Published in final edited form as:
Water Air Soil Pollut. 2014 October ; 225(10): . doi:10.1007/s11270-014-2187-3.

Air Quality in Lanzhou, a Major Industrial City in China: Characteristics of Air Pollution and Review of Existing Evidence from Air Pollution and Health Studies

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Electronic supplementary material The online version of this article (doi:10.1007/s11270-014-2187-3) contains supplementary material, which is available to authorized users.

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Abstract

Air pollution contributes substantially to global health burdens; however, less is known about pollution patterns in China and whether they differ from those elsewhere. We evaluated temporal and spatial heterogeneity of air pollution in Lanzhou, an urban Chinese city (April 2009–December 2012), and conducted a systematic review of literature on air pollution and health in Lanzhou. Average levels were 141.5, 42.3, and 47.2 μg/m^3 for particulate matter with an aerodynamic diameter ≤10 μm (PM_{10}), NO_2, and SO_2, respectively. Findings suggest some seasonality, particularly for SO_2, with higher concentrations during colder months relative to warmer months, although a longer time frame of data is needed to evaluate seasonality fully. Correlation coefficients generally declined with distance between monitors, while coefficients of divergence increased with distance. However, these trends were not statistically significant. PM_{10} levels exceeded Chinese and other health-based standards and guidelines. The review identified 13 studies on outdoor air pollution and health. Although limited, the studies indicate that air pollution is associated with increased risk of health outcomes in Lanzhou. These studies and the high air pollution levels suggest potentially serious health consequences. Findings can provide guidance to future epidemiological studies, monitor placement programs, and air quality policies.

Keywords

Air pollution; China; Human health; Lanzhou; Particulate matter; Sulfur dioxide; Nitrogen dioxide

1 Introduction

Recent reports from China document severe levels of air pollution where poor air quality dramatically lowered visibility, and airports and schools were closed (Armstrong 2013; Wong 2014). The Beijing Olympics of 2008 brought further attention to air quality in China, as efforts to lower pollution in the city were largely successful, although dependent on the continued implementation of abatement policies (Chen et al. 2013). While the health burden from ambient air pollution has declined in recent decades in many parts of the world, in China, ambient particulate matter's contribution to mortality increased from 1990 (11.58 %) to 2010 (14.86 %) (Global Burden of Disease 2014). The Global Burden of Disease project estimates that over 1.2 million persons died from ambient particulate matter in China in 2010. Ambient particulate matter is the fourth leading cause of death and disability-adjusted life years in China. Studies of the human health effects of air pollution in China have identified associations with cardiopulmonary effects (Wu et al. 2014 (in press)), blood pressure (Zhao et al. 2014), hospital admissions (Zhang et al. 2013), and years of life lost (Guo et al. 2013). Other concerns for air pollution in China include emissions of greenhouse gases (Kurokawa et al. 2013), agricultural losses (Wei et al. 2014), economic consequences (Guo et al. 2010), soil acidification (Zhao et al. 2013), and long-range transport to other regions such as the USA (Lin et al. 2014).

China is not alone with respect to air quality problems. At least one fourth of the world's population is exposed to unhealthy concentrations of ambient air pollutants (WHO 2006). Air pollution has been linked with a range of adverse human health effects, including aggravated respiratory and cardiovascular disease, reduced lung function, changes in lung tissue, acute respiratory infections, adverse pregnancy outcomes, and premature mortality (Bell et al. 2006, 2007a; US National Library of Medicine 2012). Most studies of air pollution and health were conducted for North America and Europe, with comparatively few studies examining health impacts in Latin America, and particularly Africa and parts of Asia (O'Neill et al. 2008; Wong et al. 2008). Asia is estimated to account for 65 % of all deaths from out door air pollution (Cohen et al. 2005). The relatively smaller contribution of scientific evidence from China is pronounced, given the high pollution levels, large population exposed, and increasing contribution of air pollution to overall mortality even using estimates based on studies from other parts of the world (Global Burden of Disease 2010).

When studies of air pollution and health do not exist for a particular area of interest, results from other regions are often extrapolated. A recent example of this method is the Global Burden of Disease project, which estimated mortality and loss of health by age and sex for regions of the world, using exposure-response estimates from one region to estimate health consequences in another, as local studies have not been conducted for all health outcomes and exposures (Lopez et al. 2006). A study of the economic costs of health impacts from particulate air pollution in Lanzhou for 2002 to 2009 used epidemiological associations of pollution and health from other areas of the world, finding economic losses over a billion renminbi (RMB) in most years and the highest loss of 1.66 billion RMB in 2009 (Hou et al. 2011).

This approach of applying estimates of health impacts or cost from another area, while useful, is limited because of differences in populations (e.g., demographics, health care systems, susceptible subpopulations, and activity patterns) and because of variation in air pollution characteristics (O’Neill et al. 2003). For example, earlier work has shown that the chemical structure of particulate matter varies substantially by region (Bell et al. 2007b; Son et al. 2012), and that the health impacts from particles also exhibit spatial patterns (Dominici et al. 2003, 2006).

Air pollution monitoring networks also differ across areas in terms of the pollutants measured, monitor density, and strategy for selecting monitoring sites, which can dramatically affect estimates of exposure (Bravo and Bell 2011). In many regions, air pollution monitors are placed in urban areas where air pollution levels are anticipated to be high, in order to track compliance with regulatory standards. The time when air pollution monitoring began, frequency of measurement, and population characteristics near monitoring stations can impact the design and results of studies on air pollution. Further, local studies can be more meaningful to decision makers who develop and implement efforts to protect public health from air pollution.

Although a growing number of air pollution studies have been conducted in Asia, this region remains understudied given its population and air pollution burden, especially in comparison with the depth of research in North America and Europe. A first step toward understanding the consequences of air pollution is to examine the air quality itself in terms of the overall pollution levels, spatial distribution, and pollution patterns. Recent trends in China have resulted in unprecedented access to air quality data, such as the real-time reports from air quality monitors in many areas. Still, air quality in major Chinese cities is less understood than in many major Western urban areas. Analysis of air pollution index (API) values for particulate matter with an aerodynamic diameter less than or equal to 10 μm (PM_{10}), and monitoring data in Beijing suggest potential discrepancies between measurements and reported API values and indicate the need to investigate original monitoring data (Andrews 2008).

The purpose of this paper is to investigate air pollution in Lanzhou, a major industrial city in China, using the available data for several common ambient air pollutants. We examine the spatial heterogeneity of pollutant concentrations, as previous work demonstrated that some pollutants are more heterogeneous than others and such heterogeneity can vary by season and location (Jo et al. 2000; Zhang et al. 2006). These analyses have implications for the choice of method to estimate exposure to outdoor air pollution for future studies on health. We investigate whether the spatial patterns of air pollution, for various pollutants, support assessment of exposure based on a city-wide average or if strong spatial variation exists such that more localized exposure assessment would be needed. Further, this information could be used to aid the design of air monitoring networks. We also explore whether air pollution patterns differ by season or day of the week, which has been shown in other parts of the world due to differences in weather and sources (Marr and Harley 2002). Such findings would inform the degree of potential confounding for these variables for epidemiological analysis and can provide insights into differences in sources and patterns of emissions. Pollutant levels were compared to air quality standards and guidelines to help demonstrate the overall air quality in this area. Finally, we summarize the existing, limited scientific literature on outdoor air pollution in Lanzhou.

