Population Exposure to Ambient $PM_{2.5}$ Pollution in China

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4 Results

4.1 Overall pattern

Using the above data and method, we estimate daily average $PM_{2.5}$ concentrations for each sub-district (see supplementary materials for validation results). A sub-district is polluted if its $PM_{2.5}$ level is above 75 μg/m^3 on a particular day. First of all, we report the frequency (equivalent number of months in a year) that a sub-district violates national ambient air quality standards. See Figure 2 and the online visualization at the Beijing City Lab.[1] Our results highlight three pollution hotspots in China indicated in Figure 2. The most pronounced hotspot is a diamond-shaped large area that sprawls across eastern and central China. The area is anchored by four major metropolitan areas: Beijing in the north, Shanghai in the east, Guangzhou in the south, and Chengdu in the west. The other two hotspots are the Harbin-Shenyang Corridor in Northeast China and northern Xinjiang with Urumqi as the center.

[Figure 2 about here]

The estimation results show that the mode of the months of $PM_{2.5}$ pollution for the Chinese sub-districts is 1-2 months in a year. Since the population centers tend to be more polluted, the mode of population exposure to $PM_{2.5}$ reaches 3-4 months in a year. Cumulatively, a total area of 243 million km^2 has $PM_{2.5}$ pollution longer than 3 months. In terms of the population exposed, 827 million people are exposed to $PM_{2.5}$ pollution for longer than a quarter of a year. These results are summarized in Table 1.

[Table 1 about here]

Nearly 11 percent of sub-districts (or 4,100 sub-districts) suffer from $PM_{2.5}$ pollution over half a year. These sub-districts are mainly located in Beijing, Tianjin, southern and central Hebei, central and eastern Henan, central and western Shandong, and central Hubei. The total area of these highly exposed sub-districts is 347,432 km^2, or approximately 3.65% of mainland China's land area. These highly exposed sub-districts combined have more than 223 million people, almost 17% of total population in mainland China.

[1] Website: http://www.beijingcitylab.com

Moreover, the number of polluted months in some sub-districts is over 8 months and even up to 9 months in a year. These areas are mainly distributed in southern Hebei, northern Henan and western Shandong, covering more than 121,000 km^2 area and 90 million residents.

By contrast, less than half of the total sub-districts, or merely 18,664 sub-districts, have less than 3 polluted months. Low exposed sub-districts are mainly in the plateau and alpine regions like Tibet and Northwest China, southeastern coastal regions (Fujian, Guangdong, and Hainan), and southwestern border regions (Yunan, part of Guizhou, and Guangxi). Although the low exposure regions cover three-quarters of China's land areas, or 7,097,097 km^2, they only accommodate 38% of total population.

We calculate exposure intensity based on the estimated days of exposure and the population density for each sub-district according to equation (2). The results are mapped in Figure 5. **Because the $PM_{2.5}$ pollution and population density are highly correlated, exposure intensity has the same spatial pattern as its two determinants.** For each sub-district, the higher the population density is, the more pollution the area is exposed to, and the greater exposure intensity it has. Therefore, nearly all the densely populated sub-districts are among the worst polluted regions (Figure 3a). In particular, the areas with high exposure intensity almost cover the entire eastern-central China apart from east Fujian, the Harbin-Dalian corridor in the northeast, and the Guanzhong and Chengdu Plain in the west. Therefore, the spatial pattern of exposure intensity is more concentrated compared with population density. Although some sub-districts have relatively low pollution levels, high population density still gives rise to serious exposure intensity.[2]

Studies reveal that seniors and children are more susceptible to $PM_{2.5}$ pollution (Zhang et al, 2002; Ashmore, 2009). We also estimate the exposure intensity for the susceptible subpopulation defined as the age groups younger than 14 years old or elder than 65 years old. **We find that the pattern of the susceptible groups' exposure intensity to $PM_{2.5}$ (Figure S2) is similar to that of the population exposure in Figure 3b.**

[Figure 3 about here]

4.2 Seasonality of $PM_{2.5}$ pollution

In this section, we aggregate the daily pollution level to the monthly level. More specifically, we calculate the percentage of days within a month that is subject to $PM_{2.5}$ pollution. Figure 4 illustrates the spatiotemporal variation of pollution exposure (population density not accounted). Overall, Chinese people are exposed to $PM_{2.5}$ pollution in almost every month of a year. The seasonal fluctuation spreads and congregates in space due to a complex interplay with climate difference, diffusion conditions, and coal combustion (Fenger, 1999; Stanners and Bourdeau, 1995).

