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RESEARCH ARTICLE

The relationship between urban form and air pollution depends on seasonality and city size

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Abstract

Understanding how urban form is related to air pollution is important to urban planning and sustainability, but the urban form-air pollution relationship is currently muddled by inconsistent findings. In this study, we investigated how the compositional and configurational attributes of urban form were related to different air pollution measures ($PM_{2.5}$, API, and exceedance) in 83 Chinese cities, with explicit consideration of city size and seasonality. Ten landscape metrics were selected to quantify urban form attributes, and Spearman's correlation was used to quantify the urban form-air pollution relationship. Our results show that the urban form and air pollution relationship was dominated by city size and moderated by seasonality. Specifically, urban air pollution levels increased consistently and substantially from small to medium, large, and megacities. The urban form-air pollution relationship depended greatly on seasonality and monsoons. That is, the relationship was more pronounced in spring and summer than fall and winter, as well as in cities affected by monsoons. Urban air pollution was correlated more strongly with landscape composition metrics than landscape configuration metrics which seemed to affect only $PM_{2.5}$ concentrations. Our study suggests that, to understand how air pollution levels are related to urban form, city size and seasonality must be explicitly considered (or controlled). Also, in order to mitigate urban air pollution problems, regional urban planning is needed to curb the spatial extent of built-up areas, reduce the degree of urban fragmentation, and increase urban compactness and contiguity, especially for large and megacities.

Keywords $PM_{2.5}$ · Air Pollution Index · Exceedance · Built-up area · Urban sprawl · Urban morphology

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Introduction

China's urbanization during the past three decades has been unprecedented in human history in terms of both speed and scale (Ma et al. 2016a; Wu et al. 2014), resulting in a number of environmental problems, particularly the deterioration of air quality in many urban regions across the nation (Bechle et al. 2011; Huang 2015; Liu et al. 2017; Lue et al. 2010; Peng et al. 2016; Shao et al. 2006; Song et al. 2017). In 2016, less than a quarter of Chinese cities reached the Chinese air quality standard (Air Quality Index < 100) (MEP 2017). Urban air pollutants come mainly from within-city emissions and regionally transported pollutants which originated from several sources, including industrial emissions (Wang et al. 2012), transportation emissions (BJEPB 2014), crop stalks burning activities (Shi et al. 2014), and dust-fall processes (Lue et al. 2010). For example, 64–72% of $PM_{2.5}$ in Beijing came from local emissions such as industrial sources, vehicle transportation, and coal burning for heat (BJEPB 2014). The contributions from secondary organic aerosol (SOA) and secondary

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inorganic aerosol (SIA) were also non-negligible (Huang et al. 2014).

A number of studies have shown that urban form (including both compositional and configurational features) affects the emissions and transportation of air pollutants. For example, the percentage of artificial surface areas, a composition metric, was positively correlated with $PM_{2.5}$ concentrations in the urban agglomerations of China (Feng et al. 2017) and with NO_2 and PM_{10} concentrations in more than 200 European cities (Cárdenas Rodríguez et al. 2016). The total area of green space was negatively correlated with $PM_{2.5}$ concentrations in Beijing (Wu et al. 2015) and Nanjing (Chen et al. 2016) of China, as well as with SO_2 concentrations in the 17 South Korean cities (Cho and Choi 2014). Effects of compact versus sprawling forms of cities on air quality have been debated, with inconsistent findings (Bechle et al. 2011; Bereitschaft and Debbage 2013; Cárdenas Rodríguez et al. 2016; Cho and Choi 2014; Gaigné et al. 2012; Han et al. 2014; Lu and Liu 2015; Mansfield et al. 2015; Martins 2012; Stone 2008). On the one hand, compact cities may enhance accessibility and reduce energy consumption and mobility needs (Cárdenas Rodríguez et al. 2016). Bechle et al. (2011) reported that cities with highly contiguous built-up areas generated lower NO_2 emissions from vehicle activity, with city size, shape complexity, and connectivity as influencing factors (Bechle et al. 2011). Weber et al. (2014) found that there was a positive correlation between PM_{10} concentration and the edge and patch density of residential areas. Process-based model simulations also suggested that compact cities tend to have better air quality conditions than dispersed and sprawling cities (Borrego et al. 2006; Martins 2012). On the other hand, studies also have shown that compact cities may trap air pollutants from urban construction, thereby leading to high pollution concentrations and inducing a higher proportion of population exposed to pollution (Cárdenas Rodríguez et al. 2016).

The studies mentioned above were carried out mainly at one single spatiotemporal scale (Bechle et al. 2011; Bereitschaft and Debbage 2013; Cárdenas Rodríguez et al. 2016; Cho and Choi 2014; Feng et al. 2017; Gaigné et al. 2012; Lu and Liu 2015; Mansfield et al. 2015; Martins 2012; Stone 2008; Weber et al. 2014; Zou et al. 2016), without systematically considering the potential effects of urban landscape pattern and meteorological background on air pollution levels across multiple scales in space and time. In particular, how city size and seasonality affect the urban form-air pollution relationship is still poorly understood. Thus, the objectives of this study were threefold: (1) to examine what compositional and configurational attributes of urban form may affect air pollution, (2) to explore how seasonality may change the urban form-air pollution relationship, and (3) to investigate whether the urban form-air pollution relationship changes with city size.

Data and methods

Study cities

We selected 83 major cities in mainland China, most of which are located in the eastern half of the country (Fig. 1). These cities cover a wide range of climatic zones, ranging from coastal and moist climate zones in the east to arid and semiarid climate zones in the west, and from tropical and subtropical climate zones in the south to temperate and cold-temperate climate zones in the north. These cities also cover a wide range of sizes, including 10 super large-sized cities, 30 very large-sized cities, 24 large-sized cities, and 19 medium-sized cities and small-sized cities according to the population-based city size classes (Appendix A1). In the 83 cities, there are 5 super large-sized cities with built-up area more than 150,000 ha and 21 large-sized cities with built-up areas ranging from 50,000 to 150,000 ha. Rapid urbanization and industrialization during the past 3 decades have resulted in deteriorating air quality (Han et al. 2014). We acquired land use/cover data and air pollution data, including $PM_{2.5}$ concentrations, Air Pollution Index (API), and exceedance levels for all the study cities. The details of data acquisition are described below.