2 Materials and Methods

2.1 Data and Study Area

The city of Lanzhou is in the Gansu Province in northern China with a population of approximately 3.5 million. It is the Gansu Province's largest city and capital. A number of industries are based in the city including an oil refinery, petrochemical industries, machinery and metallurgical industries, textile mills, food processing centers, cement manufacturing, coal mining, rubber processing, electrical power generation, medical industries, lead and zinc mining and smelting (Zhang et al. 2012), and fertilizer plants (Chen and Sun 2010; Costabile et al. 2010; Zhang et al. 2008). In addition to local pollution, dust transported from other regions affects air quality in this area. Because the city is situated in the Lanzhou Valley surrounded by mountains, pollution levels are often elevated by a stable atmosphere (Fig. 1). The annual rainfall is about 315 mm, and almost all of the rainfall occurs from May to October. Average temperature is 11.7 °C based on a weather monitor in Lanzhou (April 2009 to December 2012). Lanzhou has some of the highest air pollution levels in China and in the world (Wang et al. 2009).

Air pollution data included daily observations of PM_{10}, sulfur dioxide (SO_2), and nitrogen dioxide (NO_2) for four stations in Lanzhou. Particulate matter with aerodynamic diameter less than or equal to 2.5 μm ($PM_{2.5}$) was not measured in Lanzhou before 2013. These data were obtained from Lanzhou air monitoring stations and were available as 24-h averages. The four monitoring locations are shown in Fig. 1 and in the online supporting material in Fig. S1: (1) Huanghebei in the Chengguan District, a residential area near the Lanzhou Institute of Biological Products, which performs research and manufacturing of biological products; (2) Tieluju in the Chengguan District, residential and commercial areas near a machinery industry; (3) Xizhan in the Qilihe District, residential and commercial areas near the Lanzhou Petro-Chemical Machinery Plant, which produces large machines for oil production; and (4) Xigu in the Xigu District, an industrial area with an oil refinery company, petrochemical plant, textile mill, and other small industries. The monitors were located in the southern part of the city in the metropolitan area with high population density (Fig. 2).

Two monitoring locations, Xigu and Huanghebei, had 45 months of daily observations of PM_{10}, SO_2, and NO_2 (April 1, 2009–December 31, 2012). The other stations, Tieluju and Xizhan, had daily monitoring data for 24 months (January 1, 2011–December 31, 2012). Table 1 contains the start and end dates and percent of days with observations recorded for each station. In total, 4,114 daily observations were included in the study for SO_2, 4,138 observations for PM_{10}, and 4,137 observations for NO_2.

2.2 Analysis of Air Pollution

Since relatively little is known about ambient air pollution concentrations in China compared to some other parts of the world, identifying average pollutant levels and possible trends in pollution levels over time is of interest. Temporal trends in pollutant concentrations were evaluated by calculating monthly average concentrations for each pollutant and monitoring station. Pollutant levels were compared to multiple health-based guidelines and regulations: the US National Ambient Air Quality Standards (NAAQS), Chinese ambient air quality standards, and the World Health Organization (WHO) air quality guidelines for PM_{10}, SO_2, and NO_2 (Chan and Yao 2008; US Environmental Protection Agency 2012; WHO 2006).

The overall purpose of these standards and guidelines are similar, to protect public health from harmful air pollutants; however, their design and implementation differ. The US NAAQS are regulatory standards set at a level intended to protect human health including the protection of sensitive populations, such as children, asthmatics, and older persons. The Chinese regulatory standards are based on different levels of stringency by type of area (e.g., nature reserves, residential areas, and industrial areas). In contrast, the WHO guidelines are not enforceable standards but were published by WHO in order to provide recommendations to help lower the public health burden of air pollution by providing policy makers with targets for air quality. For this analysis, we compare air quality guidelines and standards for particulate matter to levels of PM_{10}, although guidelines and standards exist for other forms of particulate matter as well. The US regulates $PM_{2.5}$, as well as PM_{10}. The Chinese ambient air quality standards control particles through PM_{10}, $PM_{2.5}$, and total suspended particles (TSP). The WHO provides guidelines for both $PM_{2.5}$ and PM_{10}.

In addition to potential time trends and comparison to air quality standards, spatial heterogeneity of pollutants was considered. To evaluate possible spatial heterogeneity, for each monitor pair and pollutant, Pearson correlation coefficients and coefficient of divergence (COD) values were calculated and compared to the distance between monitors. Latitude and longitude coordinates of each monitoring station were used to determine distances between individual monitor pairs. The COD is defined as follows:

$$COD_{jk}=\left(\frac{1}{p}\sum_{i=1}^{p}\left[\frac{x_{ij}-x_{ik}}{x_{ij}+x_{ik}}\right]^2\right)^{1/2} \quad (1)$$

where x_{ij} and x_{ik} are the concentration of a specific pollutant (24-h average) for day i at sites j and k, and p is the number of observations (i.e., days with data for that pollutant for both monitors) (Pinto et al. 2004; Wongphatarakul et al. 1998). A low COD value indicates small differences between concentrations at sampling sites, while a value close to 1 signifies higher disparity between pollutant concentrations. COD values were calculated for each pollutant and monitor pair (i.e., six values for each pollutant based on the four monitors).

Correlation coefficients and CODs provide different types of information regarding the spatial distribution of pollutants. A correlation coefficient shows whether pollutant levels at different locations co-vary over time but does not provide information on whether the absolute levels are similar. For example, a monitor that consistently has values exactly twice that of another monitor would have different absolute levels but a correlation of 1.0. Conversely, monitors could have similar absolute levels but a low correlation. While correlation coefficients are commonly used to assess uniformity of pollutant concentrations, studies in the US indicate that they poorly predict concentration uniformity because they track temporal similarity of paired sites but do not exhibit a strong relationship with spatial homogeneity of pollutant concentrations (Pinto et al. 2004; Wilson et al. 2006). This study considers both how pollutant levels co-vary (correlations) and the relationship among absolute levels (COD). Because we compare correlations and COD values across time within monitor pairs, both spatial and temporal variations are incorporated. Both types of statistics have been used to estimate relationships among air pollutant levels in previous studies (Bell et al. 2011; Bravo and Bell 2011; Krudysz et al. 2009). All analyses were conducted in R statistical software version 2.11.1.

2.3 Review of Studies of Air Pollution and Health in Lanzhou

To better understand the state of scientific literature on human health and air pollution in Lanzhou, we performed a systematic review. We identified studies of outdoor air pollution and human health in Lanzhou by searching two scientific literature databases: (1) PubMed of the US National Library of Medicine, National Institutes of Health (US National Library of Medicine 2012), and (2) Scopus, an Elsevier database of research literature (SciVerse 2012). The final search was performed February 17, 2014. Search terms were for the title or abstract in the PubMed, and the title, abstract, or key words in Scopus. Searches were performed for the following terms: (1) Lanzhou; AND (2) “air pollution” or “air pollutant” or “air pollutants” or “particulate matter” or PM_{10} or SO_2 or NO_2; AND (3) health or respiratory or cardiovascular or mortality or hospital*, where * represents a wildcard symbol (e.g., hospital* may be hospitals or hospitalizations).

