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Increasing impact of urban fine particles (PM_{2.5}) on areas surrounding Chinese cities

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The negative impacts of rapid urbanization in developing countries have led to a deterioration in urban air quality, which brings increasing negative impact to its surrounding areas (e.g. in China). However, to date there has been rare quantitative estimation of the urban air pollution to its surrounding areas in China. We thus evaluated the impact of air pollution on the surrounding environment under rapid urbanization in Chinese prefectures during 1999 – 2011. We found that: (1) the urban environment generated increasing negative impact on the surrounding areas, and the PM_{2.5} concentration difference between urban and rural areas was particularly high in large cities. (2) Nearly half of the Chinese prefectures (156 out of 350) showed increased impact of urban PM_{2.5} pollution on its surrounding areas. Those prefectures were mainly located along two belts: one from northeast China to Sichuan province, the other from Shanghai to Guangxi province. Our study demonstrates the deterioration in urban air quality and its potential impacts on its surrounding areas in China. We hope that the results presented here will encourage different approaches to urbanization to mitigate the negative impact caused by urban air pollution, both in China and other rapidly developing countries.

China's rapid urban and economic development over a short period has not only led to better living standard, but also caused severe environmental pollution, particularly air pollution, in urbanized regions^{1–3}. Despite the decrease in “traditional pollutants” (e.g. NO₂, SO₂), fine particulate matter (PM_{2.5}) has become a major air pollutant that threatens human health, including morbidity and mortality, and decreases meteorological visibility^{4–5}. As this major urban air pollutant increases both totally and proportionally in Chinese cities, concentrations of PM_{2.5} have attracted increasing concern due to its effects on visibility and public health^{3,6}. Owing to the differences in emission magnitudes, urban and rural areas exhibit heterogeneous PM_{2.5} concentrations, which indicate varied interactions between urban and surrounding areas³. When PM_{2.5} concentrations are higher in urban areas than surrounding areas, urban air pollution can negatively impact the surrounding rural areas; when PM_{2.5} concentrations are lower in urban areas than surrounding areas, urban air quality can be negatively impacted by the surrounding rural areas. To monitor PM_{2.5} concentration changes, the monitoring networks have been well established in many developed countries, but fewer in developing countries which were suffering severe PM_{2.5} pollution^{7–8}. Critically, networks with limited spatial distribution make it difficult to quantitatively illustrate the spatial patterns and impacts of urban air pollution on the surrounding rural areas. Thus, remote sensing derived PM_{2.5} concentrations were introduced for large-scale air quality analysis.

Remote sensing and modeling derived PM_{2.5} concentration records suggest that PM_{2.5} concentrations are higher in many regions of China than in other countries, particularly in urban areas^{9–10}. Few studies, however, have quantitatively examined the annual or multi-year averaged spatial pattern of PM_{2.5} concentrations in Chinese cities, or the impact of urbanization on PM_{2.5} concentrations¹¹, and multi-year analysis is limited due to poor long-term large-scale PM_{2.5} concentration data^{3,12}. However,

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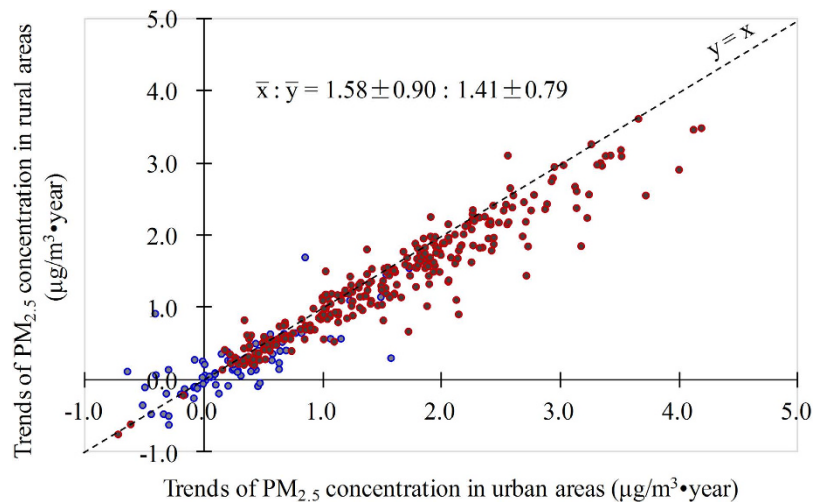


