Short communication

City as a major source area of fine particulate (PM_{2.5}) in China Lijian Han, Weiqi Zhou^{*}, Weifeng Li

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ARTICLE INFO

Article history:

Received 20 March 2015

Received in revised form

23 June 2015

Accepted 27 June 2015

Available online 12 July 2015

Keywords:

Urbanization

Urban air quality

Land cover

Health risk

Susceptible population

ABSTRACT

The PM_{2.5} concentration in 31% of China's territorial areas was less than 10 µg/m³, and in 26% of China's territorial areas was higher than 35 µg/m³. High concentrations of PM_{2.5} were found in the East China Plain, Sichuan province, and the Taklimakan desert. East China Plain was also found with strong significant positive trends. 73% of artificial surface (L01) was found with significant positive trends, but only 2% with significant negative trends. 76% of cropland (L02) was observed with significant positive trends, but only 2% with significant negative trends. The mean significant trends of PM_{2.5} concentration were 1.81 µg/m³·year for L01 and 1.71 µg/m³·year for L02, higher than that for the rest land covers. The PM_{2.5} pollution brought potential health risk to susceptible population: only 1% of them lives at a safe level (<10 µg/m³), but 69% of them were exposed to heavy PM_{2.5} pollution (>35 µg/m³).

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1. Introduction

Since the establishment of “Chinese economic reform” in late 1970s, China's economy has been growing rapidly. Along with the booming economy, the urbanization level has increased from 18% in 1978 to 52% in 2012, and is projected to be 65% in 2030 (Zhu et al., 2011). China's rapid urbanization in such a short period has not only improve the material wealth and living standard, but also caused several environmental problems, particularly air pollution in recent decades (Han et al., 2014; Chan and Yao, 2008; Huang et al., 2009).

Severe air pollution can be clearly observed by satellite measurements over China and India, particularly in China (van Donkelaar et al., 2010, 2015). China's air pollution has become severe due to the shift of energy structure and increase of intensive human activity caused by rapid urbanization (Han et al., 2014). With these shifts in cities, the primary air pollutant changed from the traditional pollutants (NO₂, SO₂) to new pollutants (e.g. PM_{2.5}) (Han et al., 2015). High concentration of PM_{2.5} can result in visibility impairment (Hyslop, 2009) and threaten public health (Pope and Dockery, 2012), and thus attracted special concern by both governmental agencies and common citizens, particularly those who lives in cities. Only 24 of 350 prefectures in China had annual PM_{2.5} concentrations within the air quality guidelines of the World

Health Organization (AQG of WHO, 10 µg/m³), whereas 165 prefectures had annual PM_{2.5} concentrations higher than the WHO Interim Target-1 (IT-1; 35 µg/m³) based on the annual averaged remotely sensed measurements of PM_{2.5} concentration during 2001–2006 (Han et al., 2014). Such level of PM_{2.5} concentration can also bring negative impact on population, especially the susceptible population (Brunekreef and Holgate, 2002).

Vary rare studies have used limited ground measurement, model simulation, and satellite imagery to suggest that urban human activity is a major cause of PM_{2.5} in China (van Donkelaar et al., 2010, 2015; Han et al., 2014). Therefore, quantification of how PM_{2.5} concentration varies for different land covers, as well as the intensity of pollution in cities was needed. This information is essential for China to achieve the goals of the Long-term Plan for Controlling Air Pollution and the National New-type Urbanization Plan (Bai et al., 2014). The objectives of this research were 1) to examine the mean spatial pattern and changes of PM_{2.5} concentration for different types of land cover in China during 1998–2012, and 2) to quantify the susceptible population exposed to PM_{2.5} pollution.

