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The characteristics of ambient air quality in urban forest areas and other urban areas of Fuzhou city, China

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Abstract
Air quality directly relates to human health and economic and social sustainable development. In this study, we aim to explore the characteristics of the air pollutant in urban forest areas (UFA) and the relationship of the air pollutant between UFA and other urban areas (OUA). As one of the major vegetated spaces in urban area, UFA are places that can provide better air quality to the public. To investigate the characteristics of the ambient air pollutants in UFA, six monitoring stations in Fuzhou collected six criteria of air pollutant data ($PM_{2.5}$, PM_{10}, CO, SO_2, NO_2 and O_3) between May 1st, 2014 and April 30th, 2017. To reveal the characteristics of the air quality in the UFA and compare the difference between UFA and OUA, variations of air pollutant concentrations, attainment rates, major air pollutants (MAP), and the air pollutant source were analyzed. Results showed that compared to the most cities in China, the six criteria air pollutants concentrations were relatively low in Fuzhou; the annual average attainment rate in UFA was higher than in OUA; in all seasons, except winter, PM_{10} was the most frequent MAP in UFA, followed by $PM_{2.5}$ and O_3, and the correlations of the MAP between UFA and OUA, indicated that the source of air pollution came from the urban areas of Fuzhou city. Monitoring and analyzing the variations of the ambient air quality in UFA are therefore of considerable significance to the public, as well as to green space managers, designers and urban policymakers.

Keywords Air pollution · Ambient air quality · Conditional probability function · Major air pollutants · Urban forest areas

1 Introduction

Quiet spaces, beautiful forest landscapes, good air quality, comfortable microclimates and close proximity to nature are benefits of UFA to the public. UFA provide people with recreational spaces that are very different from OUA. Therefore, UFA are often the primary

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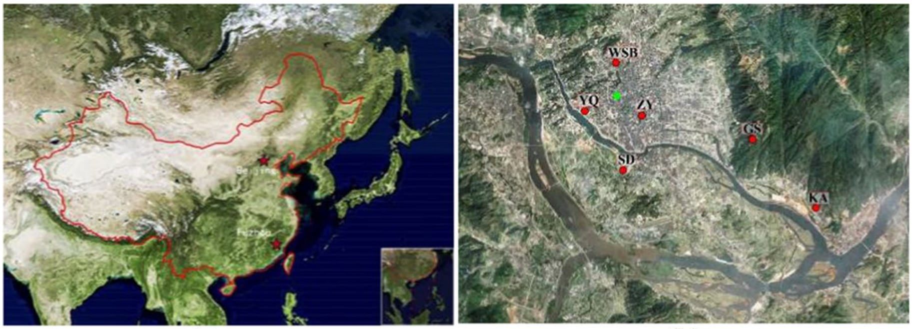
destination for the public to engage in exercises, recreational activities and general relaxation (WolchByrne & Newell, 2014). These activities in UFA are important contributors to public health (Akpinar, 2016; Chiang & Li, 2019; Ekkel & de Vries, 2017; Li et al., 2019; Mytton et al., 2012; Ngulani & Shackleton, 2019; Sugiyama et al., 2018).

As the primary urban green space in China, UFA have strongly been supported and promoted by the Chinese central government (Liu, 2018; Wang, 2016). The "13th Five-Year Plan" proposal of the central government and the "Several Opinions of the Central Committee on Strengthening the Management of Urban Planning and Construction" listed the construction of urban forests as an important point, marking that management and construction of the UFA have become a focus in the national development strategy (Liu, 2018; Wu, et al. 2017; Ye, Z. and Qie, G.F, 2017). Prioritized functions of urban forests include, among other, improving the landscape quality, reducing the heat island effect, maintaining ecological stability and improving urban ecological diversity (Liu, 2018; Wang, 2016; Wu, et al. 2017; Ye, Z. and Qie, G.F, 2017). In the most rapidly industrializing countries, including China, air pollution has become one of the major problems that affect public health and concern urban policymakers. UFA are increasingly becoming the most important outdoor spaces for the public to escape from urban areas with air pollutants (Guo et al., 2019; Lin, Kroll, Nowak, & Greenfield, 2019). As a result, reducing urban air pollutants or creating areas with better air quality is one of the main functions of UFA in China. The public visits UFA to pursue spaces with better air quality for relaxation, exercises and social activities (Ekkel & de Vries, 2017; Guo et al., 2019; Wolch et al., 2014). However, air pollutants are highly diffused, and the concentration of air pollutants in UFA is receiving public attention (Fitzky et al. 2019; Jim et al. 2009; Manes et al. 2008). The public are concerned about whether air pollution affects the air quality of UFA, what are characteristics of air pollutants and what is the current quality of air.

Monitoring and analyzing the spatial and temporal variations of the ambient air quality in urban areas, especially in UFA, can provide evidence that inform policymakers, designers and managers, and help the public to decide the best locations and timing for visits. Studies have revealed air quality variations between cities in different urban areas and spatial variations in specific areas of the urban areas, which have brought some practical results to the public (Chang et al., 2015; Leung et al., 2011; Selmi et al., 2016; Song et 1stal. 2016; Viippola et al., 2018; Wu, Schwab, Yang, Zheng, & Yuan, 2015a; Yan et al., 2016; Zhang et al., 2019; Zhao et al., 2018). Zhao et al. (2018) studied the spatial and temporal patterns of air pollutants in the cities in southwest China (Zhao et al., 2018). Some scholars have also identified the variation characteristics of pollutant concentrations in different urban areas. Yan et al. (2016) revealed the temporal and spatial characteristics of atmospheric pollutants in urban areas of Beijing, by exploring the variation of air quality, major air pollutants and by analyzing the influences of meteorological factors (Yan et al.,. 2016). Studies on the characteristics of the air pollutants in urban green spaces have also been carried out, though most of these have focused on the analysis of the characteristics of pollutant concentration in green spaces, such as the retention of air pollutants on the surface of leaves (Leung et al., 2011; Selmi et al., 2016), or the concentration of green space and road pollutants (Viippola et al., 2018). To date, few studies have analyzed the air quality variations in UFA and compared air quality in UFA and OUA simultaneously, in order to provide evidence for better decision making.