Non-English articles were included. Due to the scarcity of studies on air pollution and health in Lanzhou, we included conference proceedings.

3 Results

3.1 Characteristics of Air Pollution in Lanzhou

Table 1 summarizes concentrations for each pollutant and monitor location in terms of minimum, maximum, and average 24-h values. Boxplots of each pollutant and station are provided in Fig. 3. Median levels of PM_{10} recorded at each station were similar (Fig. 3a), and two stations (Xigu and Huanghebei) had one day with PM_{10} levels greater than 1,500 $\mu g/m^3$. One of the stations (Huanghebei) had outliers of high concentrations on 80 days (6 % of days in the study period). Here, outliers were defined as any observation greater than 1.5 times the interquartile range added to the 75th percentile value or any observation less than 1.5 times the interquartile range subtracted from the 25th percentile. For NO_2, median levels recorded at each station were similar, and one of the four stations (Huanghebei) had outliers of high concentrations on nearly 5 % of days in the study period (Fig. 3b). In the case of SO_2, median values were some what similar across stations, although Xigu had slightly higher median SO_2 concentration than the other three stations (Fig. 3c). Two of the four stations had outliers of high concentrations for SO_2 on at least 7 % of days in the study period.

Monthly average pollutant levels were calculated to evaluate temporal trends within the study period. Figure S2, S3, and S4 in the supporting material provide results for each station for PM_{10}, NO_2, and SO_2, respectively. Figure 4 shows temporal trends averaged across all monitors for each pollutant. Average levels for all pollutants fluctuated from month to month, and temporal trends were not easily identifiable. Findings suggest some seasonality in pollution levels, particularly for SO_2, which tends to have higher concentrations during colder months (e.g., October–March) relative to warmer months. However, analysis is limited by the availability of air pollutant data, for which we have three years of data for the months January to March and four years of data for the months April to December. While our findings indicate seasonal trends, data are available for only three to four sets of data per season; thus, a longer time frame of data is needed to evaluate seasonality fully. In general, the highest PM_{10} levels occurred in November–December, with higher levels also occurring in October–May, and the lowest levels in June–August. Average concentrations of SO_2 are also highest between November and February. Monthly or seasonal differences in NO_2 are less pronounced, though concentrations of NO_2 during warmer months (e.g., July–September) tend to be lower relative to cooler months (Fig. 4).

Pollutant levels can vary by day of the week in some locations because of differences in emissions from industry and traffic. For this city, analysis by day of the week did not demonstrate strong differences among concentrations across days (Fig. S5). Concentrations were similar across different days, although highest on Fridays compared to other days for all pollutants, lowest on Mondays for SO_2 or NO_2, and lowest on Tuesdays for PM_{10}.

The spatial heterogeneity of pollutant levels was examined by calculating correlation coefficients and CODs for daily (24-h) average concentrations observed at monitor pairs for each pollutant. Correlation coefficients between monitoring locations for PM_{10}, SO_2, and NO_2 plotted against the distance between monitor locations are shown in Fig. 5, and CODs for these three pollutants are shown in Fig. S6 in the supporting material. In general, correlation coefficients declined with increasing distance between monitors, while CODs increased with increasing distance between monitors. However, these trends were not statistically significant ($p>0.05$). Using a linear model for the data in Fig. 5, the average correlation for a distance of 10 km is 0.85, 0.71, and 0.57 for PM_{10}, NO_2, and SO_2, respectively, indicating less spatial heterogeneity for PM_{10} than the other pollutants. The relatively high correlations among the pollutants within the city are evidence against the hypothesis of spatial heterogeneity, especially for PM_{10} and NO_2.

3.2 Comparison to Air Quality Regulations and Guidelines

Table 2 contains the values of PM_{10}, NO_2, and SO_2 averaged across all four stations over the duration of the study period, as well as the US NAAQS, Chinese ambient air quality standards, and WHO guidelines. Figure 6 depicts the average levels for each station in comparison to US and Chinese standards and WHO guidelines. The Chinese regulations have three grades of ambient air quality standards. Grade I (first level standard) applies to nature reserves, scenic spots, and other areas of special protection; Grade II (second level standard) applies to residential areas; commercial, transportation, and mixed-residential areas; cultural areas; and general industrial areas specified in urban planning, as well as rural areas; and Grade III (third level standard) apply to industrial zones (Ministry of Environmental Protection of the People's Republic of China 1996). Grade I standards are the most stringent and Grade III the least stringent. Although we present the standards for all grades, the study region is Grade II. Chinese standards are set for both daily (24-h) and annual periods, whereas the USNAAQS and WHO guidelines are for a range of time frames including 1-h, 24-h, and annual values. The primary US NAAQS standards presented here are intended to protect public health, with an adequate margin of safety to be protective of the health of sensitive subpopulations, such as children, the elderly, and people with asthma (US Environmental Protection Agency 2012). Guidelines provided by the WHO are developed with the goal of protecting human health from adverse impacts of air pollution and are intended to inform policy makers from different countries (WHO 2011).

In the case of PM_{10}, the average concentration over the study period was higher than the Chinese Grade I standard and WHO guidelines for all stations; for three of four stations, the average concentration over the study period was lower than the US standard and the Chinese Grade II standard (Fig. 6a). Average NO_2 concentrations across the study period did not exceed Chinese ambient air quality standards, while US standards and WHO guidelines are not applicable with this data set because they both refer to 1-h concentrations instead of 24-h averages (Fig. 6b). For SO_2, the average concentration over the study period was lower than the Chinese Grade I standard at three of the four stations (Fig. 6c). The US NAAQS for SO_2 applies to a 1-h concentration and thus is not applicable to the 24-h averages available in this data set. Average SO_2 concentrations at all four stations were higher than the WHO guidelines for SO_2 of 20 μg/m^3.

3.3 Summary of Studies of Air Pollution and Health in Lanzhou

The city of Lanzhou, with about three million people, has been the subject of very few studies of how air pollution affects health compared to other cities of similar size. For example, our literature search identified 13 such studies. In contrast, Chicago, IL, in the US, also with approximately three million residents, has hundreds of such studies. Table 3 summarizes the identified studies, including the pollutants considered, time frame, health outcome, methods, and key results.

Although we searched for non-English studies, all identified studies were in English, with the exception of one study (Wang et al. 2012) in Chinese with English abstract. Of the 13 studies, four used questionnaires to assess health status, mostly for respiratory symptoms. Nine used data on hospital admissions, two for cardiovascular and cerebrovascular disease and seven for respiratory disease. The findings generally indicate that higher levels of air pollution were associated with higher risk of health outcome. However, a wide range of health outcomes have not been studied in Lanzhou, including mortality and adverse birth outcomes. The time frame of the studies was generally a few years, with the longest study at 5 years.