[2] These sub-districts include the Pearl River Delta, eastern Guangdong, southeaster Zhejiang, Guangxi, Hunan, and the Sichuan Basin.

[Figure 4 about here]

Influenced by downdraft and coal-fired heating, $PM_{2.5}$ pollution in winter half year (from October to March) is generally much more serious than that of summer half year (from April to September) (Zheng et al., 2005; Meng et al., 2007; Yang et al., 2011). The whole country is suffered from incredibly high $PM_{2.5}$ pollution in winter half year. Typically in December and January, an overwhelming majority of sub-districts are exposed to $PM_{2.5}$ pollution longer than 50% of days in a month. Except for the regions with low human activities such as forests and plateaus, the southeastern coastal areas like Fujian and Hainan are the only densely populated regions with good air quality.

Pollution starts to abate from February and reach the minimal level in August. In spring and summer, pollution is limited to a number of areas in the north due to the spring dust storm (He et al., 2001). As demonstrated in Figure 4, the population in North China still suffers from high $PM_{2.5}$ concentrations even between May and September.[3] After August, pollution starts to increase again; it expands from the north to the south gradually until it covers the most part of China in December.

4.3 City-Level $PM_{2.5}$ pollution

In this section, we aggregate the sub-district pollution level to the city level. Figure 5 illustrates the spatial heterogeneity of $PM_{2.5}$ pollution across 654 cities. The pollution pattern shows that the northern cities are worse than southern cities, the inland cities are worse than the coastal cities, and the plain and basin cities are worse than the plateau and hilly cities.

[Figure 5 about here]

The top polluted cities include the Beijing-Tianjin-Hebei region (BTH), Henan, mid-western Shandong (except cities in the Shandong Peninsula), central Hubei, and central Shaanxi (eg, Xi'an). The next tier of polluted cities with exposure between 111 and 158 days include the northeastern Yangtze River Delta (YRD, eg, Nanjing), Chengdu Plain (eg, Chengdu), east Hubei, and Hunan (eg, Wuhan and Changsha). Residents in the major urbanization city-regions like BTH, YRD, Chengdu-Chongqing, and the middle reaches of Yangtze River are exposed to $PM_{2.5}$ pollution for longer than 100 days a year. The exception is that the Pearl River Delta (PRD), east Fujian, the Shandong Peninsula, and the Liaodong Peninsula have relatively lower $PM_{2.5}$ exposure.

Furthermore, we rank all cities in terms of days of exposure to $PM_{2.5}$ pollution (see Table S1). We find that the worst 20 cities are mostly from central or southern part of Hebei province. This region is clustered with of the iron and steel industry that highly rely on coal consumption. The cities in Tibet, Yunnan, and Fujian are among the cleanest cities in China in terms of $PM_{2.5}$ pollution.

We propose to use total exposure, product of pollution days and population, to identify cities

[3] These areas include the Beijing-Tianjin-Hebei (BTH) region, southeastern Shanxi, northern-central Henan, and western Shandong.

with the worst $PM_{2.5}$ pollution. All cities are ranked by this indicator and the top 20 worst cities are listed in Table S2. Beijing ranks the top in this category, indicating a huge amount of population was exposed to $PM_{2.5}$ pollution in the past year. The other three metropolitan cities—Tianjin, Shanghai, and Chongqing—are all on the top of the list among other big cities. Although some cities have relatively short duration of exposure, the risk of pollution is still high because of the concentrated population.

Furthermore, we focus on the $PM_{2.5}$ exposure in the thirteen major urbanization regions that are identified by the Ministry of Environmental Protection of China as key regions in air quality management. Table 2 presents various exposure indicators in the thirteen major urbanization regions via aggregating indicators of cities within each region. The troubling fact is that half of these city-regions had over 100 pollution days in the past year. Only Fujian province's annual average concentration achieved a relatively low level of 37μg/m^3 but still slightly above the national standard of 35μg/m^3. The percentage of city-regions that attained the $PM_{2.5}$ standard is negligible.

[Table 2 about here]

4.4 Simulation Results

We first simulate the implication of several stages of $PM_{2.5}$ standards proposed by the WHO in 2005. The WHO recommended standard for daily average $PM_{2.5}$ concentration is 25 μg/m^3. Its adopters include Canada and Australia. The three interim targets are: 75 μg/m^3 adopted by China, India, and Mexico (interim-target 1, IT-1), 50 μg/m^3 adopted by EU and Thailand (interim-target 2, IT-2), and 37.5 μg/m^3 adopted by the United States, Japan, and Singapore (interim-target 3, IT-3). We simulate population exposures under each standard for the counterfactual analysis. If the IT-2 standard (50 μg/m^3) is used, 776 million people are exposed to PM2.5 pollution for longer than half a year; if the standard is raised to IT-3 (37.5 μg/m^3), the exposed population increases to 1195 million. **Under the WHO recommended standard of 25 μg/m^3, 1,322 million people, or 96.5% of the Chinese population in 2010, live in the polluted environment for over half a year.** The simulation results of population exposure under various hypothetic standards are summarized in Figure 6.

