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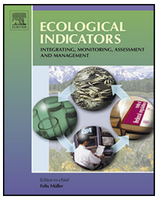

Characterizing spatiotemporal patterns of air pollution in China: A multiscale landscape approach

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ABSTRACT

China's tremendous economic growth in the past three decades has resulted in a number of environmental problems, including the deterioration of air quality. In particular, fine particulate matter (PM) has received increasing attention from scientists, governmental agencies, and the public due to its adverse impacts on human health. Monitoring the spatiotemporal patterns of air pollution is important for understanding its transport mechanisms and making effective environmental policies. The main goal of this study, therefore, was to quantify the spatial patterns and movement of air pollution in China at annual, daily, and hourly scales, so that the underlying drivers could be better understood. We used remote sensing data and landscape metrics together to capture spatiotemporal signatures of air pollution. Our results show that, at the annual scale, $PM_{2.5}$ concentrations in China increased gradually from 1999 to 2011, with the highest concentrations occurring in the North China Plain as well as the middle and lower reaches of the Yangtze River Basin. The total population affected by air pollution was about 975 million in 2010 (about 70% of China's population). Our more detailed analysis on daily and hourly scale further revealed that a heavy air pollution event occurred, expanded, aggregated, and finally dissipated over Northern China during Oct. 6–12, 2014, suggesting that the Beijing-Tianjin-Hebei region a center of severe pollution. Crop stalks burning in agricultural areas in this region seemed to be one of the leading drivers, along with coal burning and transportation emissions. Our study demonstrates that spatial pattern analysis with landscape metrics is effective for analyzing source-sink dynamics of air pollution and its potential drivers. Our findings of major source areas and movement trajectories should be useful for making air pollution control policies to improve China's air quality.

1. Introduction

China is the most populous country in the world, with more than half of its population now living in cities since 2010 (Liu et al., 2014; Wu et al., 2014). During the past three decades, the concurrent rapid economic growth and urbanization in China are unprecedented in terms of both speed and scale (Ma et al., 2016a; Wu et al., 2014), and have resulted in a number of environmental problems, including the deterioration of air quality in many urban regions across the nation (Huang, 2015; Lue et al., 2010; Shao et al., 2006). Air pollution can have both acute and chronic effects on human health, ranging from reversible respiratory problems to lung and heart failure-related mortality (Cox, 2013; Folinsbee, 1993; Kampa and Castanas, 2008; Lave and Seskin, 1970; Pant et al., 2016; Phung et al., 2016; Tsangari et al., 2016). For instance, increased air pollution due to fine particulate matter smaller than 2.5 micrometers ($PM_{2.5}$) may lead to the cardiopulmonary morbidity and mortality of people (Lelieveld et al., 2015; Pope and Dockery, 2006; Schwartz et al., 1996; Wu et al., 2014). A recent Chinese case study concluded that the reduction in life expectancy of about 3 years may be expected from long-term exposure to an additional 100 $\mu g/m^3$ of Total Suspended Particles (TSPs) (Chen et al., 2013). Especially for elder persons, their relative risks for deaths could be larger than for all ages (Schwartz et al., 1996).

In 2012, the Ministry of Environmental Protection of the People's Republic of China (MEP) updated National Ambient Air Quality Standards, which for the first time included $PM_{2.5}$ (MEP, 2012a).

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Table 1
Air Quality Index categories, air pollution levels, and health implications (MEP, 2012b).

AQI	Air pollution level	Health implications
0–50	Excellent	No harm to human health
51–100	Good	Hypersensitive individuals should limit the outdoor activities
101–150	Light Pollution	Children, elder and people with breathing or heart problems should reduce outdoor activities
151–200	Moderate Pollution	Children, elder and people with breathing or heart problems should avoid outdoor exercise
201–300	Heavy Pollution	Children, elder and people with breathing or heart problems should stop outdoor exercise
>300	Severe Pollution	Children, elder and people with breathing or heart problems should stay indoors

Table 2
Air quality standards for specific air pollutants (MEP, 2012b).

IAQI (No unit)	SO_2 ($\mu g/m^3$)	NO_2 ($\mu g/m^3$)	CO (mg/m^3)	O_3 (mg/m^3)	PM_{10} ($\mu g/m^3$)	$PM_{2.5}$ ($\mu g/m^3$)
0	0	0	0	0	0	0
50	50	40	2	100	50	35
100	150	80	4	160	150	75
150	475	180	14	215	250	115
200	800	280	24	265	350	150
300	1600	565	36	800	420	250
400	2100	750	48	–	500	350
500	2620	940	60	–	600	500