4 Discussion

We found high levels of air pollution in the city of Lanzhou, with an average PM_{10} concentration (141.5 μg/m^3) across the four monitors and duration of the study period more than six times greater than the WHO annual average guideline of 20 μg/m^3. NO_2 and SO_2 concentrations averaged across all monitors and over the duration of the study period also exceeded WHO guidelines. Previous work in Lanzhou has noted that the area’s topography (Fig. 1) of increased susceptibility to inversion layers, creating a stable atmosphere that allows pollution to accumulate near ground level. In addition, local coal-fueled industries, household use of coal for cooking, industry including smelters, rapidly increasing vehicle ownership and use, freight transfer stations, and transport of dust from the Hexi region of Gansu Province contribute to the air quality issues in Lanzhou (Chen and Sun 2010; Feng and Wang 2012; Niu et al. 2011; Qi et al. 2001; Ta et al. 2004; Xie et al. 2010). In fact, air pollution in Lanzhou has been so severe that civil servants were asked to walk to work, rather than use vehicles, on high pollution days (Lie 2007). A previous study found higher levels of TSP in Lanzhou compared to three other Chinese cities (Wuhan, Chongqing, Guangzhou), but the lowest levels of NO_x, and second highest levels of SO_2 (Qian et al. 2001). That study also measured several size fractions of particulate matter in schoolyards in the four cities, finding Lanzhou to have the highest coarse particulate matter and TSP. Results from our study suggest that concentrations of pollutants in Lanzhou remain a cause for concern.

In general, the measured pollutants did not exhibit spatial heterogeneity, with less heterogeneity in PM_{10} than the other pollutants. This result suggests that issues of spatial misalignment, where health and pollution data are on different spatial scales (e.g., city-level health data vs point-level exposure data) may be less problematic for epidemiological research in Lanzhou than in other areas with more spatially heterogeneous pollution patterns, and underscore the need to investigate spatial heterogeneity of the locations and pollutants of interest (Peng and Bell 2010).

Our results indicate a lack of strong day-of-the-week patterns and some seasonal patterns for pollution levels, with lowest PM_{10} in summer and higher SO_2 in November through February. This indicates that day of the week may not be an important confounder in studies of short-term exposure to air pollution in this area. However, sensitivity analysis (e.g., including and then omitting day of the week as a variable in separate models) could further investigate this issue. Further, our finding of generally higher pollutant concentrations in winter compared to summer months is consistent with the sparse previous studies of ambient air pollution in Lanzhou (Chu et al. 2008a, b; Costabile et al. 2010; Ma 2013; Qian et al. 2001; She et al. 2011; Ta et al. 2004; Wang et al. 2009). Winter in this area is characterized by a stable atmosphere, particularly during the nighttime (Chu et al. 2008a).

Data availability remains an issue in this region of the world. Additional monitor locations, hourly concentration data, information on other pollutants (e.g., ozone, size distributions of particulate matter), and a longer historical record would allow for a more detailed analysis of long-term trends in pollution levels over multiple years, examination of diurnal trends in pollution levels, and a more powerful analysis of spatial heterogeneity or spatial patterns in pollutant distribution. The current monitoring network in Lanzhou includes measurements of $PM_{2.5}$ and carbon monoxide (CO). Such information and research would contribute greatly to a more complete understanding and characterization of air pollution in Lanzhou.

The high concentrations of air pollutants in Lanzhou imply substantial health consequences to Lanzhou residents. Our findings of seasonal variability in air pollution concentrations have implications for future studies that examine how health is affected by air pollution in the region. Studies identified through our systematic review indicate that air pollution is associated with human health in Lanzhou, although a small number of health responses were investigated, typically for short time frames. These few health studies combined with the high levels of pollution observed in this study and earlier work suggest a potentially substantial health burden for residents of this city and suggest the need for future epidemiological studies of health risk.

Our findings have implications for other major industrial cities in China and other growing urban centers, which may have either no or recent air quality monitoring programs.

According to Ministry of Environmental Protection of the People’s Republic of China, Lanzhou is similar to most Chinese cities suffering from heavy air pollution (Ministry of Environmental Protection of the People’s Republic of China 2014). These cities share major air pollution sources, including industrial emissions, coal combustion, fugitive dusts, and traffic emissions. Lanzhou has consistently ranked as one of the ten worst cities for air pollution since the Chinese government began releasing the air pollution index for major cities in 2003.

These results demonstrate levels of air pollutants that are likely to be associated with a strong public health burden, although little scientific research has been conducted to date to link pollution to health specifically in this city. Expanding industrial centers in China can be accompanied by air pollution levels that relate to the type, size, and ownership of industry (Wang and Deng 2013). Decisions made in the next few decades regarding the rapid urbanization of Chinese cities, with a doubling of the population from 2000 to 2030 (Cao et al. 2012; Chiu 2012) will have a profound effect on air quality and public health, especially in the context of a changing climate (Gu and Han 2010). Achieving healthy levels of air quality may be more difficult under a changing climate, for example, as higher temperatures promote tropospheric ozone formation. In fact, rapid urbanization of Lanzhou has increased the urban heat island effect in recent decades (Li et al. 2010; Pan and Yang 2013; Qin et al. 2011).

Our data includes information through 2012; however, since the end of 2011, the Gansu Provincial government has implemented a series of environmental protection initiatives, and the Ministry of Environmental Protection has stated that the air quality in Lanzhou has improved substantially in recent years (Ministry of Environmental Protection of the People’s Republic of China 2014). Therefore, the Ministry sets Lanzhou as an example for other major cities in the Beijing-Tianjin-Hebei region and Yangtze River delta region. In order to inform air quality control in other cities, understanding is needed of the spatial and temporal patterns of air pollution in Lanzhou before and during the implementation of environmental initiatives for air quality. Future work on air pollutant levels after these initiatives, combined with this work of air quality conditions up through 2012, can support investigation of the accountability of these environmental policies and initiatives.