Fuzhou, a subtropical monsoon city located southeastern China (Fig. 1), is considered as one of the most important cities in the Western Taiwan Strait Economic Zone (WTSEZ). Similar to the Beijing-Tianjin-Hebei, the Pearl River Delta and the Yangtze River Delta, WTSEZ is supported by the Chinese central government to explore a new urban



(a) (b)

Fig. 1 Location of Fuzhou city **a**; positions of the air pollutants monitoring stations (red) and meteorological stations (green) in Fuzhou city **b**. (ZY and WSB in CCA, SD and YQX in SUA, KA in EUA, GS in UFA)

construction model of urban development (Niu et al., 2013; Wu, Schwab, Yang, Zheng, & Yuan, 2015b; Zhang et al., 2013). The urban development and construction processes in Fuzhou, including the development of urban forests, will serve as a model for the OUA in southeast China (Xu, Chen, Chen, Zhang, He, & Zhao et al. 2012; Xu et al., 2013; Zhang et al., 2013). Understanding the variations of the six criteria air pollutants (the criteria air quality of Chinese government) in UFA and OUA will be of great significance to the public, manager, designer and policymakers.

A comprehensive understanding of the characteristics of UFA and OUA can help the public to have suitable recreation and policymakers air pollution management plans. The current study aims to 1) compare the air quality of UFA and the OUA and to answer the question on whether the air quality in UFA is better than OUA; and reveal: 2) the temporal variations of the major air pollutants (MAP) in the UFA and compare the variation with the monitoring sites set in OUA; 3) the attainment rates of the air quality in the monitor sites of UFA; 4) the MAP in UFA; and 5) the inter-correlation of the air pollutants, meteorological factors and provide a comprehensive understanding of the air pollution characteristics of UFA.

2 Materials and methods

2.1 Data

2.1.1 Air pollutant data

Air pollutant data from May 1st, 2014 to April 30th, 2017 were obtained from the China National Environmental Monitoring Center (CNEMC, http://www.cnemc.cn/). CNEMC controls the quality of air quality data and is respected as an authority for environmental data in China. In order to study the impact of UFA on air quality in different urban areas, six monitoring sites were set up in different urban areas, in Fuzhou (Fig. 1), which were designed by the Ministry of Environmental Protection of China. Among them, two sites are in the central city areas (CCA is defined as the areas inside the first ring road), two sites are in suburban areas (SUA is defined as the areas outside the first ring road and outside the second ring road), one site is in the exurban areas (EUA is defined as the areas outside the second ring road) and one site is located in the UFA.

Each site contained automatic air pollutant monitoring systems that automatically measured the ambient air pollutants concentrations every hour. The automatic air pollutants monitoring system (collection unit, calibration device, analytical unit, measurement unit, data collection and transport unit and other accessory equipment) were used to monitor the air pollutants per minute. China Environmental Protection Standards (CEPS, http://www.es.org.cn/download/) is used to assure and control the quality of air pollutant data. The sites were designed as a mix of urban and background sites, with most of the sites in urban area, and a few in suburban and exurban areas as background sites. The micro-oscillating balance method and the beta-ray absorption method were used to measure the concentrations of $PM_{2.5}$ and PM_{10}. The chemiluminescence method was used to measure the concentrations of NO_2; the ultraviolet fluorescence method was used to measure the concentrations of SO_2, and the UV (Ultraviolet)-spectrophotometry method was used to measure the concentrations of O_3. The non-dispersive infrared (NDIR) and the gas filter correlation infrared absorption method were used to measure the concentrations of CO. Wang et al. (2014) described the compositions of the automatic air pollutants monitoring systems and the methods used to measure the air pollutants concentrations in great detail (Wang et al., 2014).

2.1.2 Meteorological data

Meteorological hourly data from May 1st, 2014 to April 30th, 2017 were obtained through the National Oceanic and Atmospheric Administration of America (NOAA: https://www.climate.gov) and National Meteorological Information Center (NMIC: http://data.cma.cn). Additional data gathered included wind speed (WS), wind direction (WD), temperature (T), cloud coverage rate (CR), air pressure (AP), relative humidity (RH) and rainfall (RF). NOAA and NMIC are both institutions that provide high-quality and reliable data, with NOAA being considered a global authority for meteorological data sets and NMIC being considered a national authority. We further checked and rectified suspicious and incorrect data manually, and after examination, the rate of correct data approached 100% (Fu et al., 2018).

2.2 Method

We utilized five statistical approaches to investigate the variations of the ambient air quality in different urban areas of Fuzhou during May 1st, 2014 to April 30th, 2017. The statistical approaches of spatial variations, attainment rate, major air pollutants (MAP), correlations (between air pollutants and meteorological factors) and conditional probability function are explained in Sects. 2.2.1, 2.2.2, 2.2.3, 2.2.4 and 2.2.5, respectively.

2.2.1 The spatial variations of the air pollutants between UFA and OUA

To contrast the differences among air pollutant levels in UFA and OUA, we analyzed the spatial variations of the air pollutants in Fuzhou. Based on CNEMC and CEPS, we divided the six monitoring stations into four categories: CCA, SUA, EUA and UFA (as mentioned in Sect. 2.1.1). To examine the spatial variations during the study period, we analyzed the mean value of the six air pollutants concentrations, the AR and the

Table 1 The concentration standards of $PM_{2.5}$, PM_{10}, CO, SO_2, NO_2 and O_3 set by CAAQS

	PM_{10} (μg/m^3)	$PM_{2.5}$ (μg/m^3)	SO_2 (μg/m^3)	NO_2 (μg/m^3)	CO (mg/m^3)	O_3 (μg/m^3)
Grade I	40	15	20	40	4	100
Grade II	70	35	60	40	4	160

Table 2 fAQI and the correspondingly limited concentrations of each pollutant ($PM_{2.5}$, PM_{10}, CO, SO_2, NO_2 and O_3)

IAQI	PM_{10}	$PM_{2.5}$	SO_2		NO_2		CO		O_3
	Daily	Daily	Daily	Hourly	Daily	Hourly	Daily	Hourly	Daily
0	0	0	0	0	0	0	0	0	0
50	50	35	50	150	40	100	2	5	160
100	150	75	150	500	80	200	4	10	200
150	250	115	475	650	180	700	15	35	300
200	350	150	800	800	280	1200	24	60	400
300	420	250	1600		565	2340	36	90	800
400	500	350	2100		750	3090	48	120	1000
500	600	500	2620		940	3840	60	150	1200

MAP at each site. Analysis of Variance (ANOVA) was used to determine whether there were significant dissimilarities of the air impurities among the six locations.