Figure 1. Increasing trends of $PM_{2.5}$ concentrations in urban areas ($U_{PM_{2.5}}$) compared with those in rural areas ($R_{PM_{2.5}}$) at Chinese prefectures from 1999 to 2011. Red dots indicate cities with significant $PM_{2.5}$ concentration trends in both urban and rural areas, blue dots represent cities without significant $PM_{2.5}$ concentration trends in either urban or rural areas.

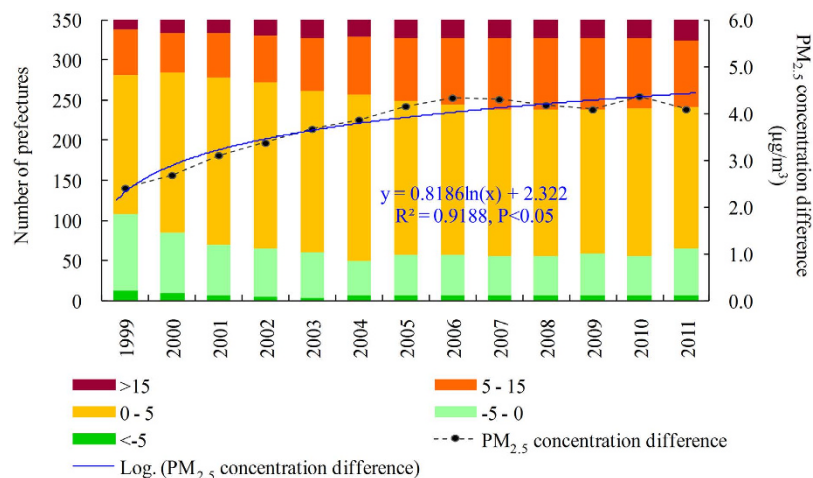


Figure 2. Mean $PM_{2.5}$ concentration difference ($D_{PM_{2.5}}$) between urban and rural areas in Chinese prefectures from 1999 to 2011. The bars represent number of cities with each $PM_{2.5}$ concentration difference group, and the dots represent prefectural mean $PM_{2.5}$ concentration difference ($D_{PM_{2.5}}$) in China during 1999–2011.

this information is critically important for China to achieve the recently released long-term plan for controlling air pollution (http://www.gov.cn/zwggk/2013-09/12/content_2486773.htm) and to accomplish the new-type urbanization plan. Therefore, the objectives of this study were to examine the changes in $PM_{2.5}$ concentration differences between urban and surrounding areas, and suggest better air quality controls to policy makers in China.

Results

$PM_{2.5}$ concentration in the urban areas ($U_{PM_{2.5}}$) showed a stronger increase trend compared with the trend of $PM_{2.5}$ concentration in the rural areas ($R_{PM_{2.5}}$) (Fig. 1; $U_{PM_{2.5}}$ trends : $R_{PM_{2.5}}$ trends = 1.58 ± 0.90 : 1.41 ± 0.79), indicating a stronger impact of human activities in urban areas than in rural areas of China. The stronger increases of $U_{PM_{2.5}}$ resulted in significantly increased $PM_{2.5}$ concentration difference ($D_{PM_{2.5}}$) (Fig. 2; $R^2 = 0.9188$, $P < 0.05$). The prefectural averaged $D_{PM_{2.5}}$ was $2.41 \mu\text{g}/\text{m}^3$ in 1999, but was increased to $4.09 \mu\text{g}/\text{m}^3$ in 2011. The amount of prefectures with $D_{PM_{2.5}} > 0 \mu\text{g}/\text{m}^3$ increased from 142 in 1999 to 285 in 2011, while the amount of prefectures with $D_{PM_{2.5}} > 5 \mu\text{g}/\text{m}^3$ increased from 69 in 1999 to 108 in 2011, and the amount of prefecture with $D_{PM_{2.5}} > 15 \mu\text{g}/\text{m}^3$ was more than doubled from