5 Conclusions

We investigated air quality in Lanzhou and identified high levels of air pollution, with PM_{10} concentrations exceeding health-based regulations and guidelines. Our systematic review of studies on outdoor air pollution and health identified 13 studies, which is an order of magnitude lower than the number of similar studies for many other cities. However, the existing studies generally found that air pollution in Lanzhou is associated with increased risk of health outcomes such as hospital admissions for respiratory disease. The findings on the spatial and temporal patterns of air pollutants can inform future epidemiological studies, as well as aid the design of networks for air pollution monitors. The high levels of air pollution combined with the review of the scientific literature indicate that ambient air pollution presents a substantial public health concern in Lanzhou.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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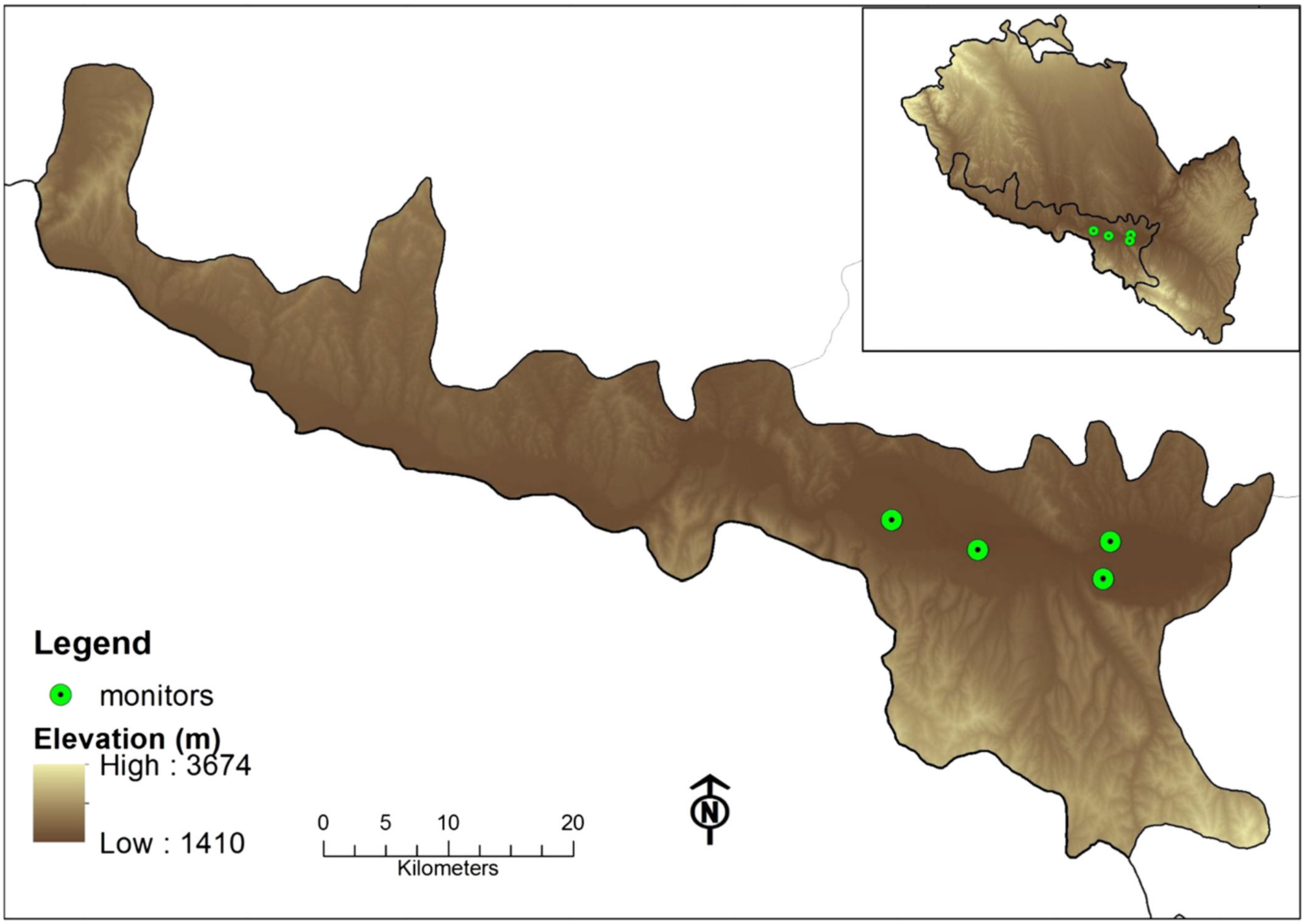

Fig. 1.

Elevation of Lanzhou City center and placement of monitors

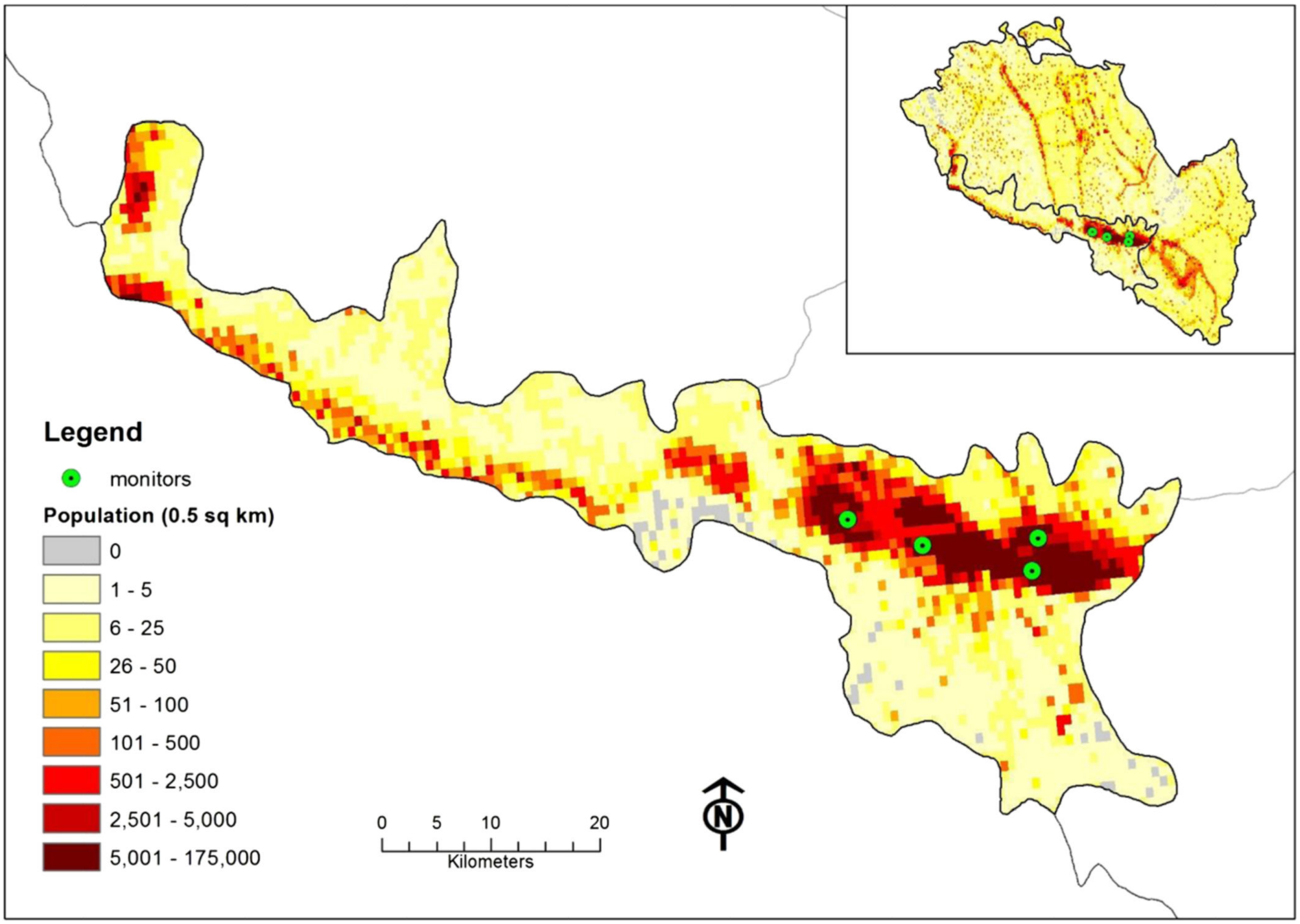

Fig. 2.