$PM_{2.5}$ data

Previous studies have shown that the satellite-based method is an effective way to retrieve $PM_{2.5}$ concentrations at regional (He and Huang 2018), national (Fang et al. 2016; Luo et al. 2017; Ma et al. 2016b; Xiao et al. 2018), and global scales (van Donkelaar et al. 2015). In this study, annual average $PM_{2.5}$ concentrations for 83 Chinese cities in 2010 were retrieved from MODIS (Moderate Resolution Imaging Spectroradiometer) and MISR (Multiangle Imaging Spectroradiometer) AOD products using a conversion factor (van Donkelaar et al. 2015). The conversion factor was a function of several parameters, including aerosol size, aerosol type, diurnal variation, relative humidity, and the vertical structure of aerosol extinction (van Donkelaar et al. 2010; van Donkelaar et al. 2006). These selected parameters were simulated by the GEOS-Chem model and directly related to the optical absorption and scattering effects of aerosol (van Donkelaar et al. 2010; van Donkelaar et al. 2006) rather than indirect parameters (e.g., land use and other socioeconomic conditions) (Fang et al. 2016; Luo et al. 2017; Xiao et al. 2018). A 3-year running median was used to reduce noise in the annual satellite-derived $PM_{2.5}$ concentration, and the mean uncertainty is about $\pm 6.7\ \mu g/m^3$ (van Donkelaar et al. 2015; van Donkelaar et al. 2006). The spatial resolution of this dataset is 10×10 km. We calculated the spatially averaged $PM_{2.5}$ concentration for each city according to its prefectural boundary.

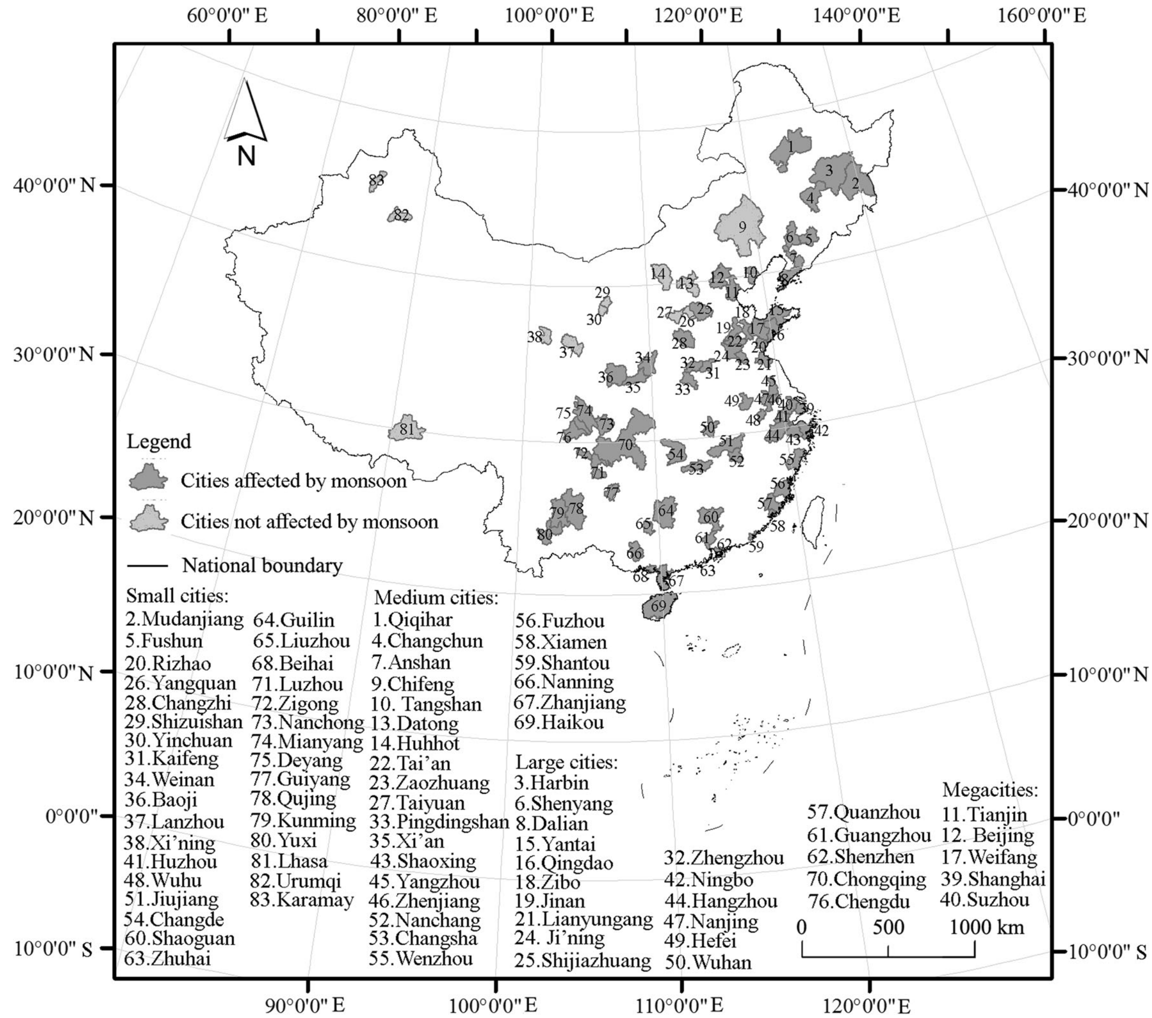

Fig. 1 Locational map of 83 Chinese cities selected in this study

API and exceedance

We obtained the daily API data in 2010 for the 83 cities from the Chinese Ministry of Environmental Protection website (MEP) (http://www.zhb.gov.cn/). The API values were determined based on the concentrations of three atmospheric pollutants: sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and suspended particulates smaller than 10 μm (PM_{10}), which were measured by monitoring stations for each city. The actual concentrations (C_p) of three air pollutants (SO_2, NO_2, and PM_{10}) were used to calculate API (MEP 2012):

$$IAPI_n = (IAPI_{Hi} - IAPI_{Lo}) \times \frac{C_p - BP_{Lo}}{BP_{Hi} - BP_{Lo}} + IAPI_{Lo} \quad (1)$$

$$API = \max\{IAPI_1, IAPI_2, IAPI_3\} \quad (2)$$

where $IAPI_n$ ($n = 1$, 2, and 3) is the individual Air Pollution Index for SO_2, NO_2, and PM_{10}, respectively, BP_{Lo} is the break-point concentration at the lower limit of the API categories, BP_{Hi} is the break-point concentration at the upper limit of the API categories, $IAPI_{Lo}$ is the index value at the lower limit of the API categories, and $IAPI_{Hi}$ is the index value at the upper limit of the API categories. API is the maximum value of all $IAPI_n$. The ground-based API data before 2012 in China did not include $PM_{2.5}$. Annual (or seasonal) exceedance refers to the total number of air pollution days with a daily API value larger than 100 per year (or season) according to China's air quality standards (MEP 1996).

Land use/cover data

Land cover data in 2010 with a spatial resolution of 1 × 1 km were obtained from the National Science & Technology Infrastructure of China, National Earth System Science Data Sharing Infrastructure (http://www.geodata.cn). There were six land cover types in this dataset: forest, cropland, grassland, barren land, water body, and built-up area.