Chinese Meteorological Administration (CMA) also updated early-warning standards for air pollution, and expanded the indicator set to include $PM_{2.5}$ concentration, horizontal visibility, and relative humidity (CMA, 2013). The threshold to define and forecast haze days is 75 $\mu g/m^3$ of 24-h mean $PM_{2.5}$ concentration according to the World Health Organization (WHO, 2005). CMA (2013) defined this threshold as 115 $\mu g/m^3$ of 24-h mean $PM_{2.5}$ concentration with relative humidity of higher than 80% and horizontal visibility of less than 3 km, or 150 $\mu g/m^3$ of 24-h mean $PM_{2.5}$ concentration with horizontal visibility of less than 5 km. As per the Chinese standard, the total number of haze days in 2013 was more than 70 in most of China's megacities, including Beijing, Tianjin, Shanghai, Guangzhou, Shenzhen, and a dozen other densely populated urban areas (MEP, 2013). In general, the increase of air pollution in China was a result of human activities such as economic developments (Xu et al., 2016), industrial emissions (Wang et al., 2012a), burning of coal for heating (Tao et al., 2014), and burning of crop stalks (Shi et al., 2014). Rapid urbanization and urban patterns/forms also have impacts on urban air quality (Bereitschaft and Debbage, 2013; Lv and Cao, 2011). Sprawl cities tend to generate more transportation emissions of pollution than more compact cities with mixed land uses (Borrego et al., 2006; Martins, 2012).

To clarify the relationship between air pollution and human health, it is necessary to monitor and quantify the spatiotemporal patterns of air pollution, as well as to understand its transport mechanisms (Blanchard et al., 2011; Yuan et al., 2014; Zhang et al., 2010). Towards this end, observations from air quality monitoring stations are crucial (Cheng et al., 2013; Tao et al., 2014; Wang et al., 2014), but the site-specific measurements must be scaled up to obtain spatial distributional patterns of air pollutants on landscape and regional scales (Pope and Wu, 2014a,b). The accuracy of quantifying air pollution patterns depends on both the density and configuration of the ground stations within a monitoring network, and is also influenced by the scale of analysis in space and time (Pope and Wu, 2014a; Wu, 1999). Air quality monitoring networks provide high temporal resolution data, but their spatial coverage is usually constrained by physical, fiscal, and technical factors (Pope and Wu, 2014b).

To complement the ground-based monitoring data, satellite-based or airborne observations covering broad areas have become increasingly available in recent decades (Tao et al., 2012). Studies have shown that Aerosol Optical Depth (AOD) from satellite observations and PM_{10}/$PM_{2.5}$ concentrations from ground stations are highly correlated (Engel-Cox et al., 2004; Green et al., 2009; Lee et al., 2011; Ma et al., 2016b; van Donkelaar et al., 2006; Wang and Christopher, 2003; Wang et al., 2010b). Based on this correlation, van Donkelaar et al. (2010) and Ma et al. (2016b) derived spatial patterns of annual $PM_{2.5}$ concentrations, indicating that the annual $PM_{2.5}$ concentrations of eastern China exceeded 80 $\mu g/m^3$, which was much higher than the WHO standard of 35 $\mu g/m^3$. In addition to ground and airborne monitoring, remote sensing and Chemical Transport Models (CTMs) have also been used for characterizing the spatiotemporal patterns and simulating the emergence, expansion, and dissipation of the air pollution (Cuchiara et al., 2014; Wang et al., 2012a; Wang et al., 2012b; Wang et al., 2010a; Yahya et al., 2014). For example, such modeling studies have indicated that local emissions (Shi et al., 2014), regional transport (Lue et al., 2010), and secondary aerosol generation (Huang et al., 2014) were the main sources of air pollution, whereas local climate conditions such as high humidity and low wind speed were the key environmental controls (Zhang et al., 2009).

The main objective of this study was two-fold: (i) to quantify the spatial patterns of air pollution on multiple time scales (annual, daily, and hourly) using landscape metrics; and (ii) to identify the potential source and sink regions and drivers of air pollution.

2. Methods

2.1. Data on $PM_{2.5}$

The annual $PM_{2.5}$ concentrations in China were retrieved from the AOD products of MODIS (Moderate Resolution Imaging Spectroradiometer) and MISR (Multiangle Imaging Spectroradiometer) (van Donkelaar et al., 2015). The relationship between total-column AOD and surface dry $PM_{2.5}$ concentrations required a conversion factor which depends on 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 parameters were obtained through simulations using the GEOS-Chem model (van Donkelaar et al., 2010; van Donkelaar et al., 2006). A three-year running median was used to reduce noise in the annual satellite-derived $PM_{2.5}$ concentration from 1999 to 2011 (van Donkelaar et al., 2015).

2.2. Air quality index

Data on Air Quality Index (AQI) from China's national air quality stations in 161 cities during October 6–12 of 2014 were down-