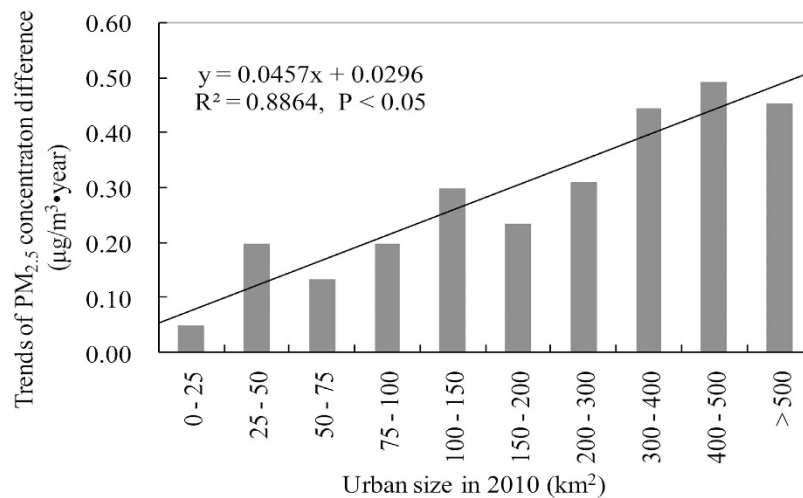


Figure 3. Relationship between urban size in 2010 and trends in PM_{2.5} concentration differences ($D_{PM_{2.5}}$) between urban and rural areas in China's prefectures from 1999 to 2011.

12 in 1999 to 25 in 2011. However, the amount of prefectures with $D_{PM_{2.5}} < 0 \mu\text{g}/\text{m}^3$ was decreased from 108 in 1999 to 65 in 2011, and the amount of prefectures with $D_{PM_{2.5}} < -5 \mu\text{g}/\text{m}^3$ decreased from 13 in 1999 to 6 in 2011 (Fig. 2).

Urban size influenced $D_{PM_{2.5}}$, with a significant positive relationship found between the trends of $D_{PM_{2.5}}$ and urban size (Fig. 3; $R^2 = 0.8864$, $P < 0.05$). The trend with more $0.4 \mu\text{g}/\text{m}^3 \cdot \text{year}$ was obtained at cities with more than 300 km^2 , however, the trend with less than $0.4 \mu\text{g}/\text{m}^3 \cdot \text{year}$ was obtained at cities with less than 100 km^2 .

The spatial pattern of $D_{PM_{2.5}}$ trend at China's prefectures showed a similar spatial pattern to the $D_{PM_{2.5}}$ (Fig. 4; Supplementary material 2). Only 42 prefectures, which were mainly located in west and central China, showed significant negative $D_{PM_{2.5}}$ trends. Conversely, 156 prefectures, which were located along two belts from northeast China to the Sichuan province and from Shanghai to the Guangxi province, showed significant positive $D_{PM_{2.5}}$ trends. The first belt showed much stronger increasing trend than that in the second belt (Fig. 4).

Discussion

Urbanization can both positive and negative impact on rapid developing countries. Accelerating urbanization is considered important for economic development in China¹³. China's central government recently released the National New-type Urbanization Plan that sets the target for urban population fraction at 52.6% in 2012 to reach 60% by 2020¹⁴. Such rapid growth will drive an increase in economic development and reduction in regional income disparity. However, rapid urbanization also enhances the magnitude of human activities, which contribute to pollution of urban and surrounding environment. Under current strategy, China's cities would bring much stronger negative impact on the surrounding areas, especially under the expansion of larger cities. Further urbanization in China must consider and establish stricter rules to conserve urban areas and the surrounding environment. Practically, the $D_{PM_{2.5}}$ values used in this work provide supplementary criteria to the $U_{PM_{2.5}}/R_{PM_{2.5}}$ data in order to quantitatively illustrate the influence of urbanization on environment.