[Figure 6 about here]

In addition, we simulate the implication of China's most recent air pollution control plan. The Chinese government has enacted the Air Pollution Prevention and Control Action Plan to tackle the challenge of air pollution. The plan requires the $PM_{2.5}$ concentrations in three major metropolitan areas—Beijing-Tianjin-Hebei, Yangtze River Delta, and Pearl River Delta—to decrease by 25%, 20%, and 15% respectively. In this plan, the target for Beijing is to limit its annual average concentration of $PM_{2.5}$ to 60 μg/m^3 as of 2017 (85 μg/m^3 in our study). There is no specific requirement for the areas beyond the aforementioned three metropolitan areas. The simulation result in Figure 6 demonstrates that population exposure to $PM_{2.5}$ is reduced significantly if the plan can achieve its target. For instance, 184 million people are exposed to

$PM_{2.5}$ over half a year in 2017, in contrast to 223 million during 2013-2014.

6 Conclusions

This paper assesses China's potential population exposure to $PM_{2.5}$. We estimate daily $PM_{2.5}$ concentrations using both ground-based measurements and MODIS AOD images at the sub-district level. We map $PM_{2.5}$ concentration for each sub-district to gain knowledge on the overall pattern and spatiotemporal variations. We also simulate the potential population exposure under various hypothetical scenarios, including different stages of standards proposed by WHO and China's most recent Air Pollution Prevention and Control Action Plan. Our results show that China's $PM_{2.5}$ pollution will still be abysmal even if it can achieve the target in the plan, which calls for further actions to mitigate the pollution of fine particles.

Tables and Figures

Table 1 $PM_{2.5}$ pollution under China's ambient air quality standards

Months of pollution	Cumulative area exposed ($10,000\ km^2$)	Cumulative population exposed (million people)
≥1	745	1,241
≥2	470	1,070
≥3	243	827
≥4	110	550
≥5	61	355
≥6	35	223
≥7	12	90
≥8	4	34
≥9	0.4	3

Table 2 Basic exposure indicators in 13 major urbanization regions

City-region	Exposed day	Annual average concentration ($\mu g/m^3$)	Percentage of qualified cities
Beijing-Tianjin-Hebei	219	107	0
Yangtze River Delta	99	64	0
Pearl River Delta	53	44	4.5
South-Central Liaoning	80	56	0
Shandong	146	80	0
Wuhan metropolitan area	161	87	0
Changsha-Zhuzhou-Xiangtan	127	71	0
Chengdu-Chongqing	113	66	0
Fujian	17	37	43.5
North Central Shanxi	128	70	0
Central Shaanxi	132	79	0

City-region	Exposed day	Annual average concentration (μg/m^3)	Percentage of qualified cities
Gansu and Ningxia	69	58	0
Northern Xinjiang	89	60	0