Table 1 Urban form and air pollution metrics used in this study and their associated references

	Metrics/measures	Specific meaning in this study	References
Urban form metrics	Total built-up area (TA)	The total built-up area of a city	(Cárdenas Rodríguez et al. 2016)
	Percentage of landscape (PLAND)	The proportion of built-up area in a city	(Cho and Choi 2014; Cárdenas Rodríguez et al. 2016)
	Mean patch area (MPA)	Mean size of urban patches	(Irwin and Bockstael 2007)
	Patch density (PD)	The density of urban patches in a city	(Irwin and Bockstael 2007)
	Largest patch index (LPI)	The proportion of the largest urban patch in a city	(Bereitschaft and Debbage 2013)
	Edge density (ED)	The density of edges of all urban patches in a city	(Bereitschaft and Debbage 2013)
	Landscape shape index (LSI)	A ratio of total length of urban patch edges to the root of area	(Bereitschaft and Debbage 2013)
	Area weighted mean fractal dimension (AWMFD)	A ratio of the change in detail to the change in scale	(Bereitschaft and Debbage 2013)
	Clumpiness index (CLUMPY)	The proportional deviation of the proportion of like adjacencies between urban patches from that expected under a spatially random distribution	(Bereitschaft and Debbage 2013)
	Aggregation index (AI)	The proportion of like adjacencies between urban patches	–
Air pollution measures	$PM_{2.5}$ concentration	Annual averaged $PM_{2.5}$ concentration	(van Donkelaar et al. 2015)
	Air Pollution Index (API)	The highest index value of SO_2, NO_2, and PM_{10}	(MEP 2012)
	Exceedance levels	Total number of days when API > 100 per year or season	(Stone 2008)

Urban form metrics

Ten landscape metrics were used to represent urban form in this study: total built-up area (TA), patch density (PD), mean patch area (MPA), percentage of landscape (PLAND), Largest patch index (LPI), area weighted mean fractal dimension (AWMFD), edge density (ED), Landscape shape index (LSI), Clumpiness index (CLUMPY), and Aggregation index (AI) (Table 1). The main justification for choosing these 10 metrics is that they have been widely used to characterize the spatial extent, fragmentation, shape complexity, and connectivity of urban landscape elements (Burchfield et al. 2006; Buyantuyev et al. 2010; Ewing 1997; Ewing et al. 2003; Fan et al. 2005; Galster et al. 2001; Irwin and Bockstael 2007; Jaeger and Schwick 2014; Li et al. 2013a; Li et al. 2013b; Luck and Wu 2002; Song and Knaap 2004; Sung et al. 2013; Sutton 2003; Tsai 2005; Wu et al. 2011), and have been shown to affect air pollution (Bechle et al. 2011; Bereitschaft and Debbage 2013; Borrego et al. 2006; Cárdenas Rodríguez et al. 2016; Chen et al. 2016; Cho and Choi 2014; Martins 2012; Stone 2008).

We used the land use/cover data to compute the 10 urban form metrics. The six original land use/cover types were reclassified into two classes: built-up area and non-built-up area that lumped the other five land use/cover types. The built-up area is a geographic region dominated by non-vegetated, human-constructed elements (e.g., settlements, buildings, roads, runways, and industrial facilities), with the proportion of built-up area higher than that of other five land use/cover types combined (Liu et al. 2014). The spatial extent of each city was delineated by its administrative boundary. We computed the 10 landscape metrics for the urban class (i.e., the built-up area) using FRAGSTATS software (v4.2) (McGarigal et al. 2012). TA and PLAND are area-related composition metrics that represent total built-up area and its proportion, respectively. PD, MPA, and LPI are measures of the fragmentation or interspersion of built-up areas. ED indicates boundary abundance of built-up areas. LSI and AWMFD are measures of the shape complexity of built-up areas. CLUMPY and AI measure degrees of clumping and the connectivity of built-up areas (Table 1).

Correlation analysis

We analyzed the associations between the 10 urban form metrics and three air pollution indicators in 2010 for the 83 Chinese cities, using the Spearman's rank-order correlation because the data of air pollution levels did not follow normal distributions. All statistical analyses were performed with SPSS software (version 18.0).

To examine the effect of seasonality on the urban form-air pollution relationship, we analyzed the associations of the 10 urban form metrics with seasonal API and exceedance levels ($PM_{2.5}$ concentrations not included because of no data available) in spring (March, April, and May), summer (June, July, and August), fall (September, October, and November), and winter (December, January, and February), respectively. In addition, because monsoons may lead to seasonal variations in the atmospheric conditions of pollution dispersion (Jiang et al. 2015; Zhou et al. 2013), we also conducted the same correlation analysis for cities affected by monsoons versus those not affected by monsoons.

To examine the effect of city size on the urban form-air pollution relationship, the 83 cities were divided into four groups based on their total built-up area: megacities (> 150,000 ha), large cities (60,000–150,000 ha), medium cities (30,000–60,000 ha), and small cities (< 30,000 ha) (see Appendix A1). These four groups largely correspond to: "super large-sized cities" (with a population of more than 10 million), "very large-sized cities" (5 to 10 million people), "large-sized cities" (3 to 5 million people), and the combination of "medium-sized cities" (0.5 to 1 million) and "small-sized cities" (< 0.5 million people), which are population-based city size classes formally established by the Chinese government (The State Council of People's Republic of China 2014).

Results

Characteristics of urban and air pollution patterns of Chinese cities

The attributes of urban form of the 83 Chinese cities varied considerably as indicated by the 10 urban form metrics (Table 2). The total build-up was arranged from 5.80×10^3 ha (Karamay) to 278.80×10^3 ha (Beijing). Shenzhen had the maximum values of PLAND (53.215%), MPA (391.54 × 10 ha), and LPI (50.131%). Lhasa had the minimum values of PLAND (0.225%), PD (1.900×10^{-3}/ha), ED (3.64×10^{-2} m/ha), and LSI (3.118). The three highest values of LSI occurred for Chifeng (15.956), Tianjin (15.516), and Ji'ning (15.491). Coastal cities generally had higher values of ED and AWMFD than inland cities. The three lowest values of CLUMPY and AI were found for Beihai (22.56×10^{-2} and 25.78%), Chifeng (29.42×10^{-2} and 29.82%), and Baoji (36.45×10^{-2} and 36.78%). Urumqi, Liuzhou, and Xi'an had the highest values of CLUMPY (77.34×10^{-2}, 74.26×10^{-2}, and 73.38×10^{-2}, respectively), while Shenzhen, Urumqi, and Shanghai had the highest values of AI (83.87%, 78.22%, and 77.85%, respectively) (Table 2).

The air pollution levels of the study cities exhibited obvious regional differences. High annual $PM_{2.5}$ concentrations, API, and exceedance levels were mainly located in the North China Plain, the middle and lower reaches of the Yangtze River Basin, and the Sichuan Basin (Fig. 2). Moreover, air pollution levels showed seasonal variations, with the values of API and exceedance levels generally higher in fall and winter than spring and summer (Fig. 3).

In general, the cities with larger built-up area (TA) and higher values of PLAND tended to have higher $PM_{2.5}$ concentration, API, and exceedance levels (Fig. 4). Meanwhile, the built-up areas with more fragmental parts (PD), edges (ED), and complex shape (LSI) also tended to show higher $PM_{2.5}$ concentration, API, and exceedance levels (Fig. 4). We conducted correlation analysis to quantify the significance of above relationships, and the results were analyzed in "Correlations between urban form and air pollution" section.