Population of Lanzhou City center and placement of monitors

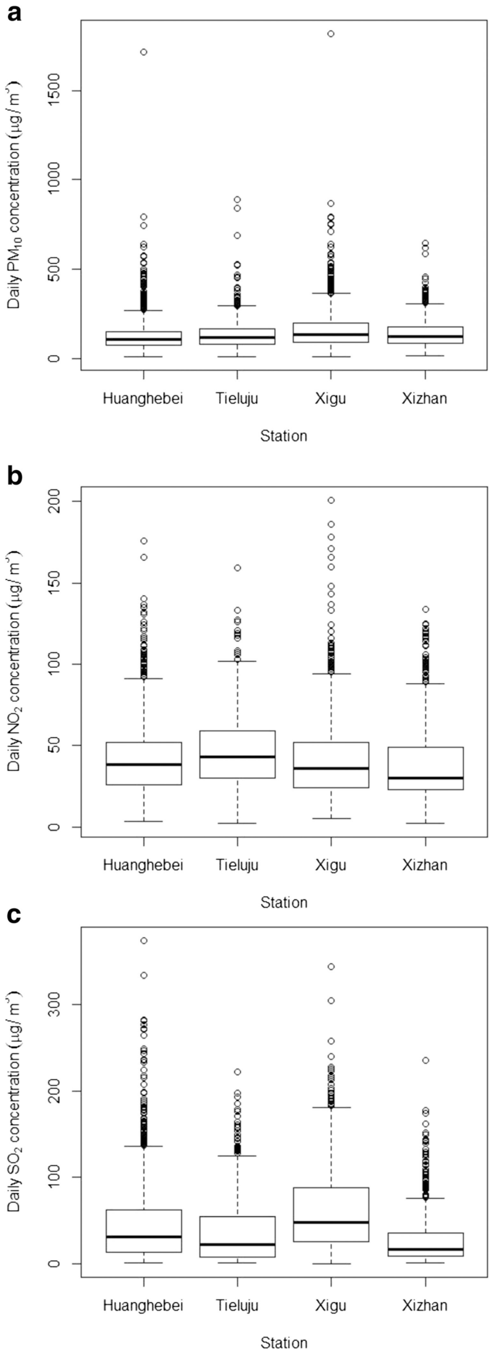

Fig. 3.

Pollutant levels over the study period, by station. **a** PM_{10}; **b** NO_2; **c** SO_2. Note: The *upper and lower horizontal lines of the box* represent the 75th and 25th percentiles, respectively. The *horizontal line within a box* represents the median. The *open circles* (outliers) represent observations less than the 25th percentile—1.5 × interquartile range (IQR), or larger than the 75th percen-tile+1.5×IQR. The *vertical line above each box* represents the 75th percentile to the lowest observation that exceeds the 75th percentile, but is not an outlier. The *vertical* *line below each box* represents the 25th percentile to the highest observation that is lower than the 25th percentile, but is not an outlier

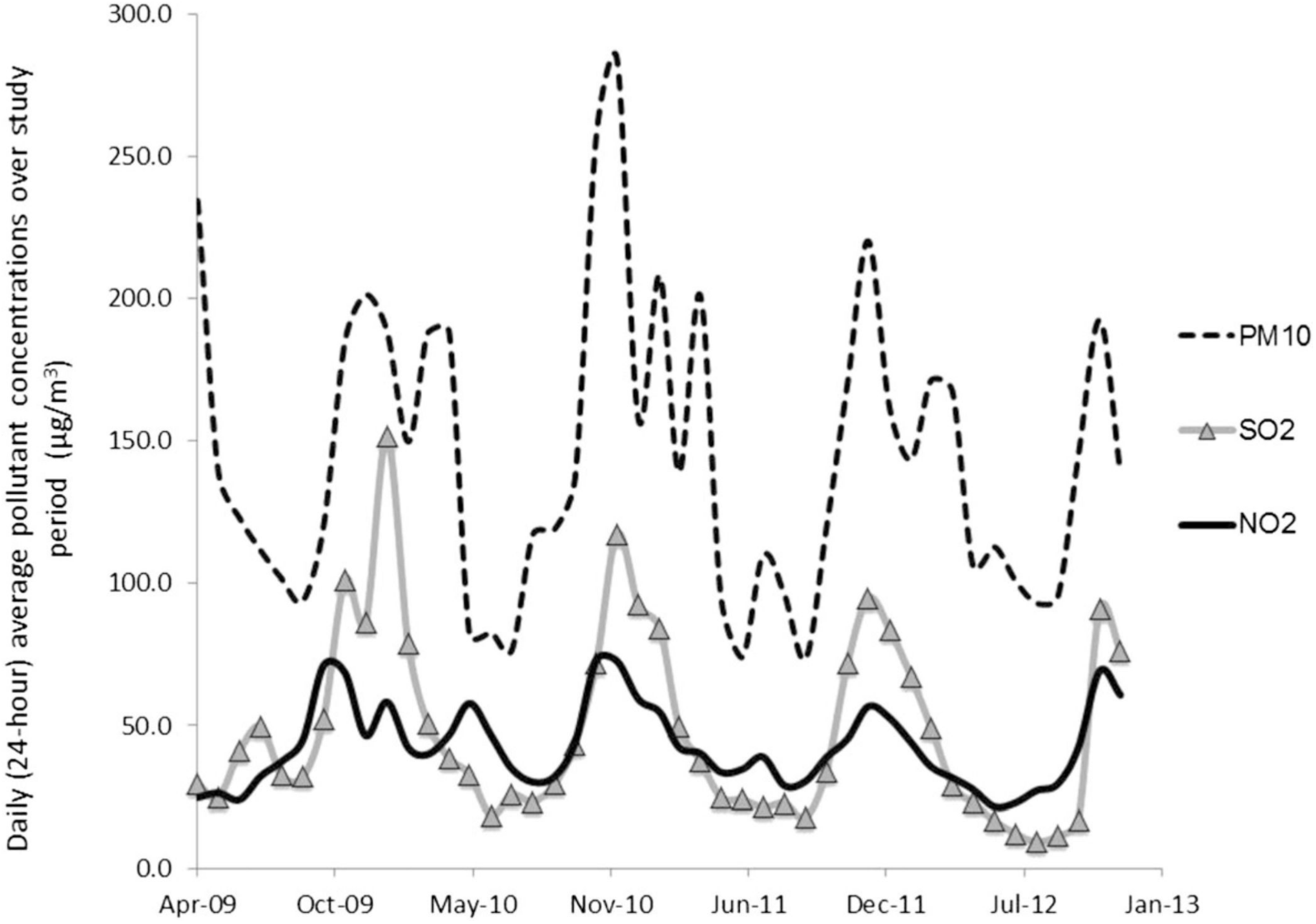

Fig. 4.