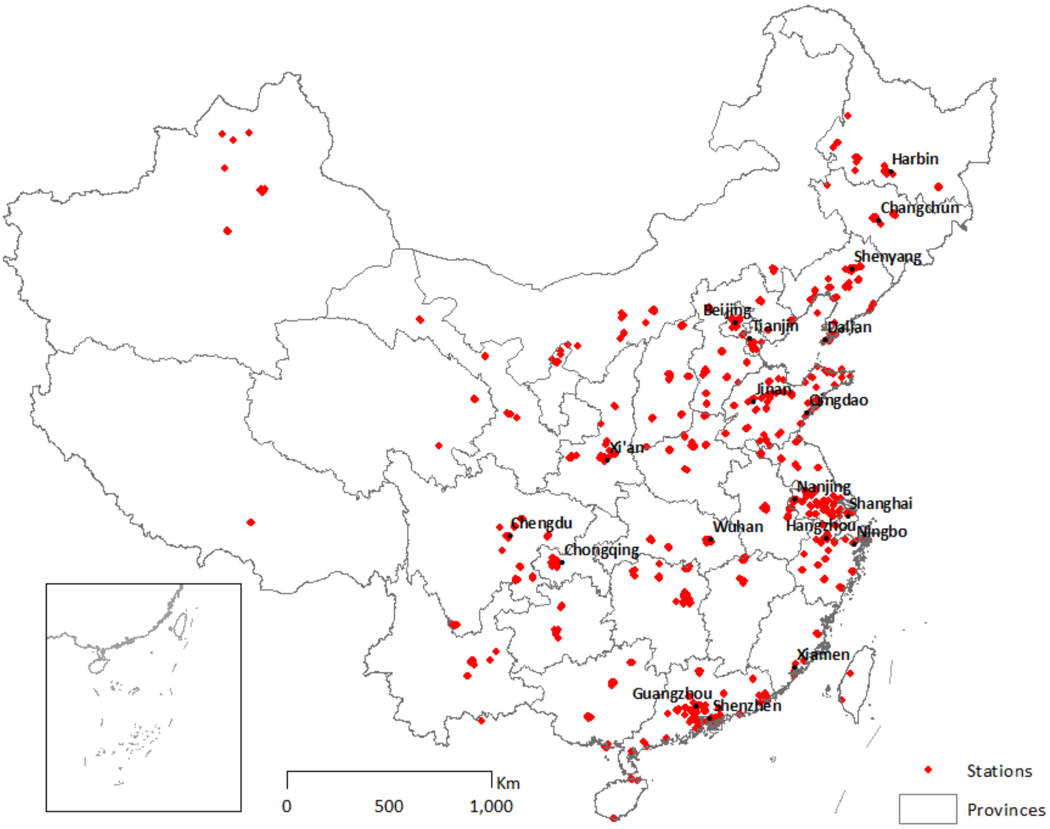


Figure 1 Spatial distribution of monitoring stations in 190 Chinese cities