Correlations between urban form and air pollution

Our results showed that not all urban form metrics were significantly correlated with air pollution levels (Fig. 4). Specifically, the highest correlation coefficient occurred between $PM_{2.5}$ concentration and PLAND ($\rho = 0.414$, $P < 0.01$), followed by ED ($\rho = 0.410$, $P < 0.01$), PD ($\rho = 0.405$, $P < 0.01$), and LPI ($\rho = 0.371$, $P < 0.01$) (Fig. 4). TA had the highest correlation coefficient with API ($\rho = 0.320$, $P < 0.01$) and exceedance levels ($\rho = 0.346$, $P < 0.01$). LPI was highly correlated with API ($\rho = 0.251$, $P < 0.05$) and with exceedance levels ($\rho = 0.267$, $P < 0.05$). LSI was significantly correlated with API ($\rho = 0.242$, $P < 0.05$) and with exceedance levels ($\rho = 0.251$, $P < 0.05$). Thus, urban composition metrics (TA and PLAND) tended to be more strongly correlated with air pollution than urban configuration metrics (Fig. 4). Among

Table 2 Summary statistics of urban form metrics for 83 Chinese cities

Urban form metrics (U)	Number of cities	Mean	Standard deviation	Minimum	Maximum
TA (× 10^3ha)	83	56.17	51.98	5.80	278.80
PLAND (%)	83	7.136	8.896	0.225	53.215
MPA (× 10 ha)	83	55.09	45.32	16.53	391.54
PD (× 10^{-3} numbers/ha)	83	12.217	9.463	1.900	39.300
LPI (%)	83	3.287	6.713	0.067	50.131
ED (× 10^{-2} m/ha)	83	99.61	86.43	3.64	382.20
LSI	83	9.188	3.428	3.118	15.956
AWMFD (× 10^{-1})	83	10.56	0.25	10.13	11.45
CLUMPY (× 10^{-2})	83	54.83	11.07	22.56	77.34
AI (%)	83	57.82	11.96	25.78	83.87

TA total built-up area, *PLAND* percentage of landscape, *MPA* mean patch area, *PD* patch density, *LPI* Largest patch index, *ED* edge density, *LSI* Landscape shape index, *AWMFD* area weighted mean fractal dimension, *CLUMPY* Clumpiness index, *AI* Aggregation index the configuration metrics, LPI was significantly correlated with all three air pollution indicators, LSI was significantly correlated with two air pollution indicators, and PD and ED were only significantly correlated with one air pollution indicator (Fig. 4).

Effects of seasonality on the urban form-air pollution relationship

There were three main findings of seasonality effects on the urban form-air pollution relationship. First, most of significant correlations were found in the monsoon affected cities (26 pairs), rather than in the non-monsoon affected cities (only 1 pair) (Table 3). Second, more urban form metrics were significantly correlated with exceedance levels (18 pairs) than with API levels (9 pairs) (Table 3). Finally, more urban form metrics were significantly correlated with API and exceedance levels in spring and summer (21 pairs) than in fall and winter (6 pairs) (Table 3). Specifically, in the monsoon affected cities, TA, PLAND, MPA, PD, LPI, and ED were all significantly and positively associated with API and exceedance levels in spring and

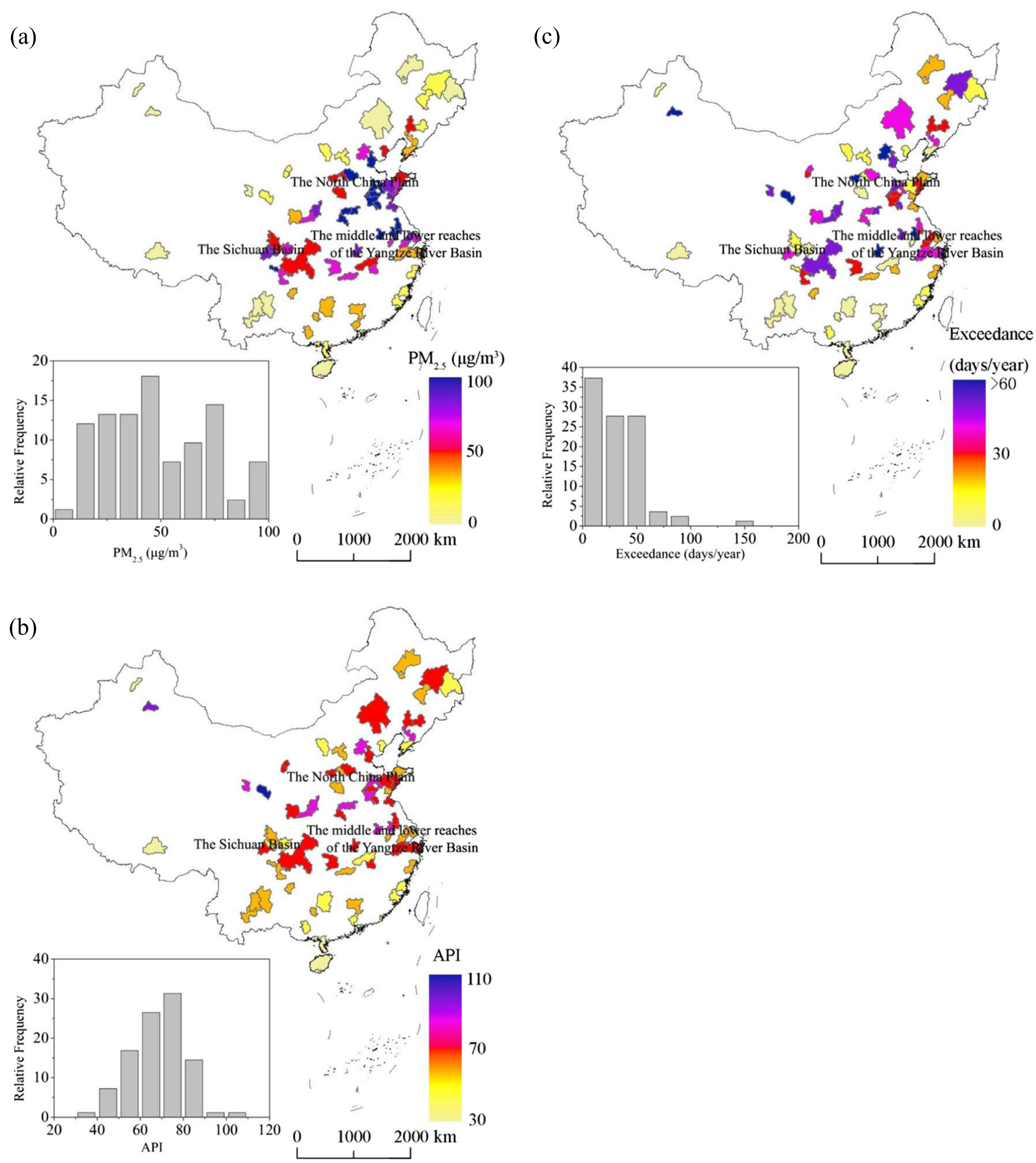

Fig. 2 Annual air pollution levels for 83 cities in 2010. **a** $PM_{2.5}$. **b** API. **c** Exceedance. Histograms of three air pollution indicators are shown in the bottom-left panels

exceedance levels in summer (Table 3). AWMFD was significantly and positively associated with exceedance levels in spring (Table 3). PLAND, MPA, PD, and LPI were all significantly and positively associated with exceedance levels in summer (Table 3). TA and ED were significantly correlated with API in summer and with exceedance levels in fall and winter (Table 3). For non-monsoon cities, only TA was significantly correlated with exceedance levels in fall (Table 3).