Average pollutant concentrations across study area and period

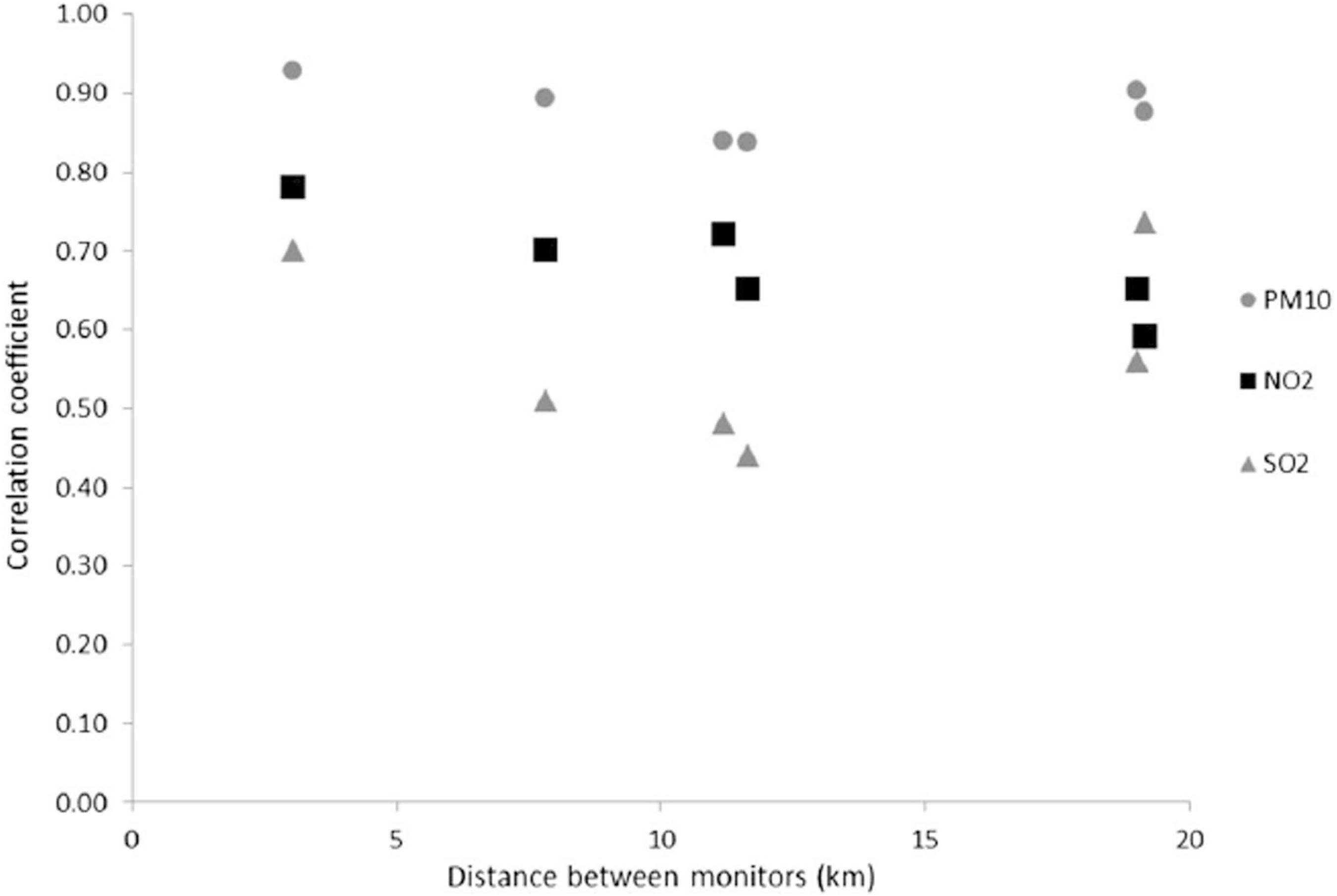

Fig. 5.

Correlation between daily average observed pollution levels versus distance between monitor locations

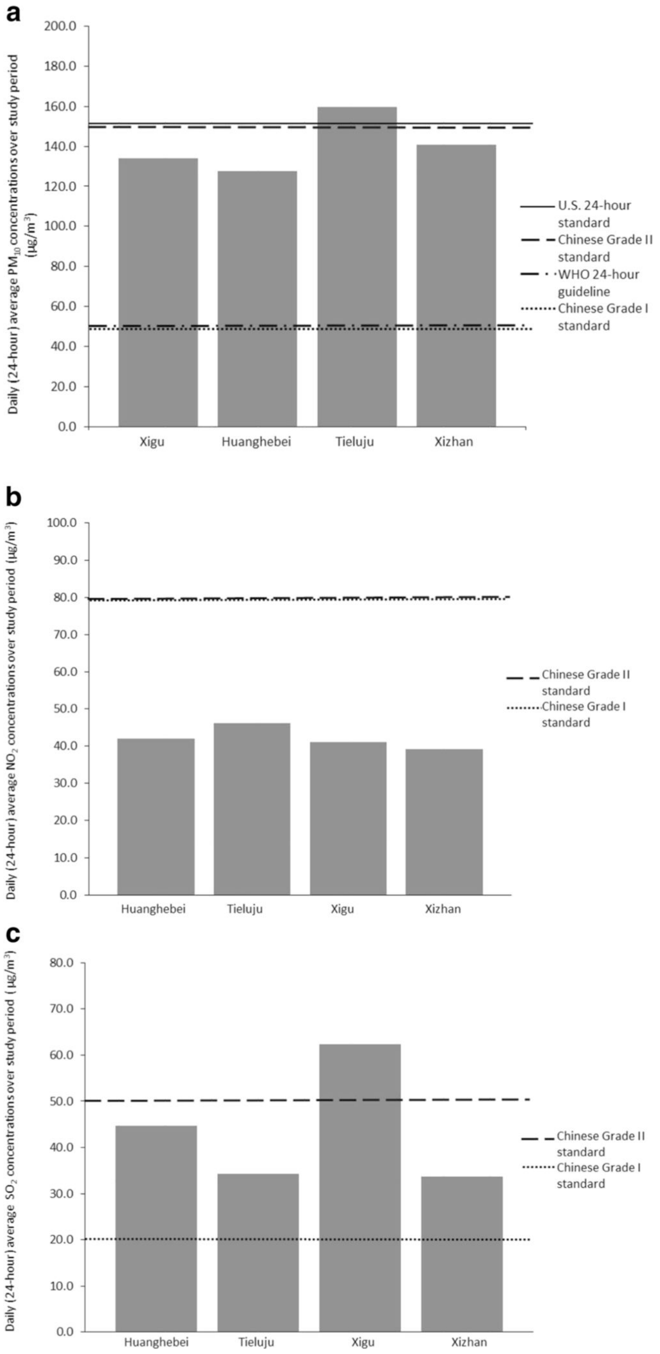

Fig. 6.

Pollutant average pollutant concentrations versus standards and guidelines, by station. **a** PM_{10}; **b** NO_2; **c** SO_2. Note: Chinese Grade III PM_{10} standard, 250 μg/m^3 (not shown). Chinese Grade III NO_2 standard, 120 μg/m^3 (not shown); US NAAQS and WHO NO_2 guidelines (not shown) are not for 24-h averages. Chinese Grade II SO_2 standard, 150 μg/m^3; Chinese Grade III SO_2 standard, 250 μg/m^3 (not shown); US SO_2 NAAQS (not shown) are for 1-h concentrations, not for 24-h averages

Table 1

Summary of 24-h pollutant concentrations and data in the study period

		Location			
	Dates of observations	**Xigu April 1, 2009–December 31, 2012**	**Huanghebei April 1, 2009–December 31, 2012**	**Tieluju January 1, 2011–December 31, 2012**	**Xizhan January 1, 2011–December 31, 2012**
PM_{10}	Average (standard deviation) (μg/m^3)	158.8 (118.0)	127.7 (95.5)	133.8 (86.6)	140.6 (79.7)
	Minimum to maximum 24-h value (μg/m^3)	9.0 to 1,818	10.0 to 1,712	11.0 to 887	15.0 to 645
	Percent of days with data	99 %	98 %	98 %	99 %
NO_2	Average (standard deviation) (μg/m^3)	41.1 (24.5)	42.2 (23.0)	46.1 (21.5)	39.1 (24.3)
	Minimum to maximum 24-h value (μg/m^3)	5.0 to 201	7.0 to 176	2.0 to 159	2.0 to 134
	Percent of days with data	99 %	98 %	99 %	98 %
SO_2	Average (standard deviation) (μg/m^3)	62.0 (46.3)	46.9 (48.0)	38.5 (39.9)	28.6 (30.5)
	Minimum to maximum 24-h value (μg/m^3)	1.0 to 344	1.0 to 374	1.0 to 222	1.0 to 235
	Percent of days with data	98 %	95 %	98 %	99 %