2.2.2 AR and MAP

AR is defined as the rates of hours where all the concentration of the six air pollutants are below the Grade I value set by CAAQS (Table 1). We computed the AR of the six monitoring sites and analyzed the difference between them.

AQI was used to define the air quality level, fluctuating from 0 to 500. To compute the AQI, the initial stage was to compute the fAQIs for the six criteria air pollutants, respectively. The highest value of the six criteria air pollutants was termed as AQI. The formula of fAQI is expressed as:

$$\mathrm{fAQI_a} = \frac{\mathrm{fAQI_{Hi}} - \mathrm{fAQI_{Lo}}}{\mathrm{TP_{Hi}} - \mathrm{TP_{Lo}}}\left(\mathrm{C_a} - \mathrm{TP_{Lo}}\right) + \mathrm{fAQI_{Lo}} \tag{1}$$

where $\mathrm{fAQI_a}$ and $\mathrm{C_a}$ are AQI and the concentration of one of the six criteria air pollutants. $\mathrm{TP_{Hi}}$ and $\mathrm{TP_{Lo}}$ are the nearest level of the $\mathrm{C_a}$ ($\mathrm{TP_{Hi}}$ is the highest one, $\mathrm{TP_{LO}}$ is the lowest one) (Table 1). $\mathrm{fAQI_{Hi}}$ and $\mathrm{fAQI_{Lo}}$ are equivalent to fAQI of the $\mathrm{TP_{Hi}}$ and $\mathrm{TP_{Lo}}$ (Table 2).

MAP was used to determine which air pollutants contributed more to air quality dilapidation. It was defined based on the Air Quality Index (AQI) scheme, using absorptions of specific contaminants. The air pollutants which showed maximum concentration in terms of AQI was then termed as the MAP.

2.2.3 Temporal variations of air quality in UFA

Temporal variations of the air quality in UFA can be used to indicate the ideal time to visit the UFA. During the study period, monthly and diurnal variations of the concentrations of MAP were revealed to demonstrate the temporal characteristics of air quality.

2.2.4 Correlations analysis

To obtain a comprehensive understanding of the air pollutants in UFA, we calculated the correlations of the MAP between CCA, SUA, EUA and UFA, and the correlations between meteorological factors and MAP. For the simplicity and effectiveness of R language, R was used to examine the Pearson correlation coefficients.

2.2.5 The source of the air pollutants in UFA

The conditional probability function (CPF) was applied to analyze the source of the air pollutants in UFA. Air pollutants data obtained from CNEMC, and the meteorological data from NOAA and NMIC were used to compute the directions of pollution sources of the UFA. $\mathrm{CPF}_{\Delta\theta}$ was computed using the following:

$$\mathrm{CPF}_{\Delta\theta} = \frac{c_{\Delta\theta}}{d_{\Delta\theta}}$$

where $c_{\Delta\theta}$ is the number of occurrences from the current air sector $\Delta\theta$ that had surpassed an inception measure, and $d_{\Delta\theta}$ is the aggregate figure of information from the identical breeze direction. The sources are probable to be positioned the directions laterally. In this study, we computed the possibility that the contaminant absorptions emanating from a given airstream subdivision ($\Delta\theta = 10°$) surpassed the standard rate for the major pollutants at the UFA in Fuzhou city. We used the software R to analyze these data.

3 Results

3.1 Air pollutants in Fuzhou city

The mean concentrations of the six criteria air pollutants in Fuzhou city during the study period are shown in Table 3 and Fig. 2. During the study period, the concentrations of SO_2, NO_2, CO and O_3 in Fuzhou were 5.93 μg/m^3, 28.62 μg/m^3, 0.70 mg/m^3 and 56.35 μg/m^3, respectively. These results were below the Grade I standard, set by CAAQS. However, the $PM_{2.5}$ and PM_{10} were relatively high. The concentrations of $PM_{2.5}$ in the six monitoring stations were all found to be below the Grade II standard. PM_{10} in Gushan and Yangqiaoxilu were 34.93 μg/m^3 and 49.41 mg/m^3, which was lower than the Grade I standard, but the other four monitoring sites, i.e., Kuaian, Shida, Wushibeilu and Ziyang had slightly exceeded the Grade I standard set by CAAQS. When compared to other cities in China (e.g., Beijing, Xi'an, Changsha, Zhengzhou and Hangzhou which are the provincial capital cities, like Fuzhou, with the highest economies and populations in their provinces (Wang et al., 2014)), our results showed that the air quality in Fuzhou city was relatively better.

Spatial variation of air pollutants found in Fuzhou city is shown in Fig. 2. In UFA, the average concentrations of all six air pollutants, except O_3, were significantly lower than in

Table 3 The concentrations (mass ± standard deviation) of the air pollutants in the six monitoring sites in Fuzhou city, from May 1st, 2014 to April 30th, 2017

Sites	Region category	AQI	$PM_{2.5}$ μg/m^3	PM_{10} μg/m^3	SO_2 μg/m^3	NO_2 μg/m^3	O_3 μg/m^3	CO mg/m^3
Gushan (GS)	UFA	42.13	23.21	34.93	5.02	15.36	77.95	0.58
Kuai'an (KA)	EUA	51.83	29.08	55.21	6.63	29.78	48.19	0.64
Shida (SD)	SUA	53.44	31.38	55.31	7.28	30.14	56.67	0.71
Wusibeilu (WSB)	CCA	51.01	28.21	55.95	5.52	32.94	51.01	0.73
Yangqiaoxilu (YQX)	SUA	48.06	26.79	49.41	5.40	30.02	53.59	0.75
Ziyang (ZY)	CCA	52.16	27.72	57.16	5.86	33.94	50.64	0.80
Average	CCA	51.59	27.97	56.56	5.69	33.44	50.83	0.77
Average	SUA	50.75	29.09	52.36	6.34	30.08	55.13	0.73
Average		49.66	27.62	51.49	5.93	28.62	56.35	0.70