Effects of city size on the urban form-air pollution relationship

Two main findings emerged of city size effects on the urban form-air pollution relationship. First, more urban configuration metrics were significantly correlated with three air pollution measures among different urban sizes. Meanwhile, more urban form metrics were significantly correlated with $PM_{2.5}$ concentrations (eight pairs) than

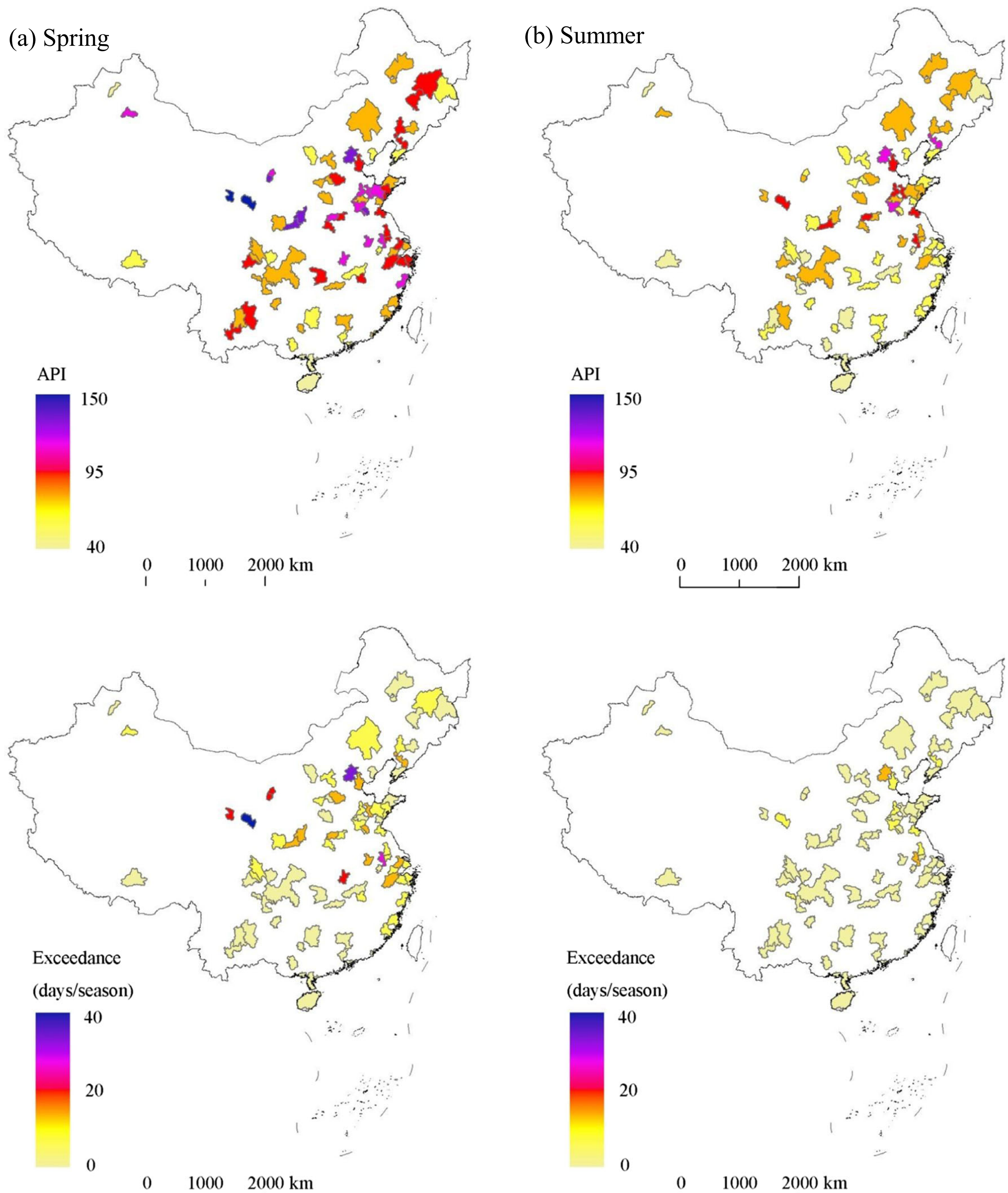

Fig. 3 Seasonal air pollution levels for 83 Chinese cities in 2010. **a** API and exceedance in spring. **b** API and exceedance in summer. **c** API and exceedance in fall. **d** API and exceedance in winter