Table 2

Comparison of daily averages to ambient air quality standards and guidelines

	Pollutant (levels, standards, and guidelines)			Percent of days in the study period in which the standard was exceeded (%)		
	PM_{10}	NO_2	SO_2	PM_{10}	NO_2	SO_2
Average 24-h concentration during study period (μg/m^3)	141.5	42.0	47.2	NA	NA	NA
US NAAQS[a,b,c]	150	188 (1 h) 99.6 (annual)	196.2 (1 h)	33.1	NA	NA
WHO guideline[b]	50 20 (annual)	200 (1 h) 40 (annual)	20	93.7	NA	36.7
China NAAQS Grade I	50 40 (annual)	80 40 (annual)	50 20 (annual)	93.7	7.4	37.1
China NAAQS Grade II	150 100 (annual)	80 40 (annual)	150 60 (annual)	33.1	7.4	2.1
China NAAQS Grade III	250 150 (annual)	120 80 (annual)	250 100 (annual)	10.3	<1	<1

All standards are for 24-h concentrations unless otherwise noted

[a] US standards for NO_2 and SO_2 are set in parts per billion (ppb) but are presented here in micrograms per cubic meter (μg/m^3). Conversions were based on standard ambient pressure and temperature

[b] US NAAQS and WHO guidelines for NO_2 concentrations are for 1-h concentrations, which were not available in this data set

[c] US NAAQS for SO_2 is for a 1-h concentration

Table 3

Summary of air pollution and health studies for Lanzhou, China

	Exposure metric	**Time frame**	**Study population**	**Health metric**	**Methods**	**Key results**
Qian et al. (2000)	Areas categorized from lowest to highest air pollution based on TSP, $S0_2$, and NO_x	Winters of 1988–1989	Children (5–14 years) in urban areas. Assessed districts from three Chinese cities (Lanzhou, Wuhan, and Guangzhou). Total of 2,789 children, 750 from Lanzhou	Long-term average respiratory symptoms and illnesses as assessed by parents' questionnaire	Unconditional logistic regression to compare health responses in Lanzhou to that of Guangzhou (cleaner city). Levels of pollution are also compared.	Compared to Guangzhou, higher risk of cough, phlegm, respiratory hospitalizations, bronchitis, and pneumonia; higher TSP and slightly higher $S0_2$ and NO_x levels
Qian et al. (2004a)	Four categories of exposure based on PM_{25}, TSP, $S0_2$, NO_x	1993–1996	Children (5–16 years) in four Chinese cities (Lanzhou, Chongqing, Guangzhou, and Wuhan). Total of 7,058 children, 1,372 from Lanzhou	Respiratory symptoms assessed by parent/ guardian's questionnaire: cough, phlegm, cough with phlegm, wheeze, bronchitis, and asthma	Cluster analysis to generate exposure categories. Logistic regression modeling	Monotonic, positive relationship between exposure category and phlegm and wheeze
Qian et al. (2004b)	Estimated lifetime exposure to heating coal smoke and cooking coal smoke	1993–1996	Children (5–16 years) in four Chinese cities (Lanzhou, Chongqing, Guangzhou, and Wuhan). Total of 7,058 children, 1,372 from Lanzhou	Respiratory symptoms assessed by parent/ guardian's questionnaire: cough, phlegm, cough with phlegm, wheeze, bronchitis, and asthma	Scenario evaluation approach to estimate exposure (none; lightly, moderately, or heavily exposed) based on questionnaire. Logistic regression	Heating coal smoke associated with risk of phlegm, cough with phlegm, and bronchitis (based on data from all four cities).
Sun et al. (2013)	Estimated, gridded PM_{10} based on TSP.	2001–2005	General population. Data from four hospitals	Daily hospital admissions for respiratory disease	Generalized additive models. Threshold effects assumed	Estimated PM_{10} associated with respiratory hospitalizations
Tao et al. (2012)	Sand dust estimated by Meteorological Bureau of Gansu Province	Spring (March-May) for 2001–2005	General population.	Daily hospital admissions for respiratory diseases	Semi-parametric generalized additive model	Sand dust associated with respiratory disease
Tao et al. (2013)	$N0_2$, PM_{10}, and $S0_2$	2007–2009	General population.	Daily hospital admissions for respiratory diseases	Semi-parametric generalized additive model	All pollutants associated with hospital visits, especially for children and the elderly
Tao et al. (2014)	$N0_2$, PM_{10}, and $S0_2$	2001–2005	General population. Data from four general hospitals.	Hospitalizations for respiratory disease	Generalized additive model	Higher risk of respiratory disease hospital admissions with higher levels of $N0_2$, PM_{10} or $S0_2$, especially for women and the elderly
(Wang et al. 2010) [conference paper]	Air pollution index (API)	2004–2007	General population	Hospitalizations for respiratory disease	Generalized additive Poisson model	Higher risk of respiratory hospitalizations with higher API
(Wang et al. 2012) [in Chinese with English abstract]	$N0_2$ and $S0_2$	2001–2005	General population	Daily hospital admissions for respiratory diseases	Semi-parametric generalized additive model	Higher risk of respiratory disease hospital visits with higher levels of $N0_2$ or $S0_2$

	Exposure metric	Time frame	Study population	Health metric	Methods	Key results
						especially for women and the elderly especially for women and the elderly
Zhao et al. (1998)	78 traffic police as the exposed group, 57 office police as the control group	1996	General population	Health questionnaires. Measures of peripheral blood lymphocytes	Comparison of questionnaire responses for 78 traffic police, 57 office police	Significant differences among groups for several health outcomes (e.g., rhinitis, trachoma). Higher levels of micronuclei and sister- chromatid exchanges in the exposed group
Zheng et al.(2012)	Daily average PM_{10} $S0_2$, and $N0_2$	2001–2005	General population	Daily hospital admissions for cardiovascular and cerebrovascular diseases	Unidirectional case crossover analysis.	PM_{10} associated with total circulatory and cardiovascular diseases. $N0_2$ associated with cardiovascular and cerebrovascular diseases
Zheng et al. (2013)	PM_{10}, $S0_2$, and $N0_2$	2001–2005	General population. Data from four large comprehensive hospitals	Daily hospital admissions for cardio-cerebrovascular disease	Generalized additive model	PM_{10}, $S0_2$, and $N0_2$ associated with hospital admissions for cardiac diseases; $S0_2$ and $N0_2$ associated with cerebrovascular disease. Higher effects in the elderly
Zhu et al. (2012)	Monthly averages of $S0_2$, $N0_2$, and PM_{10}	2001–2005	General population	Monthly average hospital admissions for lower respiratory disease for the Xigu District hospital	Optimization relation association rule based on relational algebraic theory	$S0_2$ associated with hospital admissions