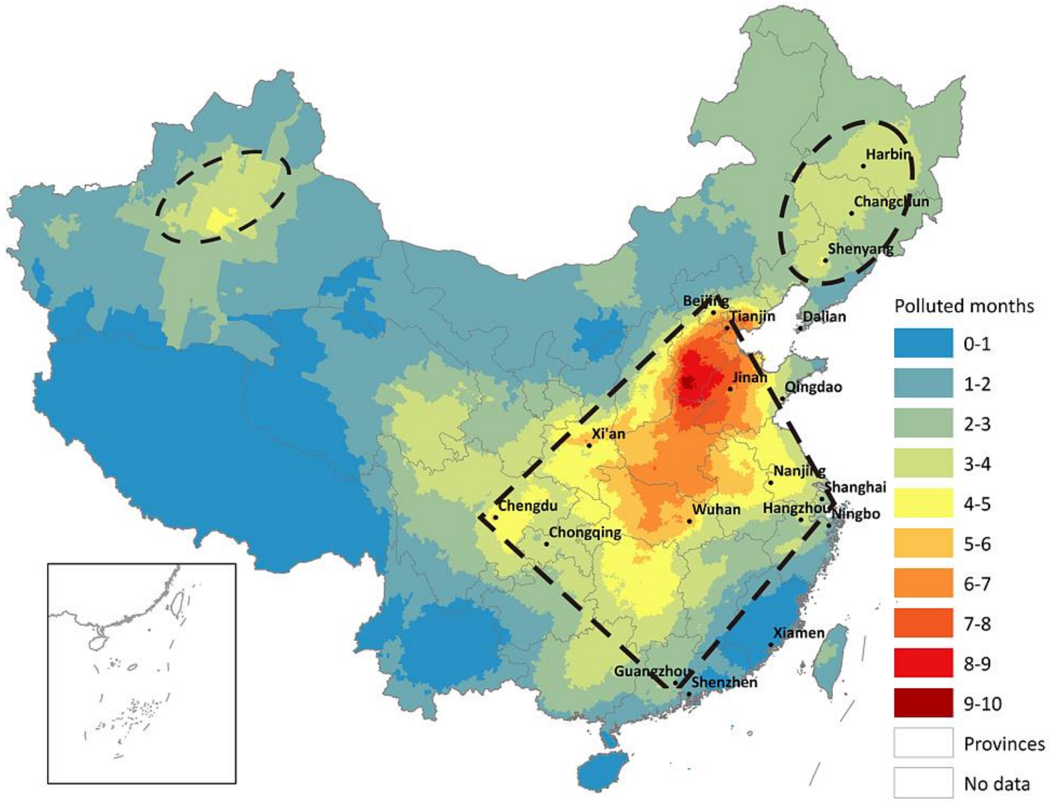
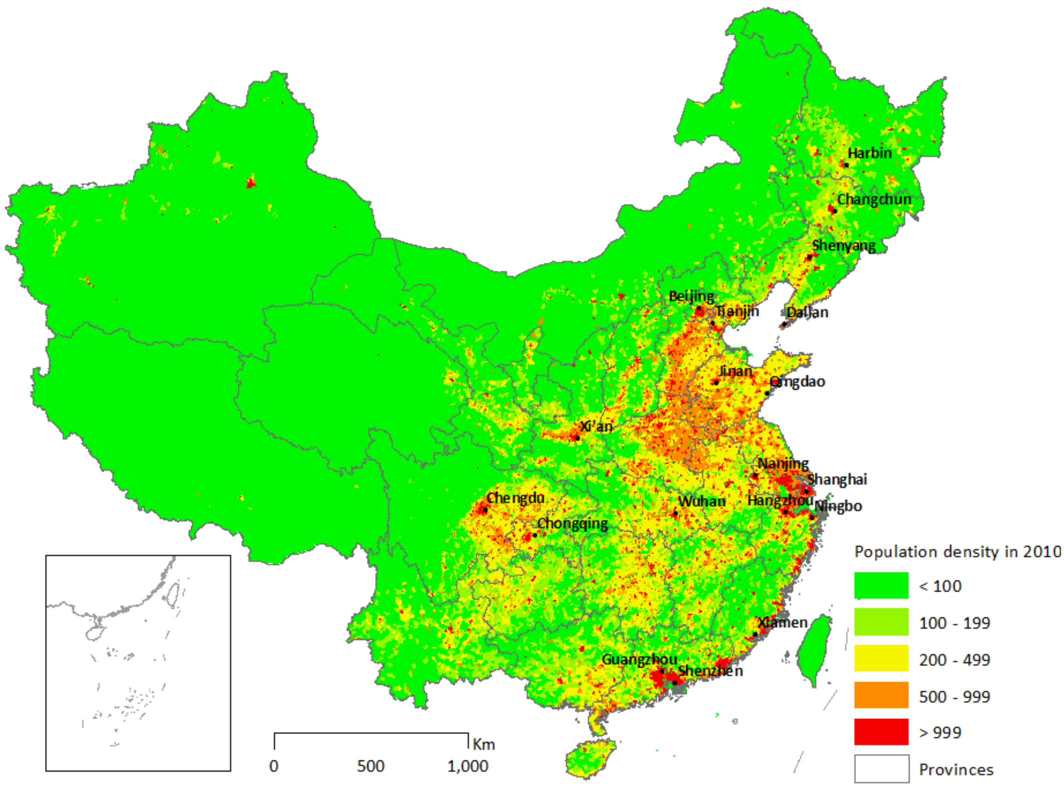
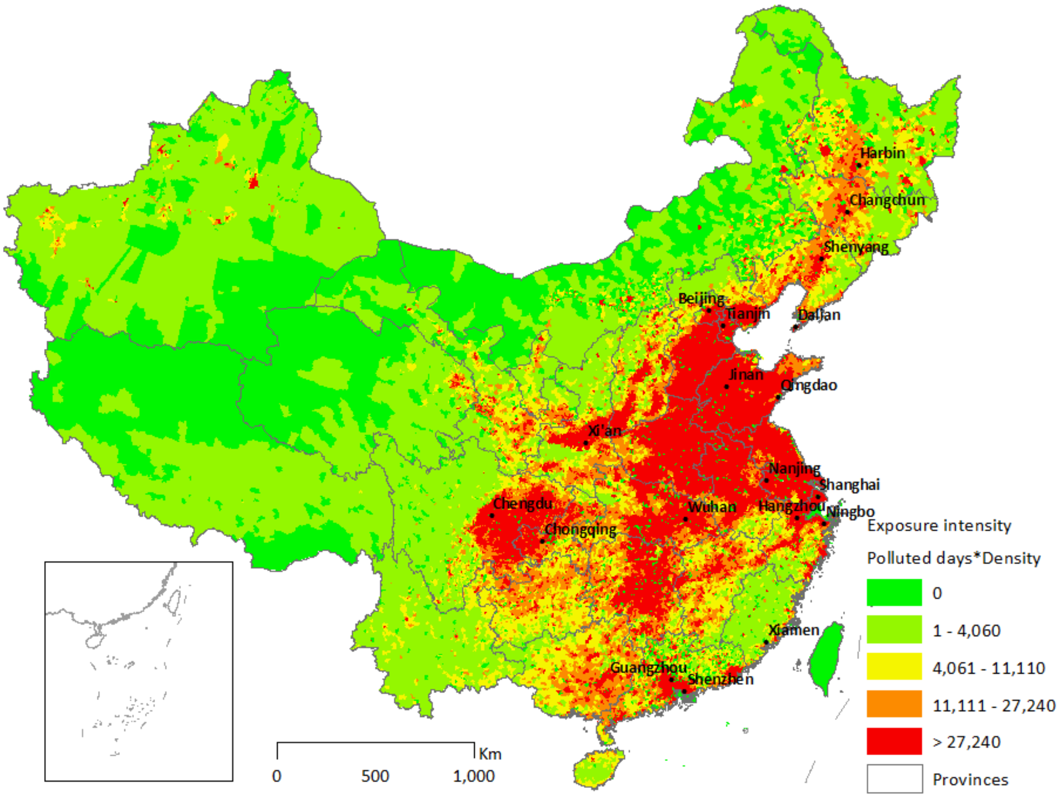