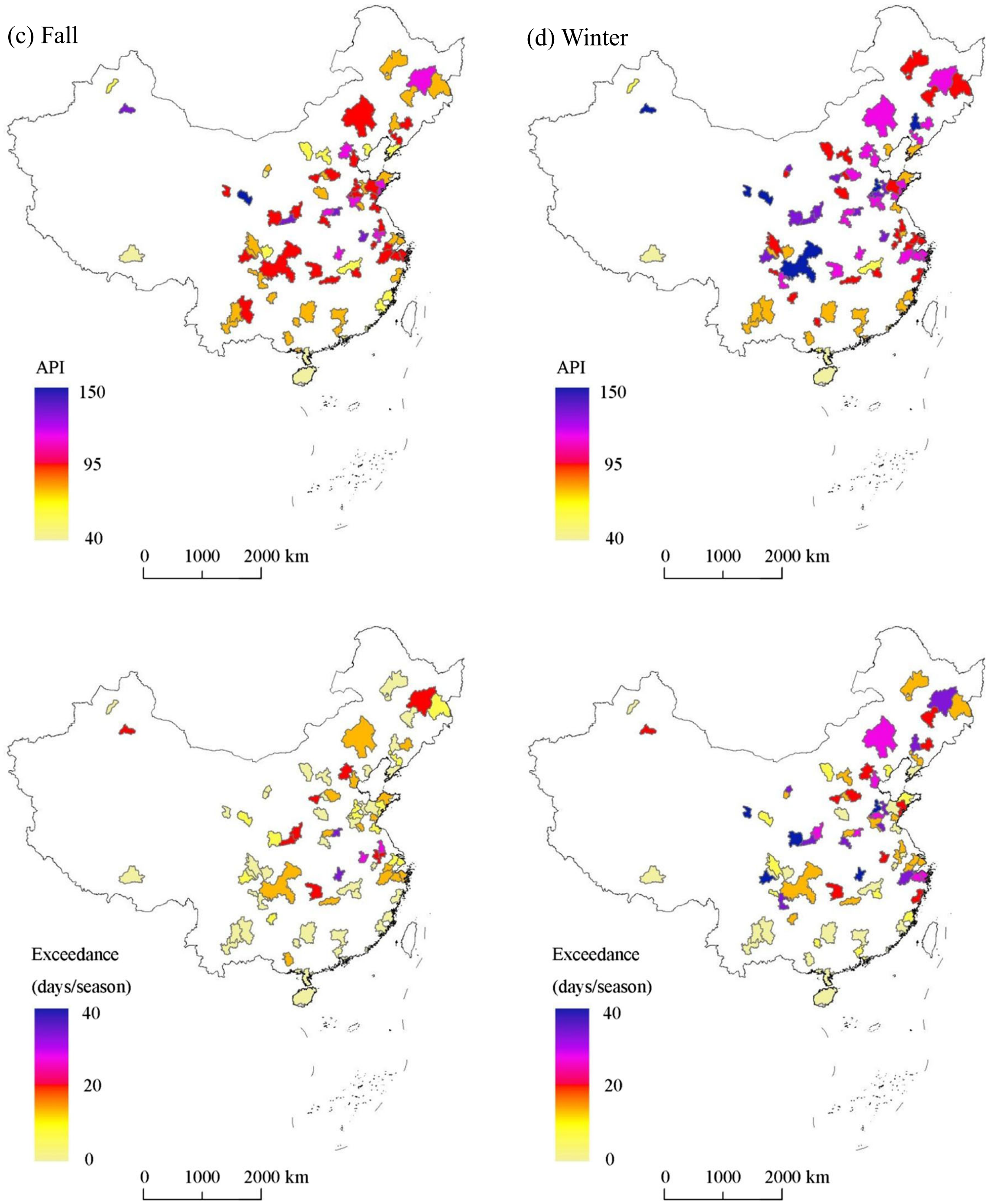

Fig. 3 (continued)

with API or exceedance levels (two pairs) (Table 4). Specifically, for Chinese megacities, $PM_{2.5}$ concentrations were significantly and negatively correlated with LPI, AWMFD, and AI, whereas significant and positive correlation was found between API and LSI and between exceedance levels and TA (Table 4). For large cities, PD was significantly and positively correlated with $PM_{2.5}$ concentrations, but no other urban form metrics were found to be significantly correlated with any of the three air pollution measures (Table 4). For medium cities, PD, PLAND, LPI, and ED were significantly correlated with $PM_{2.5}$ concentrations, but not with API and exceedance levels (Table 4). No significant correlation was found between urban form metrics and air pollution levels in small cities (Table 4).

Discussion

Which aspects of urban form affect air pollution?

Our results suggest that, when cities of all sizes were considered, cities with more built-up area (TA) were more frequently correlated with higher levels of air pollution (Fig. 4; Table 3). Closely related to the total built-up area, the percent of built-up area within the study city (PLAND) was also highly correlated with $PM_{2.5}$ concentrations (Fig. 4), as well as with API and exceedance levels (Table 3). City size mattered for air pollution in the 83 Chinese cities, because larger urban built-up areas generally emitted more primary air pollutants (e.g., NO_2 and SO_2 from fossil fuel combustion and industrial emissions).

The degree of urban landscape fragmentation, indicated by the PD and ED of urban land covers, was positively associated with air pollution levels (Fig. 4; Table 3). These results were congruent with those found in more than 200 European cities where PLAND and PD were positively correlated with the concentrations of NO_2 and PM_{10} (included $PM_{2.5}$) (Cárdenas Rodríguez et al. 2016). We also found that MPA and LPI were positively correlated with air pollution levels (Fig. 4), but their relationships varied with different seasons and city sizes (Tables 3 and 4).

How does seasonality affect the urban form-air pollution relationship?

In general, seasonality may affect air pollution levels through changes in wind (Elminir 2005), precipitation (Luo et al. 2017), relative humidity (Yuan et al. 2014; Zhang et al. 2014), planetary boundary layer (PBL) (Georgescu 2014), monsoon (Hien et al. 2011; Zhou et al. 2013), and other dissipation conditions (Hu and Zhou 2009; Luo et al. 2017). Our study indicates two salient findings about the urban form-air pollution relationship which are directly related to seasonality. First, the urban form-air pollution relationship changed greatly with seasonality in terms of both which urban form metrics were correlated with air pollution and how strongly so (Table 3). Second, almost all significant correlations between urban form metrics and air pollution were found in cities with a monsoon season (Table 3).

In general, more urban form metrics were significantly associated with air pollution levels in spring and summer than in fall and winter (Table 3). This phenomenon maybe be attributed partly to the strong Asian monsoon in spring and summer, bringing ample precipitation which washes away airborne pollutants and facilitates transport of clean air over urban area (Jiang et al. 2014). Cities with smaller proportions of built-up areas (lower values of TA and PLAND) and lower densities of built-up area patches (smaller values of ED and PD) seem to have better environmental conditions for the dispersion and dilution of airborne pollutants. In fall and winter, the inversion of temperature gradient usually occurs more frequently in cities with greater built-up areas, hindering the dissipation of air pollutants (Pardyjak et al. 2009; Pope and Wu 2014). Also, wind speed is often lower in fall and winter than in spring and summer, which slows down the transport of clean air over urban areas (Hess et al. 2015; Jiang et al. 2014). All the above factors together tend to generate a relatively homogeneous airshed or "airscape" of high-level pollutants in which air pollution levels do not change with urban form attributes below. The results of seasonal variations suggest that statistical analyses designed to detect the urban form-air pollution relationship should be more productive if data of spring and summer, rather than fall and winter, are used (for northern hemisphere).

How does city size affect the urban form-air pollution relationship?

As discussed already in the previous sections, air pollution levels tended to increase with increasing built-up areas in the 83 Chinese cities. City size (i.e., TA) also mattered in terms of evaluating the effects of urban landscape configuration attributes on air pollution (Appendix A2). By grouping all the 83 cities into four categories, we were able to examine how urban form metrics might be related to air pollution for different size groups of cities.

Our results show that, when city size was held relatively constant (i.e., grouping cities of similar size together for analysis), the number of paired significant correlations between urban form metrics and air pollution significantly decreased (Table 4). This indicates the strong impact of city size on air quality. The relationship between urban configuration metrics and air pollution varied greatly with city size groups. For small cities, none of the urban configuration metrics mattered to any of the three air pollution indicators; for medium and large cities, no urban configuration metric mattered to two of the three air pollution indicators (i.e., API and exceedance); and for megacities, several urban configuration metrics became important to both $PM_{2.5}$ and API (Table 4). These findings are sensible because small cities are rarely heavily polluted unless they are important regional sources of air pollution. Also, when the pollution level is low, then urban form cannot matter much.