Urbanization and its environmental impact experiencing different spatial patterns, suggested various urbanization and environmental protection policies should be considered and taken in different areas of China. China's current urbanization has mainly occurred in eastern and central China, with less than half the nation's land supporting more than 90% of the population¹⁵⁻¹⁶. The highest concentration of PM_{2.5} were also observed mainly along the east China plain area^{3,12}. The $D_{PM_{2.5}}$ trends obtained in this study showed similar spatial patterns to those reported in previous research³, which illustrated strong negative impacts of the urban environment in eastern and central China along two belts from Beijing to Sichuan and from Shanghai to Guangxi. Those patterns indicate different environmental protection policies or actions are required. For instance, under rapid urbanizing, heavy pollution, and strong negative impact of urban areas on the surrounding environment, very strict pollutants emission control and policy should be applied, however, under slow urbanization, light pollution, and no clear impact of urban areas to the surrounding environment, the moderate environmental policies should be adopted.

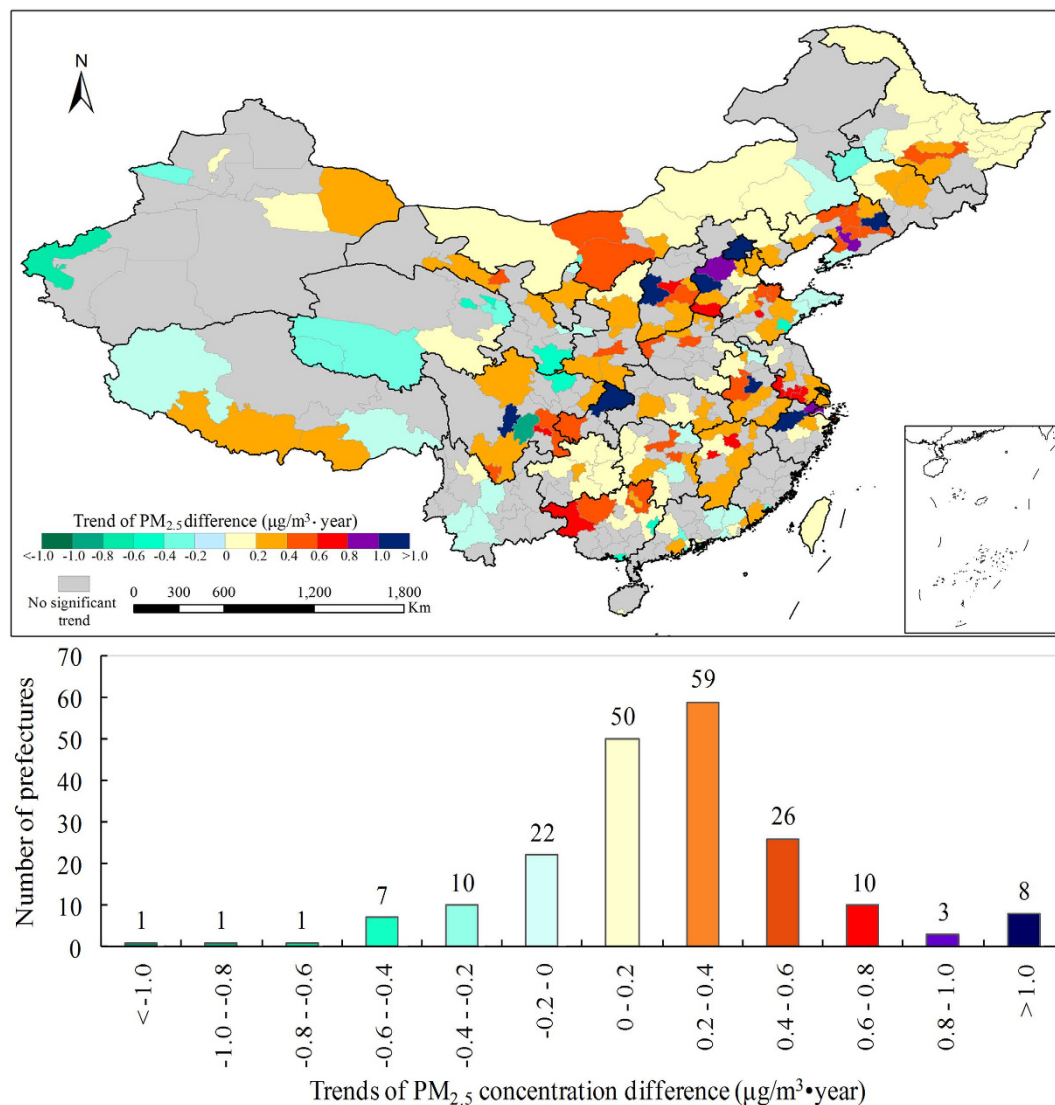


Figure 4. Spatial pattern of trends of $PM_{2.5}$ concentration difference ($D_{PM_{2.5}}$) between urban and rural areas from 1999 to 2011. (This figure was created by L. Han in ArcGIS software)

Methods

Study area. Prefecture is the basic administrative unit between province and county, and can be used to demonstrate China's urban environmental pollution. We therefore took prefectures as the basic study unit to quantify the impact of urban $PM_{2.5}$ concentration on the surrounding areas (Supplementary material 1).

Fine particulate matter ($PM_{2.5}$) data. The $PM_{2.5}$ concentration used in this research was estimated with an optimal estimation algorithm based on top-of-atmosphere reflectance observed by Moderate Resolution Imaging Spectroradiometer (MODIS) products^{9–10}. In practice, based on GEOS-Chem chemical transport model simulation, $PM_{2.5}$ concentrations were estimated from the combination of MODIS and Multi-angle