2. Materials and methodology

2.1. China land cover

The new version of the Global Land Cover-SHARE dataset (GLC-SHARE) combined various land cover results to form a standard

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dataset with overall accuracy of 80.2%, providing an improved understanding of global and regional land cover conditions. In our research, China land cover was clipped from the GLC-SHARE Beta-Release Version 1.0-2014 (Available at: http://www.glc.cn.org/databases/lc_glcshare_downloads_en.jsp). The dataset has eleven land cover classes: artificial surface (L01), which represents cities; cropland (L02); grassland (L03); tree covered area (L04); shrubs covered area (L05); herbaceous vegetation, aquatic or regularly flooded (L06); mangroves (L07); sparse vegetation (L08); bare soil (L09); snow and glaciers (L10), and waterbodies (L11). By considering the portions and potential for contribution to $PM_{2.5}$ emission, we selected eight land covers (Fig. 1), L01, L02, L03, L04, L05, L06, L08, and L09, to examine the mean and trend of $PM_{2.5}$ concentration difference among land covers.

2.2. Mean spatial pattern and trends of $PM_{2.5}$ concentration

The global $PM_{2.5}$ concentration dataset was estimated by an optimal estimation algorithm that combines MODIS observation of top-of-atmosphere reflectance with prior $PM_{2.5}$ concentration from the GEOS-Chem chemical transport model. To reduce the errors, a three years' annual moving average were adopted in this research during 1998–2012; significant agreement between satellite-derived estimates and ground-based measurements, including many ground measurements in China, outside North America and Europe was obtained ($r = 0.81$, slope = 0.68) (van Donkelaar et al., 2010, 2013, 2015). It thus provided a more extensive $PM_{2.5}$ concentration dataset for our study at a large regional scale. We then calculated the trend in China using a least squares model, and taking the trends in areas with both significance ≤ 0.05 and $R^2 \geq 0.4$ in this analysis to reduce the uncertainty of the changes.

Then, the mean spatial pattern and the trends of $PM_{2.5}$ concentration during 1998–2012, were analysed for different land covers. Portions having significant increase and decrease trends, and non-significant trends were evaluated, and the mean significant trends for different land covers were obtained.

2.3. Susceptible population exposed to various $PM_{2.5}$ concentrations in 2010

The population records in 2010 were obtained from the national population census report by the National Bureau of Statistics of the People's Republic of China (available at <http://www.stats.gov.cn/tjsj/pcsj/>). The population with ages younger than 14 and older than 60 was defined as the susceptible population in each prefecture to quantify the impact to the population in China.

The World Health Organization's air quality standard was adopted in our analysis. It has four levels, including the Air Quality Guide line (AQG; $>10 \mu\text{g}/\text{m}^3$), Interim Target-1 (IT-1; $35 \mu\text{g}/\text{m}^3$), Interim Target-2 (IT-2; $25 \mu\text{g}/\text{m}^3$), and Interim Target-3 (IT-3; $15 \mu\text{g}/\text{m}^3$). Because there are no clear standard for $PM_{2.5}$ concentrations beyond $35 \mu\text{g}/\text{m}^3$, we therefore set additional levels at equal intervals of $15 \mu\text{g}/\text{m}^3$ up to $95 \mu\text{g}/\text{m}^3$ to estimate the potential health impact on the susceptible population.

3. Results and discussion

3.1. Mean spatial pattern of $PM_{2.5}$ concentration, 1998–2012

High concentration of $PM_{2.5}$ was found in three areas of China (Fig. 2A): 1) the East China Plain, from Beijing-Tianjin in the north to Anhui and Jiangsu provinces, as well as eastern Hubei province in the south; 2) Eastern Sichuan province; and 3) the Taklimakan desert. The $PM_{2.5}$ concentration in 31% of China's territorial areas, which are mainly low population density areas, were less than $10 \mu\text{g}/\text{m}^3$, which is the AQG of WHO; and the $PM_{2.5}$ concentration in 26% of China's territorial areas, which are mainly high population density urban areas, were higher than $35 \mu\text{g}/\text{m}^3$, which is beyond the IT-1 of WHO. Only 1% of L01 and L08 had $PM_{2.5}$ concentration within the AQG of WHO, but 53% and 49% of L01 and L08, respectively, had $PM_{2.5}$ concentration beyond WHO IT-1. Similarly, only 4% of L04 had $PM_{2.5}$ concentration within the AQG of WHO, but 60% of L04 had $PM_{2.5}$ concentration beyond WHO IT-1, and, nearly 60% of L02 had $PM_{2.5}$ concentration beyond the WHO IT-1 (Fig. 2B).