Figure 2 The number of polluted months in a year for each Chinese sub-district violating national $PM_{2.5}$ standard



(a)



(b)

Figure 3 Population density (a, persons per km^2) and exposure intensity (b, polluted days*persons per km^2) at the sub-district level

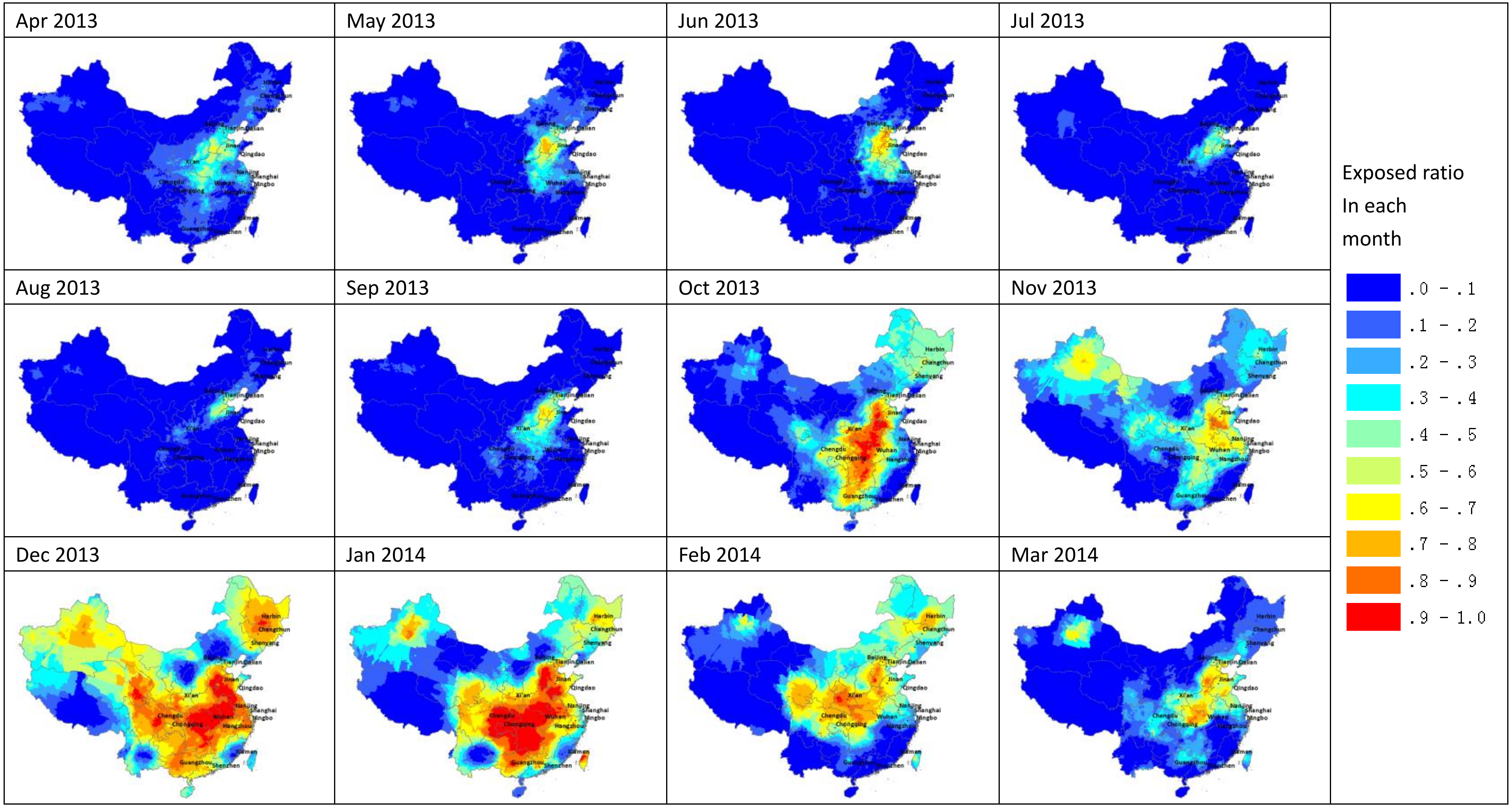


Figure 4 Exposed days in each month for each sub-district

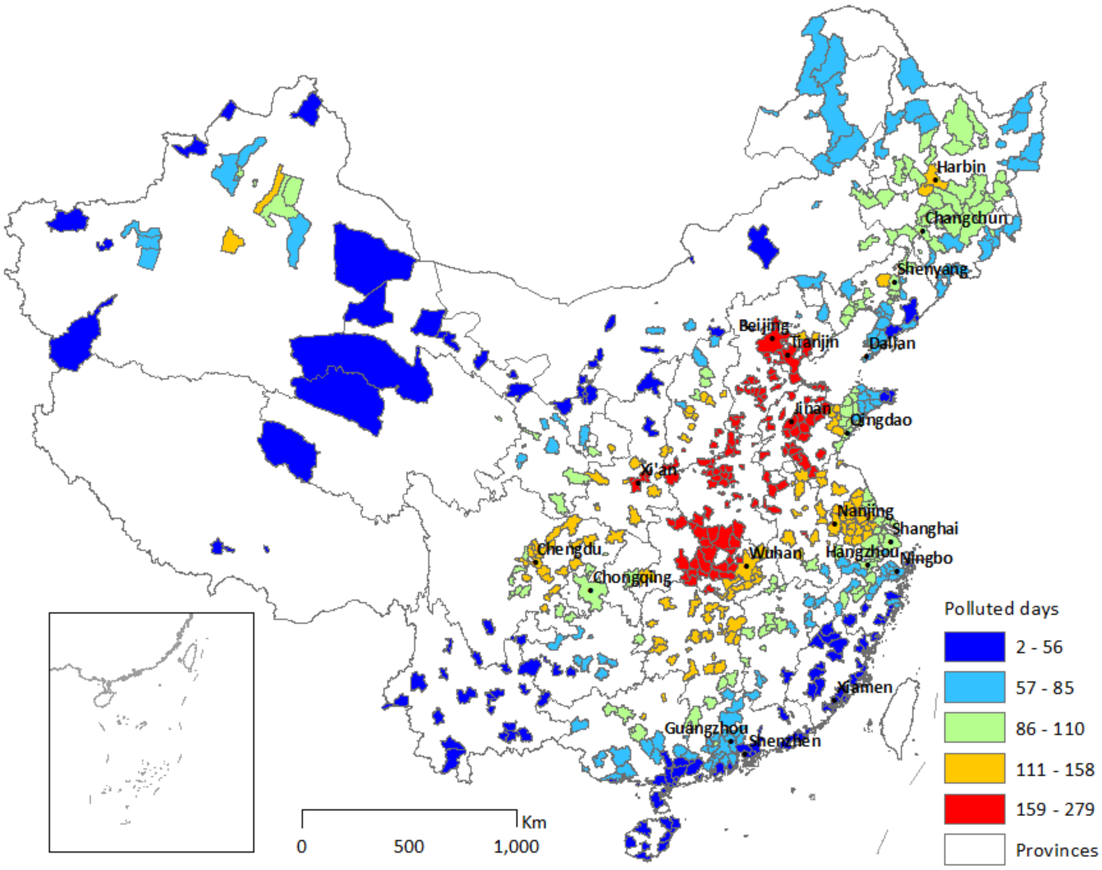


Figure 5 Polluted days for each Chinese city

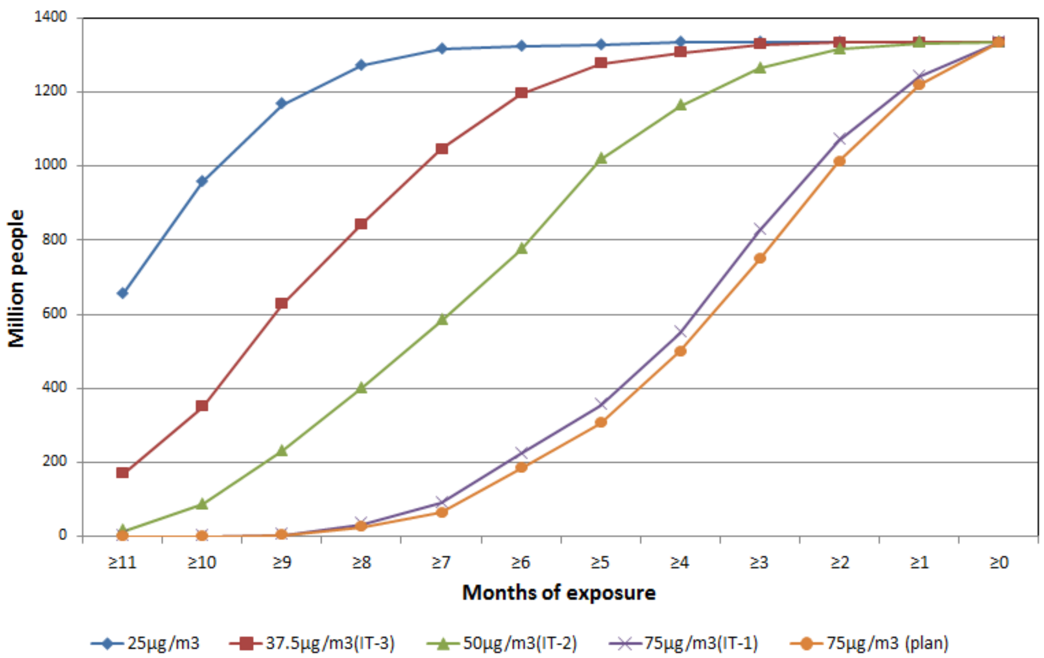


Figure 6 Statistical descriptions for polluted months under various WHO standards

Supplementary materials

S1 Inventory of estimated exposures for all Chinese cities

The inventory including a map and the raw data is available for free access at the website of the Beijing City Lab (http://www.beijingcitylab.com/projects-1/13-pm2-5/). Tables S1 and S2 rank selected Chinese cities in terms of PM2.5 pollution and the potential population exposure.