Imaging SpectroRadiometer (MISR) AOD with aerosol vertical profiles and scattering properties^{9–10}. The global $PM_{2.5}$ concentration dataset had a spatial resolution of 10 km as three years moving average from 1999 to 2011¹⁰. The approach achieved significant agreement ($r = 0.81$; slope = 0.68) between satellite-derived estimates and ground-based measurements outside North America and Europe was obtained, including many ground measurements in China. It thus provides greater possibility in large regional study of $PM_{2.5}$ concentration's dynamic¹⁰. The dataset can be directly download from Atmospheric Composition Analysis Group at Dalhousie University (Website: <http://fizz.phys.dal.ca/~atmos/martin/>). We used a subset of the global $PM_{2.5}$ concentration dataset that covered China from 1999 to 2011.

Urban distribution and prefectural boundary. Urban distribution with a spatial resolution of 1 km was used to identify urban from non-urban areas in 2000 and 2010¹⁵. The prefectural boundary layer with a scale of 1:250,000 was obtained from the National Geomatics Center of China (<http://ngcc.sbsm.gov.cn/>).

PM_{2.5} concentration differences. The PM_{2.5} concentration in the urban/non-urban areas ($U_{PM_{2.5}}/R_{PM_{2.5}}$) were firstly calculated with based on the urban map in each Chinese prefecture. $U_{PM_{2.5}}/R_{PM_{2.5}}$ was collected and averaged from the intersection of urban/non-urban areas between 2000 and 2010 to avoid the spatial inconsistency from urban expansion. The differences in PM_{2.5} concentration ($D_{PM_{2.5}}$) between $U_{PM_{2.5}}$ and $R_{PM_{2.5}}$ were then obtained for each individual year during 1999–2011 with equation (1)³.

$$D_{PM_{2.5}} = U_{PM_{2.5}} - R_{PM_{2.5}} \quad (1)$$

Then the relationship between $U_{PM_{2.5}}$ and $R_{PM_{2.5}}$ trends was then examined to explain the changes of $D_{PM_{2.5}}$. In addition, we compared urban sizes and the $D_{PM_{2.5}}$ trend to explain the different impacts of urban size on the surrounding areas. Further spatial pattern of $D_{PM_{2.5}}$ trend, when $R > 0.5$ and $P < 0.05$, was finally obtained and analyzed to illustrate geographical “hot-spot” of urban air pollution on surrounding areas.