Fig. 1. Land cover of China.

3.2. Trends of $PM_{2.5}$ concentration, 1998–2012

Areas with strong significant positive trends were obtained in the East China Plain, in southern Hebei province, and Shandong province. Moreover, some significant negative trends were observed in the conjunction between the Ningxia Hui Autonomous Region and Shaanxi province, and between the Xinjiang Uyghur Autonomous Region and Gansu province (Fig. 3A). 73% of L01 were found with significant positive trends, but only 2% were found with significant negative trends. 76% of L02 were observed with significant positive trends, but only 2% were found with significant negative trends. Less than 40% of L03, L06, L08, and L09 were observed with significant trends (Fig. 3B). Mean significant trends of $PM_{2.5}$ concentration were $1.81 \mu\text{g}/\text{m}^3 \cdot \text{year}$ at L01 and $1.71 \mu\text{g}/\text{m}^3 \cdot \text{year}$ at L02 higher than that at the rest land covers which were observed with less than $0.60 \mu\text{g}/\text{m}^3 \cdot \text{year}$. In addition, the lowest mean significant trend of $PM_{2.5}$ concentration was $0.22 \mu\text{g}/\text{m}^3 \cdot \text{year}$ at L09 (Fig. 3B).

3.3. Susceptible population exposed to various $PM_{2.5}$ concentration in 2010

The diverse mean spatial pattern of $PM_{2.5}$ concentration posed potential health risks to the susceptible population (Fig. 4). In 2010, only 1% of the susceptible population lived in areas within the AQG of WHO, with 7%, 9%, and 14% of the susceptible population within areas at the IT-3, IT-2, and IT-1 standards of WHO, respectively. By contrast, 69% of the susceptible population was exposed to heavy $PM_{2.5}$ pollution: 20%, 18%, 16%, 12%, and 3% of the susceptible population was exposed to $35\text{--}50 \mu\text{g}/\text{m}^3$, $50\text{--}65 \mu\text{g}/\text{m}^3$, $65\text{--}80 \mu\text{g}/\text{m}^3$, $80\text{--}95 \mu\text{g}/\text{m}^3$, and more than $95 \mu\text{g}/\text{m}^3$, respectively.

3.4. Evidence of the increasing effects of anthropogenic activities on $PM_{2.5}$ pollution

Asian dust was considered to be the major natural source of $PM_{2.5}$ concentration throughout northern China; however, the dust

Fig. 2. Mean spatial pattern of $PM_{2.5}$ in China during 1999–2011. L01 is artificial surface which represents cities, L02 is cropland, L03 is grassland, L04 is tree covered area, L05 is shrubs covered area, L06 is herbaceous vegetation, aquatic or regularly flooded, L08 is sparse vegetation, and L09 is bare soil.

Fig. 3. Significant trends of PM_{2.5} in China during 1999–2011. L01 is artificial surface which represents cities, L02 is cropland, L03 is grassland, L04 is tree covered area, L05 is shrubs covered area, L06 is herbaceous vegetation, aquatic or regularly flooded, L08 is sparse vegetation, and L09 is bare soil.

Fig. 4. Susceptible population exposed to various PM_{2.5} concentrations in China. The percentages in the figures indicate the portion living under a certain level of PM_{2.5} concentration.