Specifically, exceedance did not respond to urban configuration metrics for any of the city groups. Metrics of urban fragmentation (PD and ED) and contiguity (LPI) were positively correlated with $PM_{2.5}$ concentrations for medium cities, but only PD was significantly correlated with $PM_{2.5}$ concentrations for large cities (Table 4). We also found negative

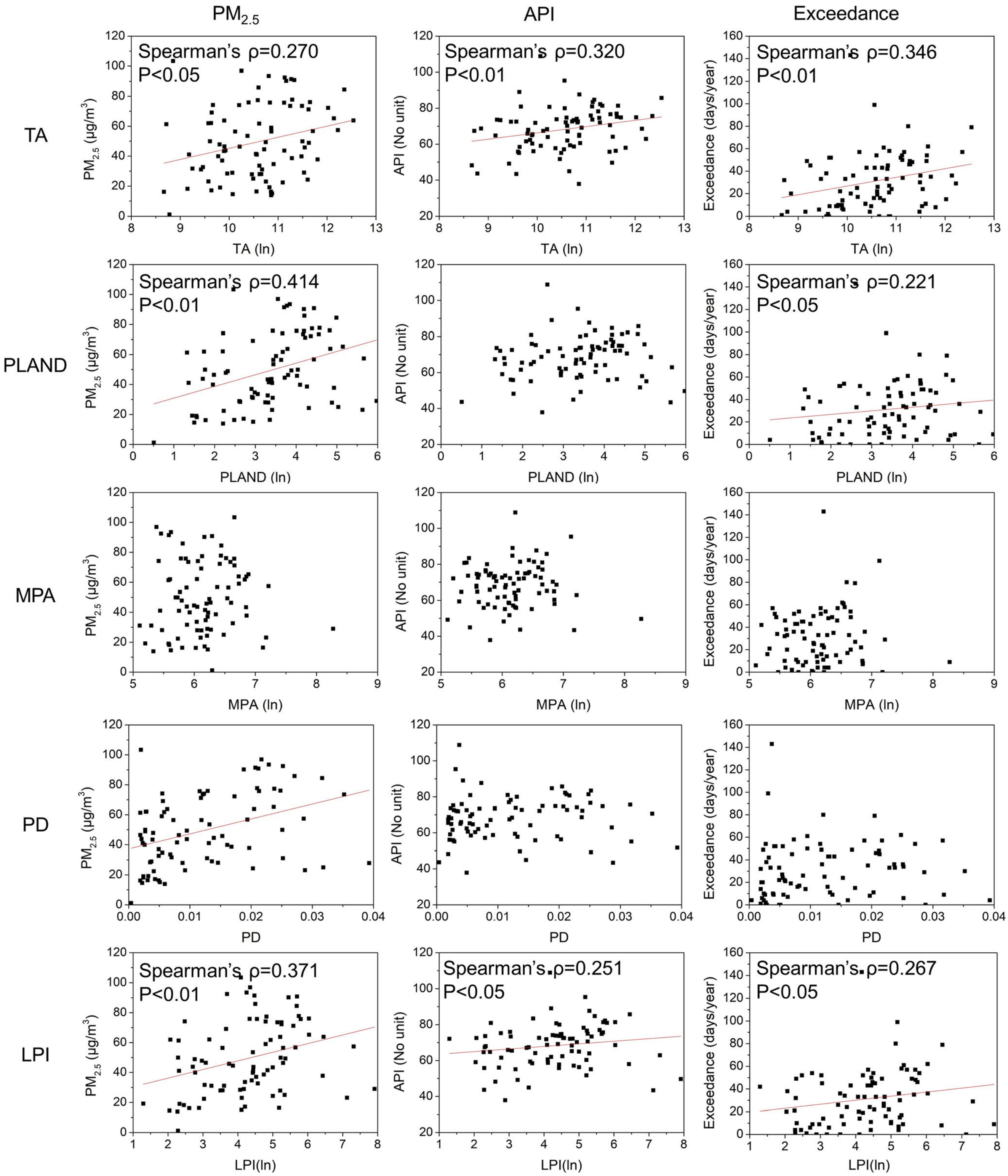

Fig. 4 Scatter plots of annual air pollution levels ($PM_{2.5}$, API, and exceedance) against urban form metrics for 83 Chinese cities. TA total area, PLAND percentage of landscape, MPA mean patch size, PD patch density, LPI Largest patch index, ED edge density, LSI Landscape shape index, AWMFD area weighted mean fractal dimension, CLUMPY Clumpiness index, AI Aggregation index

correlations between $PM_{2.5}$ concentrations and three urban configuration metrics—urban contiguity (LPI), urban compactness (AI), and urban patch shape complexity (AWMFD)—only for megacities (Table 4). Contiguous and compact urban forms tend to enhance connectivity, reduce mobility requirements and car-dependency, and promote