Current calculation of $U_{PM_{2.5}}/R_{PM_{2.5}}$ is only based on two years’ (2000 and 2010) urban maps’ intersection which could introduce errors to $D_{PM_{2.5}}$ for each year during 2000–2010. In future, when annual urban map available, we suggest to calculate $U_{PM_{2.5}}/R_{PM_{2.5}}$ based on each year’s urban cover map to minimize the uncertainty.

References

- Zhu, Y. *et al.* Understanding and harnessing the health effect of rapid urbanization in China. *Environmental Science and Technology*. **45**, 5099–5140 (2011).
- Gong, P. *et al.* Urbanisation and health in China. *Lancet*. **379**, 843–852 (2012).
- Han, L., Zhou, W., Li, W. & Li, L. Impact of urbanization level on urban air quality: A case of fine particles (PM_{2.5}) in Chinese cities. *Environmental Pollution*. **194**, 163–170 (2013).
- Chan, C. & Yao, X. Air pollution in mega cities in China. *Atmospheric Environment*. **42**, 1–42 (2008).
- Pope III C. & Dockery, D. Health effects of fine particle air pollution: Lines that connect. *Journal of the Air & Waste Management Association*. **56**, 709–742 (2012).
- Wang, S. & Hao, J. Air quality management in China: Issues, challenges, and options. *Journal of Environmental Sciences*. **24**, 2–13 (2012).
- Engle-Cox, J., Holloman, C., Coutant, B. & Hoff, R. Qualitative and quantitative evaluation of MODIS satellite sensor data for regional and urban scale air quality. *Atmospheric Environment*, **38**, 2495–2509 (2004).
- Zheng, J. *et al.* Ground-level ozone in the Pearl River Delta region: Analysis of data from a recently established regional air quality monitoring network. *Atmospheric Environment*. **44**, 814–823 (2009).
- van Donkelaar, A. *et al.* Global estimates of ambient fine particulate matter concentrations from satellite-based aerosol optical depth: Develop and application. *Environmental Health Perspectives*. **118**, 847–855 (2010).
- van Donkelaar, A., Martin, R., Brauer, M. & Boys, B. Use of satellite observation for long-term exposure assessment of global concentration of fine particulate matter. *Environmental Health Perspective*. **123**, 135–143 (2015).
- Lin, G. *et al.* Spatio-temporal variation of PM_{2.5} concentration and their relationship with geographic and socioeconomic factors in China. *International Journal of Environmental Research and Public Health*. **11**, 173–186 (2014).
- Boys, B. *et al.* Fifteen-year global time series of satellite-derived fine particulate matter. *Environmental Science & Technology*. **48**, 11109–11118 (2014).
- Bai, X., Chen, J. & Shi, P. Landscape urbanization and economic growth in China: Positive feedbacks and sustainability dilemmas. *Environmental Science & Technology*, **46**, 132–139 (2012).
- Bai, X., Shi, P. & Liu, Y. Realizing China’s urban dream. *Nature*. **509**, 158–160 (2014).
- Liu, J., Zhang, Q. & Hu, Y. Regional difference of China’s urban expansion from late 20th to early 21st century based on remote sensing information. *Chinese Geographical Science*. **22**, 1–14 (2012).
- Wei, Y. & Ye, X. Urbanization, urban land expansion and environmental change in China. *Stochastic Environmental Research and Risk Assessment*. **28**, 757–765 (2014).

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Author Contributions

L.H. contributed to the literature search, study design, data analysis and interpretation, and manuscript writing and revision. W.Z. and W.L. contributed to the data interpretation and manuscript revision.

Additional Information

Supplementary information accompanies this paper at <http://www.nature.com/srep>

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