frequency has significantly decreased during the past decades (Kan et al., 2012) and mainly occurred in L08 covered areas (Zhang et al., 2008). In our result, a large portion of L08 was observed with higher PM_{2.5} concentration, but no significant trends were obtained for most of the areas. L02 was another type of area that could be considered as a major source areas of PM_{2.5} emission in China. However, it would be a very limited contributor to the heavy concentrations. Estimation of the impact of urban air quality on its surrounding areas provided evidence that the high concentration and significant increase observed in L02 is highly attributable to urban air pollution (Han et al., 2014). An insight to the intensive anthropogenic activity showed that during 2000–2010, around 70% of the country's energy was coming from coal, and in addition, the number of vehicles has rapidly increased, contributing a huge amount of PM_{2.5} emission in the cities. On the other hand, China's rapid urbanization did not devote enough attention to urban green spaces, which could significantly remove part of PM_{2.5} through the leaf absorption and facilitated deposition (Nowak et al., 2006). In China's cities, the proportional area of vegetation slightly decreased

from 16% in 2000 to 15% in 2010. By comparison, cities in USA have relatively large proportions of vegetative coverage (Chi et al., 2015).

With the increasing recent improvements in data availability for ground-measured PM_{2.5} concentration in Chinese cities, detailed analysis on the relationship between the spatial pattern of urban PM_{2.5} concentration and emission sources is highly recommended to better understanding the impact of urban human activities on urban air quality.

3.5. Quick action and urbanization strategies that should be taken in conjunction with rapid development in China

Given the severe PM_{2.5} pollution in Chinese cities, quick actions are definitely needed. For instance, actions to replace coal with cleaner fossil fuels, and increase reliance on cleaner renewable energy sources, are strongly suggested. Reducing vehicle use intensity would be another way to reduce PM_{2.5} emissions. Now, many Chinese mega-cities have limited the vehicles usage by plate number limitation practices and strict control of new vehicle registration. Such policies/practices could be effective in the short term, but will lose effect in the near future when the pollution becomes more intense and integrated with social problems. We strongly suggest the design and construction of more efficient and convenient public transport system to reduce vehicle use.

Better urbanization strategies that minimize negative impacts on the environment are also needed. China's urbanization strategy has been erratic since the new era began in 1949. Before establishment of the "Reform and Opening-up" policy, China paid strong attention to industrial development but limited urban development by strict household registration policies to control population movement. Almost no attention was paid to the environmental protection; luckily, human activities were not intensive enough to influence the environment. Starting after the 1970s, China has expanded its market economic development, while very limited attention has been given to environmental protection. Moreover, the environmental protection policy has been mostly problem-driven rather than prevention-driven, resulting in heavy environmental pollution. To reduce the management but increase the service functions of government, to enhance the function of market regulation, and to utilize a smart growth concept would be a better strategy to realize China's "Ecological Civilization" urbanization dream.

4. Conclusions

We analysed the patterns of mean levels and trends of PM_{2.5} concentration for different land cover types during 1998–2012, as well as its potential health risk to the susceptible population. The following conclusions were obtained:

- 1) PM_{2.5} concentration in 31% of China's territorial areas was less than 10 µg/m³, and in 26% of China's territorial areas was higher than 35 µg/m³. The East China Plain, eastern Sichuan province, and Taklimakan desert were found with high PM_{2.5} concentration.
- 2) Areas with strong significant positive trends were obtained in the East China Plain, where are southern Hebei province, and

Shandong province. 73% of L01 and 76% of L02 were found with significant positive trends. The mean significant trends of PM_{2.5} concentration were 1.81 µg/m³·year for L01 and 1.71 µg/m³·year for L02 higher than those for the rest land covers, which were less than 0.60 µg/m³·year.

- 3) The PM_{2.5} concentration posed potential health risk to the susceptible population: only 1% of susceptible population was exposed to <10 µg/m³, while 69% of susceptible population was exposed to >35 µg/m³.

Acknowledgements

This research was a part of project "Spatiotemporal Pattern of Urbanized Regions' Particulate Matter (PM_x) and Its Relationship with Landscape Pattern" supported by Natural Science Foundation of China (NSFC41301199). In addition, the research received financial support from the Project Sponsored by the Scientific Research Foundation for the Returned Overseas Chinese Scholars, State Education Ministry, the "One-hundred Talented" program of the Chinese Academy of Sciences, the Science and Technology Service Network Initiative Project of the Chinese Academy of Sciences (KFJ-EW-ZY-004), and "135" Key Cultivate Project (YSW2013B04) of Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences.

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