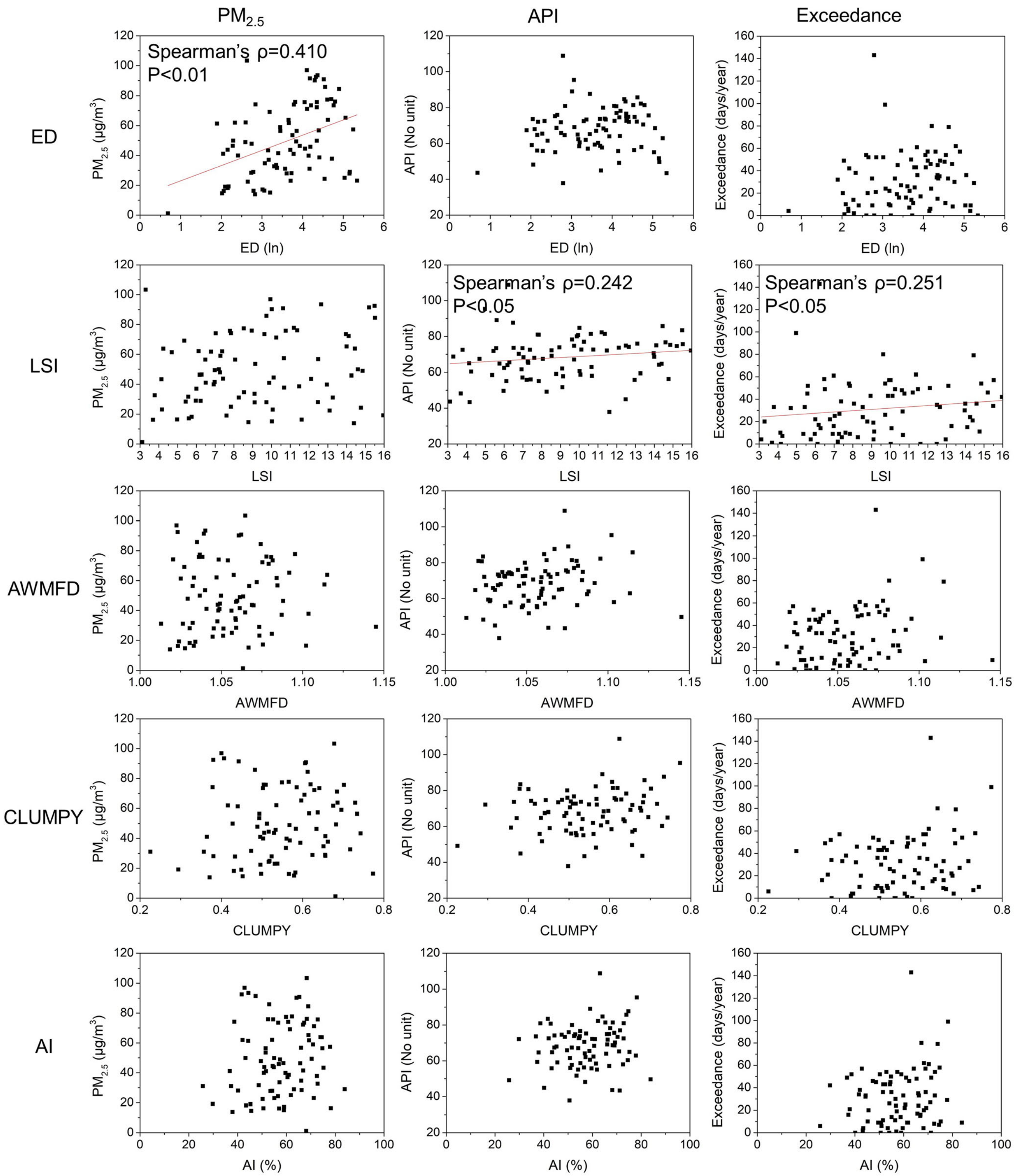

Fig. 4 (continued)

cleaner transport options such as biking and walking (Bechle et al. 2011; Borrego et al. 2006; Martins 2012). Our results suggest that these benefits became prominent only when cites were extremely large.

Conclusions

Our study of 83 Chinese cities has produced several important findings: (1) Urban air pollution (including $PM_{2.5}$, API, and

Table 3 Spearman rank correlation coefficients between urban form metrics and air pollution levels across four seasons

Landscape metrics	Spring				Summer				Fall				Winter			
	API		Exceedance		API		Exceedance		API		Exceedance		API		Exceedance	
	M	Non-M	M	Non-M	M	Non-M	M	Non-M	M	Non-M	M	Non-M	M	Non-M	M	Non-M
TA	.365**	.063	.416**	.067	.404**	.182	.429**	.290	.260*	.538	.286*	.628*	.233	.301	.296*	.350
PLAND	.270*	.259	.350**	.175	.198	.245	.364**	− .441	.142	.196	.188	.421	.060	.245	.089	.336
MPA	.263*	.098	.313**	.133	.216	− .042	.411**	− .253	.117	.042	.219	.193	.042	.112	.063	.070
PD	.275*	.406	.349**	.291	.223	.364	.267*	− .360	.193	.273	.160	.469	.116	.329	.120	.427
LPI	.258*	.105	.342**	.088	.192	.042	.416**	− .382	.100	.105	.183	.287	.023	.126	.065	.147
ED	.318**	.049	.323**	.105	.413**	.105	.508**	.430	.192	.476	.278*	.483	.207	.238	.257*	.210
LSI	.059	.336	.159	.210	− .004	.392	.027	− .290	.020	.077	− .021	.298	− .030	.196	− .020	.322
AWMFD	.167	.503	.252*	.371	.131	.503	.137	− .091	.100	.476	.064	.516	.099	.469	.120	.559
CLUMPY	.130	.308	.162	.200	.126	.322	.022	− .290	.181	.035	.079	.240	.099	.203	.082	.322
AI	.132	.343	.204	.231	.094	.336	.061	− .290	.127	.049	.066	.265	.059	.210	.057	.350

TA total built-up area, *PLAND* percentage of landscape, *MPA* mean patch area, *PD* patch density, *LPI* Largest patch index, *ED* edge density, *LSI* Landscape shape index, *AWMFD* area weighted mean fractal dimension, *CLUMPY* Clumpiness index, *AI* Aggregation index

*$p < 0.05$

**$p < 0.01$

M monsoon region, *Non-M* non-monsoon region

exceedance) generally increased with city size; (2) the urban form-air pollution relationship varied greatly with seasonality and monsoons; (3) urban air pollution levels were more strongly correlated with urban landscape composition metrics (e.g., TA and PLAND) than urban landscape configuration metrics (e.g., metrics of urban fragmentation, dispersion, and patch shape complexity); and (4) while urban composition properties (especially total built-up area) seemed to affect $PM_{2.5}$, API, and exceedance, urban configuration attributes were only correlated to $PM_{2.5}$ concentrations of medium cities and megacities.

These findings help improve our understanding of how different aspects of urban form may affect air pollution in cities by clarifying the influences of city size and seasonality. They also suggest that, in order to mitigate urban air pollution problems, China needs to limit the number of megacities and curb the spatial rampage of its numerous large-sized and very large-

Table 4 Spearman rank correlation coefficients between urban form metrics and air pollution levels for cities with different total built-up areas

Landscape metrics	Megacity (built-up area > 150,000 ha)			Large city (150,000 ha > built-up area > 60,000 ha)			Medium city (60,000 ha > built-up area > 30,000 ha)			Small city (built-up area < 30,000 ha)		
	$PM_{2.5}$	API	Exceedance	$PM_{2.5}$	API	Exceedance	$PM_{2.5}$	API	Exceedance	$PM_{2.5}$	API	Exceedance
TA	− .200	.600	.900*	− .240	− .370	− .380	− .184	.063	.035	.225	.194	.293
PLAND	− .500	− .700	.000	.006	− .106	− .281	.625**	.275	.318	.285	.065	.120
MPA	− .800	− .600	.100	− .183	− .090	.065	.067	.131	.158	− .087	− .194	− .197
PD	.100	− .200	.300	.477*	.190	− .344	.465*	− .018	− .003	.258	.138	.209
LPI	− .900*	− .300	.300	.155	.110	− .042	.411*	.266	.329	.196	.085	.095
ED	− .500	− .700	.000	.044	− .125	− .386	.567**	.133	.141	.298	.118	.178
LSI	.700	.900*	.600	− .018	− .184	− .298	− .284	− .234	− .281	.194	.188	.251
AWMFD	− .900*	.000	.300	− .256	− .151	− .027	.061	.179	.144	− .172	.008	− .002
CLUMPY	− .600	.300	.200	− .038	.079	.238	.128	.245	.275	− .067	− .122	− .116
AI	− .900*	− .300	.300	− .027	.035	.121	.174	.243	.293	− .081	− .164	− .161

TA total built-up area, *PLAND* percentage of landscape, *MPA* mean patch area, *PD* patch density, *LPI* Largest patch index, *ED* edge density, *LSI* Landscape shape index, *AWMFD* area weighted mean fractal dimension, *CLUMPY* Clumpiness index, *AI* Aggregation index

*$p < 0.05$

**$p < 0.01$

sized cities. In addition, regional urban planning should be emphasized (Forman and Wu 2016), particularly aiming to reduce the degree of urban fragmentation and increase urban compactness for ameliorating air pollution (especially $PM_{2.5}$).

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