Table S1 Ranking of Chinese cities in $PM_{2.5}$ pollution

Top 20 worst cities			Top 20 best cities		
City	**Population (million)**[4]	**Days of Exposure**	**City**	**Population (million)**	**Days of Exposure**
Xingtai	0.7	279	Fuqing	1.2	15
Shahe	0.5	260	Fuzhou	2.9	15
Nangong	0.5	255	Ruili	0.2	14
Handan	1.4	253	Yongan	0.3	14
Linqing	0.7	253	Putian	1.9	12
Shijiazhuang	2.6	252	Kunming	3.5	11
Jizhou	0.4	252	Shishi	0.6	11
Gaocheng	0.8	250	Longhai	1.0	11
Jinzhou	0.5	248	Chuxiong	0.6	11
Anyang	0.6	246	Longyan	0.7	11
Xinji	0.6	245	Jinjiang	1.9	10
Wuan	0.8	244	Zhangping	0.2	10
Hengshui	0.5	241	Zhangzhou	0.5	10
Dezhou	0.6	240	Quanzhou	1.5	9
Xinle	0.5	239	Xiamen	3.5	8
Luquan	0.4	238	Nanan	1.4	8
Shenzhou	0.6	238	Yuxi	0.5	7
Liaocheng	1.1	238	Anning	0.3	6
Anguo	0.4	238	Lhasa	0.3	2
Yucheng	0.5	238	Shigatse	0.1	2

Table S2 Ranking of cities in potential population exposure to $PM_{2.5}$ pollution

City	Population (million)	Exposed days	Total exposure (million people*days)	Annual average concentration ($\mu g/m^3$)	Area(km^2)[5]