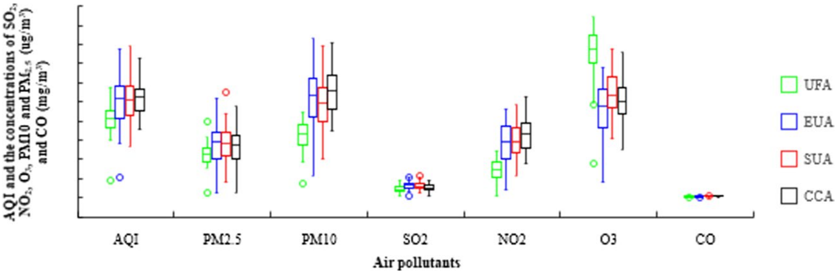


Fig. 2 The mean concentrations of the air pollutants in UFA, EUA, SUA and CCA of Fuzhou city

OUA. O_3 was highest in the UFA, followed by the EUA, CCA and SUA. The concentrations of NO_2 and CO, also showed significant spatial characteristics, i.e., NO_2 and CO were highest in the CCA, follow by the SUA, EUA and UFA. SO_2 was highest in SUA and EUA, followed by the CCA and UFA. $PM_{2.5}$ was highest in EUA, followed by SUA, CCA and UFA, but the difference was small. PM_{10} was higher in CCA and SUA than the EUA and UFA.

3.2 AR of air quality and the MAP in UFA and OUA of Fuzhou

Based on CAAQS, the AR in UFA was higher than EUA, followed by SUA and CCA (Fig. 3). The annual average AR was highest for the monitoring site of Gushan (in UFA) (64.12%), followed by Yangqiaoxi (in SUA) (51.03%), Ziyang (in CCA) (44.52%), Kuai'an (in EUA) (43.94%) Wusibei (in CCA) (42.67%) and Shida (in SUA) (42.22%). The AR also revealed different temporal pattern in the urban areas. Generally, the AR in the warm seasons (summer and fall) was higher than that in the cold seasons (spring and winter). In UFA and EUA, autumn was the season with the highest AR. CCA (ZY station and WSB station), also showed the same pattern, e.g., the highest AR appeared in fall, followed by summer, winter and spring. For SUA (SD station and YQX station), the highest AR was in summer during June 2014 to February 2015, but in fall AR was the highest in fall during March 2016 to February 2017. The seasonal variations in CCAs and SUA had significant

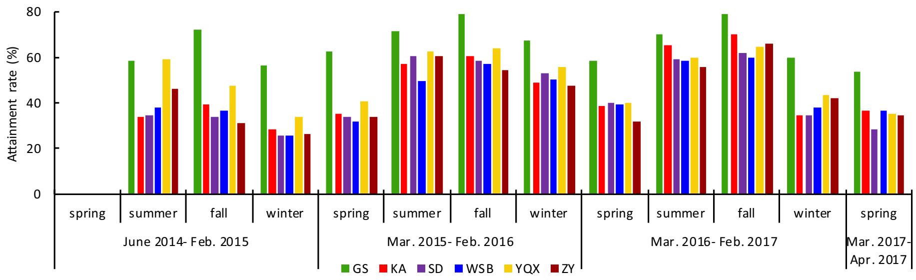


Fig. 3 Seasonal characteristics of the attainment rates in the six stations in Fuzhou city from May 1st, 2014 to April 30th, 2017. ZY and WSB in CCA, SD and YQX in SUA, KA in EUA, GS in UFA

amplitude, with the AR in warm seasons being almost twice as high as that in cold seasons. In addition, the annual mean AR of Fuzhou from 2014 to 2017 showed a slight increase.

PM_{10}, $PM_{2.5}$ and O_3 were the most frequent three MAP in Fuzhou (PM_{10} was the most frequent MAP, followed by $PM_{2.5}$ and O_3) (Fig. 4). CO, NO_2 and SO_2 occurred as the MAP were much less frequent. The frequencies of the MAP also showed spatial and temporal variations, e.g., O_3 as MAP was more frequent in UFA than OUA. For temporal variation, we found that in summer and fall, $PM_{2.5}$ as MAP was less frequent than that in spring and winter. In addition, during warm seasons, the O_3 occurred as the MAP more frequently than in cold seasons. (Fig. 4).

3.3 Temporal variation in the major air pollutants in UFA

3.3.1 The MAP in UFA

As mentioned above, the most frequent 3 MAP in the UFA was PM_{10} (with a rate of 16.24%), $PM_{2.5}$ (with a rate of 11.16%), and O_3 (with a rate of 2.76%). We compiled the fractions of the 3 MAP in the four seasons (Table 4). In all seasons except winter, PM_{10} was the most frequent MAP in the UFA, followed by $PM_{2.5}$ and O_3. In winter, the most frequent MAP was $PM_{2.5}$, (accounting for 19.89%). While PM_{10} was second (with a rate of 15.27%), and O_3 being third (with a rate of 0.10%). To an extent in the summer, PM_{10}

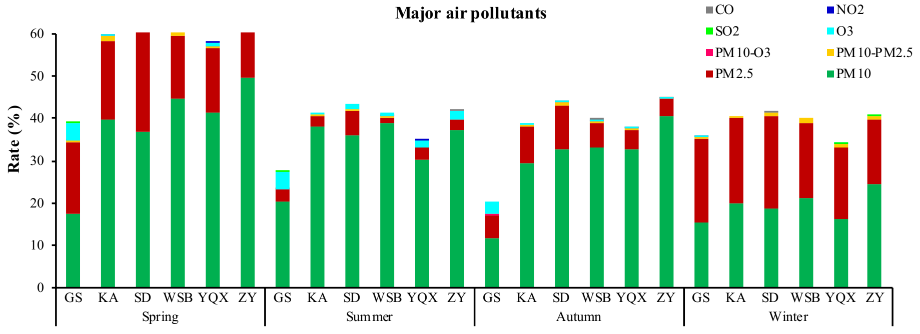


Fig. 4 Non-attainment rates and the MAP in the six stations of Fuzhou city. (The non-attainment rate is defined as the rates of hours where the concentration of the air pollutants exceed the Grade I value of CAAQS. "PM_{10}-$PM_{2.5}$" and "PM10-O3" means these two air pollutants exceed the standard at the same)

Table 4 The rate of the air pollutants as the MAP (%) in UFA from May 1st, 2014 to April 30th, 2017. (The non-attainment rate is defined as the rate of hours where the concentration of the air pollutants exceeds the Grade I value of CAAQS)

	$PM_{2.5}$ (%)	PM_{10} (%)	SO_2 (%)	NO_2 (%)	CO (%)	O_3 (%)	PM_{10}–$PM_{2.5}$ (%)	No attainment rates (%)
Spring	16.76	17.49	0.03	0	0	3.92	0.56	38.82
Summer	2.70	20.46	0.02	0	0	3.95	0.24	27.41
Autumn	5.27	11.72	0	0	0	3.09	0.28	20.40
Winter	19.89	15.27	0	0	0	0.10	0.58	35.85
Yearly	11.16	16.24	0.01	0	0	2.76	0.41	30.62

was the most frequent MAP (with a rate of 20.46%), with O_3 (with a rate of 3.95%) in second, and $PM_{2.5}$ being third (with a rate of 2.70%).

