compact urban form, such as land use mix and the spatial concentration pattern of population, contribute to better air quality. More directly, communities that have more mixed land use and a higher spatial concentration pattern are likely to encourage less automobile dependence and an increase in walking and public transit, resulting in a significant decrease in days where the air quality is in excess of 100 ppb ozone per hour.

Interestingly, global Moran's I index, which presents the degree of population clustering, is positively related to ozone concentration. However, because the cluster includes both low-low and high-high population clusters, it is difficult to correctly interpret the results. To address this, we used the other regression models with G-statistics, indicating that a higher value denotes a high-high population cluster.

As confirmed in Table 5, the spatial lag model is still the most effective for explaining the relationship between independent variables and ozone exposure, when the G-statistic is the variable for measuring the degree of development clustering in the urban form factors. According to the results of the spatial lag model, the G-statistics presenting spatial clustering pattern show an insignificant negative influence on the ozone concentration. In other words, the negative relationship between population clusters and ozone concentration suggests that communities with greater high-high population clusters are more likely to have better air quality, even though this likelihood is not expressed as statistically significant. Thus, the interpretation of the results in the spatial lag model using global Moran's I index, as described in Table 4, became clear. The low-low population clusters show statistically significant contributions to the increase in ozone concentration. Overall, these findings suggest that characteristics of compact urban form, such as land use mix, concentration, and clustering, can be significant factors in air quality issues.

The main purpose of this study was to examine whether compact urban form characteristics influence actual ozone concentration in Korea as a critical example of Asian countries with different developmental, environmental, and cultural backgrounds. This is in contrast to western countries, where urban form studies have been more extensively studied. This study supports previous literature, which states that compact urban form factors, such as mixed land use, concentration, and clustering at the city level have effects on air quality.

Daily maximum temperature is also a critical factor affecting the increase in the number of days in which air in local communities exceeds ozone thresholds. This result aligns with some previous literature, indicating that temperature increase caused by climate change is more likely to exacerbate poor air quality.

With regard to polluter factors, communities with a larger number of polluting facilities tend to have more extreme ozone concentrations. The number of registered cars in a community significantly affected air pollution in the OLS regression model, but this became insignificant when considering spatial effects.

With regard to land-use factors, contrary to our expectations, none of the models statistically supported the theory that communities with a larger percentage of green space experience fewer excessive ozone days. However, the relationship between the ratio of green space and ozone concentration did show a negative direction. All regression models, including the OLS, spatial lag, and spatial error ones, revealed that the percentage of residential land use substantially impacted ozone concentration, as measured by the number of days where air quality was in excess of 100 ppm ozone per hour. Communities with a larger percentage of residential land use could be expected to experience fewer days of excessive ozone. Industrial land use did not statistically influence ozone, even though the relationship between industrial land use and air quality had a positive trend.

When considering the results regarding polluter factors and land use factors, the number of pollution-causing facilities is found to be more impactful on ozone pollution than is the simple ratio of industrial land use.

Discussion and conclusions

The influences of urban form have been an issue of much debate (Newman, 2005). Concerns about sprawl have changed trends in urban planning, and compact urban form has been introduced as a critical strategy for new urbanism and smart growth, in order to achieve sustainable communities. However, the characteristics of compact urban form can have different impacts depending on their location. The influence of these characteristics in Korea has been vague. By attempting to identify the relationship between urban form and air quality, with a focus on ozone, this study contributes to the existing literature on urban planning and environmental planning, and provides evidence of the influences of compact urban form in Asian countries. One contribution of this study is that it extends the application of the spatial regression model, which considers spatial autocorrelation of ozone diffusion.

Our findings from the spatial regression models can be summarized as follows:

- First, the characteristics of compact urban form significantly influence air quality. A city with a greater degree of mixed land use and clustered and concentrated spatial patterns is more likely to experience fewer days of extreme ozone, which is harmful to human health.

This result implies that compact urban form reduces the need to travel long distances or use automobiles and ultimately contributes to better air quality. In other words, higher compactness in urban design and development patterns is critical, not only to travel behavior and energy use, but also to air quality and, subsequently, air quality management. This finding both validates the use of strategic compact urban form, and suggests directions for integrating urban land use and spatial policies regarding air quality management in urban areas.

- Second, an increase in population density results in poor air quality with regards to ozone concentration.

It can be concluded that high population density is associated with traffic volume, inducing more traffic congestion, which in turn causes more pollution. As emphasized by Newman and Kenworthy (1991), density needs to be examined with modal splits, such as the percentage of trips taken by public transit, automobile, bicycle, or on foot. If a large proportion of residents takes public transit, cycles, or walks, it is possible to decrease energy use, air pollution, and the total travel distance in which an automobile is used. However, if privately owned vehicles are used, thus increasing the number of trips, this will contribute to an increase in air pollution.

The positive relationship in our study between population density and ozone concentration seems to support Nam et al. (2012)'s argument that, with an increase in population density, the number of automobile trips increases also. Density is a critical factor in compact urban form; however, the ideal population density for a given location is subject to the conditions of walkability and availability of public transit, infrastructure capacity, and the history of growth in that area. It is not easy to define the ideal population density threshold for sustainable development, and it is up to individual cities to determine their desired level of density. Achieving an ideal density standard could provide benefits, but other desirable conditions, such as public transit, updated infrastructure, and vast open spaces, may still remain unaddressed. Infrastructure and public investments should support density as a planning tool (Beatley and Manning, 1997). Further study is needed regarding ideal population density standards in Korea. For example, Newman and Kenworthy (1991) suggested that an ideal population density standard in U.S. cities would be an average overall density of between 30 and 40 persons per hectare. They specified that inner-city density should be higher than 300 persons per hectare, with an outer density of 20 to 30 persons per hectare.

- Third, we found that ozone concentration was considerably affected by maximum daily temperature and the number of polluting facilities.
- Fourth, our findings indicate that communities with a larger ratio of residential area tended to experience fewer days of excessive ozone level.

This study has some possible limitations. We restricted air quality to measurements of ozone, but further research should give consideration to other pollutants, such as PM10 and PM2.5, which are the source of serious problems in Korea. Public health issues related to air quality and urban form also demand further attention. This study was conducted at the city level. Future research needs to focus on the neighborhood level for more detailed and spatial analysis of urban development patterns over time.

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