Beijing	18.9	161	3048	84	12163
Tianjin	10.4	204	2130	94	7158

[4] The population is for the whole county if a city is county-level city. For other cities with higher administrative rank, the population is for the city proper.
[5] The area is for the administrative boundary of each city, rather than the urban built-up area.

City	Population (million)	Exposed days	Total exposure (million people*days)	Annual average concentration (μg/m^3)	Area(km^2)[5]
Shanghai	22.4	88	1964	60	5476
Wuhan	9.7	158	1535	85	8583
Chengdu	7.4	150	1114	81	2171
Chongqing	11.4	97	1104	61	15385
Xi’an	6.5	162	1056	91	3569
Nanjing	7.2	138	991	76	4736
Jinan	4.1	213	873	98	3070
Zhengzhou	4.1	201	832	96	1015
Guangzhou	11.1	65	723	50	3412
Shenyang	6.3	108	676	64	3471
Harbin	5.8	115	668	69	7016
Tangshan	3.2	205	653	96	3253
Shijiazhuang	2.6	252	645	136	379
Hangzhou	6.3	98	619	66	3344
Zibo	3.1	188	589	91	2984
Suzhou	5.3	109	581	68	4606
Foshan	7.4	75	551	52	3798
Xuzhou	3.1	148	451	80	3038