3.3.2 Monthly variation of the major air pollutants in UFA

Temporal variations of air quality in UFA is very important to the public, as it helps them decide the best time to visit urban green spaces. We show the temporal variations of the most frequent 3 MAP (PM_{10}, $PM_{2.5}$ and O_3) and AQI in Fig. 5. As shown in Fig. 5, the three major air pollutants and AQI showed distinct monthly peaks and seasonality. The peak concentrations of $PM_{2.5}$ and PM_{10} occurred in the cold seasons, and low concentrations of air pollutants occurred in the summer and autumn. As the AQI is the most affected by PM10 and PM2.5, the value of AQI also showed a similar monthly variation, e.g., higher in the warm seasons and lower in the cool seasons. O_3 showed the opposite monthly characteristics when compared to the other MAP, with high concentration appearing in warm seasons and low concentration in the cold seasons.

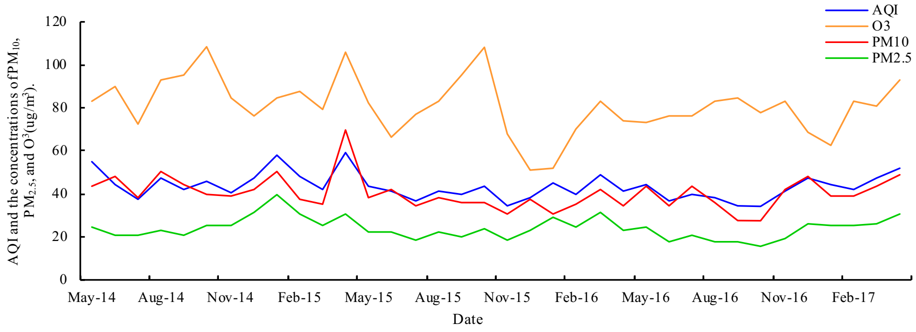


Fig. 5 Temporal variation of AQI and the concentrations of PM_{10}, $PM_{2.5}$ and O_3 in the UFA, Fuzhou, China from May 2014 to April 2017

3.3.3 Diurnal variation of the major air pollutants in UFA

For the three most frequent MAP (PM_{10}, $PM_{2.5}$ and O_3, as described in Sects. 3.2 and Sect. 3.3.1), diurnal variations of hourly mean concentrations were analyzed (Fig. 6). Generally, the diurnal characteristics of AQI and the concentrations of PM_{10} and $PM_{2.5}$ were similar in the four seasons: with two peaks at noon and at nightfall, and two valleys at the late afternoon and early morning, which generally exhibited a flat "M" shape. However, their amplitudes had large discrepancies between warm seasons and cold seasons. The daily trends of O_3 concentrations in UFA were almost similar among the four seasons with the peak value at noon and afternoon (10:00–18:00) and the valley value at early morning (6:00–8:00) and midnight (23:00–1:00). In addition, the weather during summer 2015 was mainly cloudy and rainy, which meant less sunshine and the concentration of O_3, being similar to the values found during winter 2014.

3.4 Correlations between the major air pollutants in UFA

3.4.1 Correlations of the MAP between CCA and SUA, EUA, UFA

The relationship of AQI and the concentrations of $PM_{2.5}$, PM_{10} and O_3 between CCA and UFA, SUA, EUA during the study periods were analyzed (Fig. 7). The relationship of AQI, the concentrations of PM_{10} and O_3 between CCA and SUA had higher coefficient of determination, followed by the value between CCA and EUA or UFA. This indicated that the relationship of AQI, PM_{10} and O_3 between CCA and SUA was significantly higher than the relationships between CCA and UFA, EUA. The relationship of $PM_{2.5}$ between CCA and SUA had higher coefficient, followed by the value between CCA and EUA, UFA. AQI, $PM_{2.5}$, PM_{10} and O_3 between CCA and SUA with coefficient higher than 0.80 were significantly better than that between CCA and EUA, CCA, UFA. This suggested that the sources of air pollution in UFA were inside the urban areas of Fuzhou city.

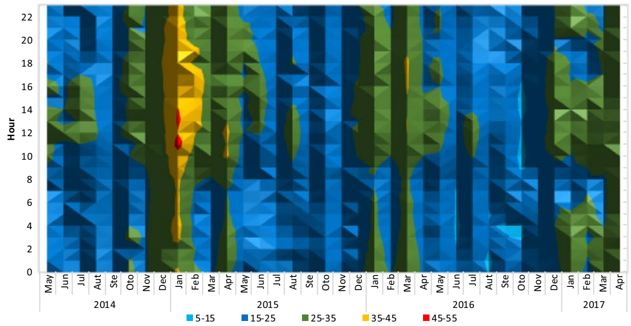
3.4.2 Correlation between the air pollutants

Pearson correlation coefficients (R) were also analyzed (Table 5). PM_{10}, $PM_{2.5}$ and SO_2 showed significant positive correlation with all other air pollutants, indicating that PM_{10}, $PM_{2.5}$ and SO_2 had similar sources. CO and NO_2 showed significant positive correlation with PM_{10} $PM_{2.5}$ and SO_2, and significant negative correlation with O_3.

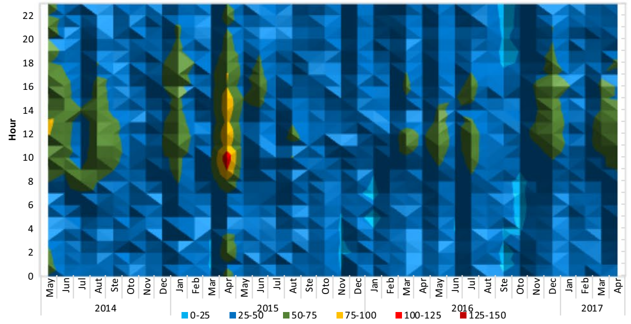
The Pearson correlation coefficient values with ** indicates a p value < 0.01.

3.4.3 Correlation between air pollutants and meteorological data

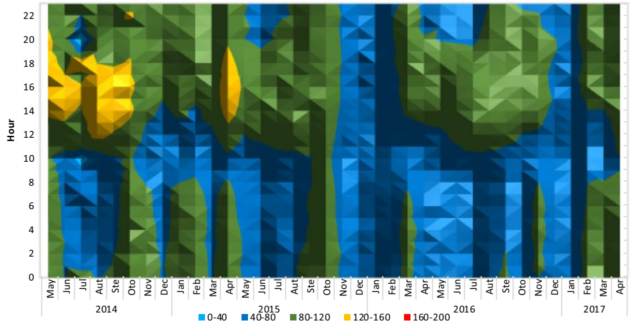
Overview of the meteorological data are shown in Table 6. R value between the meteorological factors and the air pollutants in UFA are shown in Table 7. Generally, PM_{10}, $PM_{2.5}$, SO_2, NO_2 and CO showed negative correlations with WS, T, CR and RF, and positive correlations with AP, RH. The R values of the correlation between O_3 and WS,



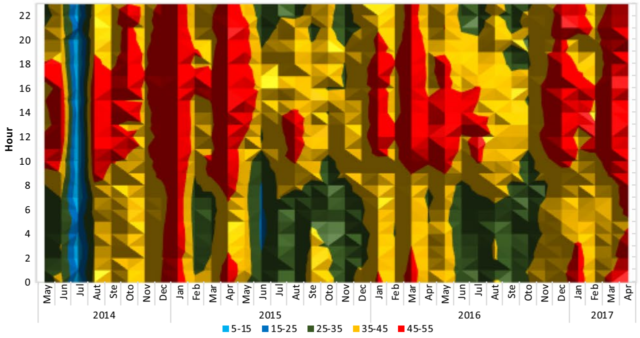
(a) PM2.5 (μg/m³)



(b) PM10 (μg/m³)

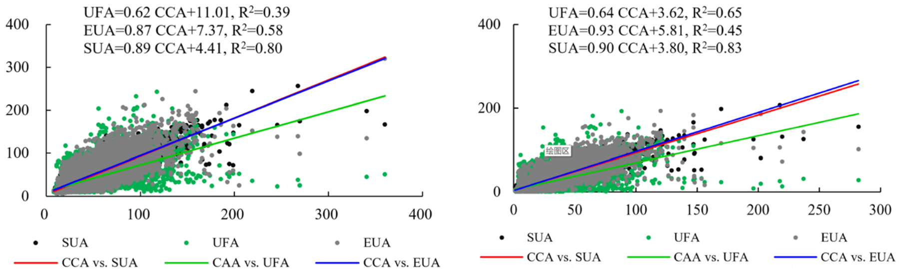


(c) O3 (μg/m³)

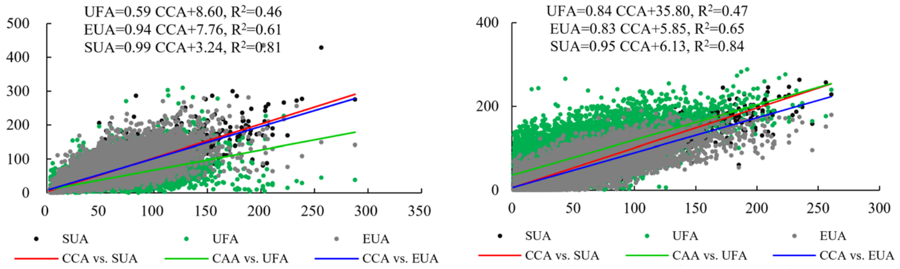


(d) AQI

Fig. 6 Diurnal and monthly variations of the concentrations of MAP in UFA of Fuzhou, during May 2014 and April 2017 **a** $PM_{2.5}$, **b** PM_{10}, **c** O_3 and **d** AQI



(a) AQI **(b)** $PM_{2.5}$



(c) PM_{10} **(d)** O_3

Fig. 7 Relationships of **a** AQI, **b** $PM_{2.5}$, **c** PM_{10} and **d** O_3 between city central area (CCA) and suburban areas (SUA), exurban areas (EUA) and urban forest areas (UFA) in Fuzhou during May 1st, 2014 and April 30th, 2017. R^2 means coefficient of determination

Table 5 Correlations of the criteria air pollutants in UFA

	PM_{10}	CO	SO_2	NO_2	O_3
$PM_{2.5}$	0.86**	0.40**	0.37**	0.34**	0.24**
PM_{10}		0.28**	0.32**	0.39**	0.26**
CO			0.17**	0.45**	−0.13**
SO_2				0.21**	0.17**
NO_2					−0.36**

Table 6 Overview of the meteorological data in UFA

	Min	Max	Ave	SD
Meteorological data				
WS	0.00	12.00	2.26	1.27
T	−0.13	38.30	20.61	7.23
CR	0.00	100	47.63	45.97
AP	739.00	779.60	761.48	10.50
RH	18.00	99.00	75.53	15.61
RF	0.00	114.00	0.68	4.07

Table 7 Correlations between air pollutants and meteorological factors in UFA

	WS	T	CR	AP	RH	RF
Air pollutants						
$PM_{2.5}$	−0.16**	−0.24**	−0.14*	0.14*	0.16**	−0.10*
PM_{10}	−0.09*	NS	NS	0.52**	0.25**	−0.15*
CO	−0.15**	−0.09*	0.13*	NS	0.14*	NS
SO_2	NS	−0.22**	NS	NS	0.31**	NS
NO_2	−0.37**	−0.26**	NS	NS	0.22**	NS
O_3	0.30**	NS	−0.43**	NS	0.57**	−0.38**

**means the p value < 0.01, * means significant at $p < 0.05$ and NS means no significant correlation

CR, RH and RF were 0.30, -0.43, 0.57 and -0.38, respectively. In this study, AP showed no significant correlation with the air pollutants, except with PM_{10} and $PM_{2.5}$.

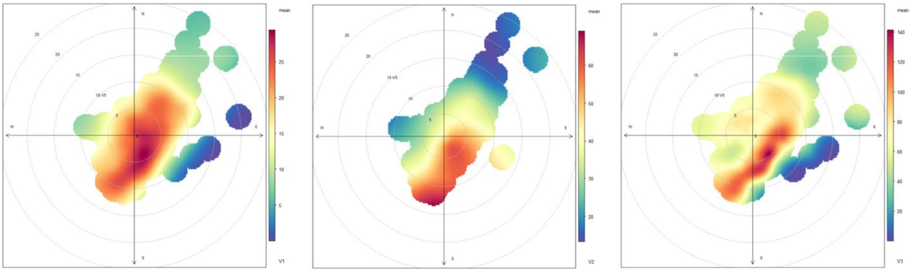
3.5 Effect sources of the air pollutants in UFA

The CPF plots of the most frequent 3 MAP ($PM_{2.5}$, PM_{10} and O_3) during the study period are shown in Fig. 8, which revealed the potential sources of the 3 MAP in UFA. The CPF plots of $PM_{2.5}$, PM_{10} and O_3 showed similar patterns, which exhibited that $PM_{2.5}$, PM_{10} and O_3 may be affected by the same factors. PM_{10} exhibited a slightly different pattern with $PM_{2.5}$ and O_3, which meant the source of PM_{10} may be different for $PM_{2.5}$ and O_3. Generally, higher values of the 3 MAP concentrations had similar direction (i.e., southerly direction), which was significantly associated with the pollutant emissions from higher population density areas, e.g., CCA and SUA.

4 Discussion

4.1 Overview of air quality in Fuzhou city

During the study period, it was found that the air quality in Fuzhou was relatively better when compared to other cities in China (Wang et al., 2014). In Fuzhou, the annual mean concentrations of the six criteria air pollutants, except PMs, were relatively low (according



(a) PM2.5 **(b)** PM10 **(c)** O3

Fig. 8 CPF plots of **a** $PM_{2.5}$, **b** PM_{10} and **c** O_3 in UFA, from May 1st, 2014 to April 30th, 2017 to CAAQS, the concentrations were below the Grade I standard), which indicated that SO_2, NO_2, CO and O_3 had limited negative influence on public health. The concentrations of $PM_{2.5}$ and PM_{10} were below the Grade II standard. The reasons for low concentration of air pollutants in Fuzhou could be the following: 1) the industry in Fuzhou city is mainly light industry (Light industry accounts for 67.90% of industry), which means low levels of industry sourced air pollutants (http://tjj.fuzhou.gov.cn/zz/fztjnj/2020tjnj/zk/indexch.htm); 2) the urban areas of Fuzhou are located along the river and ocean; 3) the urban areas of Fuzhou are located in a subtropical climate with high WS and high frequency of RF, which creates condition for diluting air pollutants; and 4) the forest coverage rate in Fuzhou city is one of the highest among cities in China (Chinese yearbook, 2016).

4.2 Air quality in UFA of Fuzhou city

4.2.1 Air quality in UFA is better than OUA

The air pollutants, except O_3, were found to be lower in UFA than in OUA. Our results, to some extent, support the conclusion that UFA have better air quality (Akpinar, 2016; Chen et al., 2019; Jayasooriya et al., 2017; Mytton et al., 2012). Studies of different research scales and study methods revealed similar results, e.g., Chen (2019) studied five Chinese megacities and revealed that higher green space coverages displayed lower $PM_{2.5}$ concentrations at the neighborhood scale (Chen et al., 2019). However, studies in Australia, USA, and some European countries found that urban forests have the highest percentage uptake for O_3 when compared to the total pollutant uptake, which differed from our results (Sicard et al. 2018; Jayasooriya et al., 2017). This can be explained as follows: 1) Urban forests have their limit in the deposition capability. In Fuzhou city, even though the air quality is higher than the most cities in China, the air pollutant concentration is still higher than that in cities in developed countries. This indicates that, in order to mitigate the air pollution in urban areas, urban forest can be a solution, but should not be seen as the sole solution. 2) Studies have stated that biogenic volatile organic compounds (BVOCs) emitted by certain plant species increased the O_3 concentration (Denning, 2006). O_3 formation requires BVOCs, NOx and radiation energy and some time (Calfapietra et al. 2013). Thus, O_3 formation due to BVOCs might happen in a kilometer or more distance from the monitor station. In contrast, the higher O_3 concentrations in UFA that are sometimes observed (Cohen et al. 2014) may simply result from trapping air pollutants below the canopy of the trees (Li et al. 2018). Some observations also reported lower O_3 in parks and forests because BVOCs might be not so reactive (García-Gómez et al. 2016).

4.2.2 The attainment rate and major air pollutants in UFA

The major air pollutant in UFA was $PM_{2.5}$, PM_{10} and O_3, similar to what has been found by previous studies in other cities in China (Guo et al., 2019; Wang et al., 2014; Yan et al., 2016) and the Santiago Metropolitan Region (Chile) (Escobedo & Nowak, 2009), i.e., all cities facing serious air pollution. The MAPs in UFA of Fuzhou were significantly different than the areas of Strasbourg (France) (Selmi et al., 2016) and ten North American cities (Nowak et al., 2013), all of which have higher air quality. Previous studies found that in Fuzhou, the primary factor contributing to air pollution in urban areas was vehicular emission, which was also the source affecting the air quality in UFA (Wu et al., 2015a; Xu, Chen, Chen, Zhang, He, & Du et al. 2012; Xu et al., 2012a, 2012b; Xu et al., 2013).

4.2.3 Temporal variation of the MAP in UFA

The monthly variation of PM_{10}, $PM_{2.5}$, SO_2, NO_2 and CO showed similar patterns (Fig. 2), reflecting the effects of meteorological factors and anthropogenic emissions, e.g., fast winds and frequent rain in the summer blows off and cleans up the air pollutants, which leads to higher air quality. Similarly, airflow from the ocean and forest areas bring higher air quality and cleans up air pollutants in Fuzhou (Niu et al., 2013; Wu et al., 2015a; Xu et al., 2013, 2012a, 2012b). O_3 formation rates depend on the peroxide concentration and intensity of solar radiation (Bai, 2014; Guo et al., 2019). In UFA, O_3 showed an opposite seasonal variation, with the highest concentration occurring in warm seasons and the lowest in cold seasons. In the warm seasons, under the conditions of strong sunlight, O_3 concentration was relatively high; in cold seasons, under the conditions of weak sunlight, the O_3 concentration was relatively low. This indicated that the concentration of peroxide was relatively high in UFA. Solar radiation intensity, terrain and air pollutants have been found to impact the variations of O_3 concentrations(Escobedo & Nowak, 2009; Guo et al., 2019; Jayasooriya et al., 2017; Leung et al., 2011; Ma, Ban, Wang, & Li, 2020; Mytton et al., 2012; Selmi et al., 2016; Wang et al., 2014; Yan et al., 2016; Bai, 2014). In addition, high O_3 concentrations in UFA reflected local resident emissions, while transportation emissions and industry emissions affected the concentrations of O_3 lingering in UFA.

For daily variation, due to air pollutant deposition and less human activity, the first valley (low concentration of air pollutants) occurred in the early morning. The second valley appeared in the late afternoon (at around 17:00) due to the relatively high temperature and low humidity, which was a condition for the air pollutants to disperse and become diluted (Niu et al., 2013; Wang et al., 2014; Xu et al., 2012a, 2012b; Yan et al., 2016; Zhao, Zhang, Xu, & Zhao, 2011). Correspondingly, peaks of the pollutants appeared around 9:00–10:00 and ~ 13:00, the peak time for vehicle emissions which showed that the bimodal peaks of $PM_{2.5}$ and PM_{10} appeared at similar times, which reflected that the pollutant sources may be similar between $PM_{2.5}$ and PM_{10}. Additionally, the amplitude of $PM_{2.5}$ was closer to the vehicle emission times than that of PM_{10}, which indicated that compared to PM_{10}, $PM_{2.5}$ concentration was influenced greatly by vehicle emissions in UFA during the study periods.

4.3 Correlation analysis

The results between the concentrations of PM_{10}, $PM_{2.5}$, SO_2, NO_2 and CO showed significant positive correlation in UFA. This means that to some extent, the sources of air pollutants in UFA are similar. Proper control of pollution sources will significantly improve air quality. Studies in other Chinese cities showed similar results (Chang et al., 2015; Deng et al. 2014; Fu et al., 2018; Guo et al., 2019; Leung et al., 2011; Niu et al., 2013; Wang et al., 2014; Xu et al., 2012a, 2012b; Xu et al., 2012a, 2012b; Xu et al., 2013; Yan et al., 2016; Zhang et al., 2013; Zhang et al., 2019; Zhao et al., 2011; Zhao et al., 2018; Zhu et al., 2020). However in this study, the R value between PMs and other air pollutants was lower than that found in other studies. This may be because the formation of PMs in UFA was impacted by the meteorological factors (i.e., T, sunlight, RH, WS and AP) (Akpinar, 2016; Leung et al., 2011; Selmi et al., 2016; Sugiyama et al., 2018) revealed the relationship between AQI and meteorological factors at different stages of development also showed the similar result.

4.4 Effect sources of the air pollutants in UFA

Studies have found that agricultural activities, vehicle emissions, cooking and industrial activities are the sources of air pollutants in most urban areas over the world (Chen et al., 2019; Fu et al., 2018; Guo et al., 2019; Niu et al., 2013; Nowak et al., 2013; Xu et al., 2012a, 2012b; Xu et al., 2012a, 2012b; Zhang et al., 2013). Deng et al. (2014) found that industry activity and vehicle emissions played a primary role of the top 3 MAP concentrations in Fuzhou (Deng et al. 2014). In our study, the CPF plots of $PM_{2.5}$, PM_{10} and O_3 (top 3 MAPs) in UFA indicated the sources were in the CCA and SUA, much in line with the findings of previous studies (Xu et al., 2012a, 2012b; Chen et al., 2019; Nowak et al., 2013; Ma et al. 2019). In Fuzhou, resident densities in the CCA and SUA were higher than the EUA and UFA, which may concentrate residents' emissions and result in air pollutant sources largely occurring in the CCA and SUA (Chang et al., 2009; Wang et al., 2014; Xu et al., 2012a, 2012b; Xue et al., 2015) Furthermore, the complex topography (UFA surround the urban areas of Fuzhou) also significantly impacted the three major air pollutant distributions in the UFA of Fuzhou(Deng et al. 2014; Wu et al., 2015a; Xu et al., 2012a, 2012b; Xu et al., 2012a, 2012b).

4.5 Limitations

The current study aimed to compare the air quality of UFA and OUA and reveal the characteristics of the air quality in the UFA. However, this study did not define pollution removal rates. In future, related studies need to compare the air pollutants between adjacent CCA and UFA sites at different places and the sites of UFA (e.g., tree density, size or species).

5 Conclusions

In the current study, $PM_{2.5}$, PM_{10}, CO, SO_2, NO_2 and O_3 levels were investigated at six monitoring stations in Fuzhou between May 1st, 2014 and April 30th, 2017. As the different monitoring sites are set in different urban areas of Fuzhou, this study aimed to reveal a comprehensive understanding of the ambient air quality in the UFA of Fuzhou city by analyzing the differences of the six air pollutants between UFA and OUA. Results showed that compared to the most other cities in China, the concentrations of criteria air pollutants were relatively lower in Fuzhou city. This is because the industry in Fuzhou city is mainly light industry; Fuzhou is located along the river and ocean; Fuzhou is located in a subtropical climate with high WS and high frequency of RF, and the forest coverage rate in Fuzhou city is one of the highest among cities in China. During the study period, air quality in UFA was indeed higher than OUA. Policies to improve urban air quality should focus on the control of pollution sources in urban and suburban areas in the CCA and SUA. The concentration of O_3 in UFA was higher than OUA. The reasons may be as follows: Urban forests have their limit in the deposition capability; O_3 diffuses slowly and the surrounding mountains affect the diffusion of O_3, more studies will be necessary. The correlations of the MAP between UFA and OUA, suggested that the source of air pollution was inside the urban areas of Fuzhou city.

This study reveal a comprehensive understanding of the concentrations of air pollution in UFA and OUA. The results showed that air pollution in urban areas caused by multiple pollutants, and the air pollution shows great spatial and temporal divergence in urban areas. Region-oriented air pollution management plans are highly suggested. Further investigation should focus on the spatial variations in the UFA, as this will provide more in-depth understanding of the role of, e.g., green space composition, different types of vegetation and tree species composition on the mitigation of air pollutants.

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Author Contribution WF, JD and YQ conceived and designed the study; WF, CCK, ZC and HC analyzed the data and discussed the results; YL, QL and XX discussed the results, and WF and YQ wrote the paper.

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Declarations

Conflicts of interest The authors declared that they have no conflict of interest.

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