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Spatial associations between social groups and ozone air pollution exposure in the Beijing urban area

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ABSTRACT

Few studies have linked social factors to air pollution exposure in China. Unlike the race or minority concepts in western countries, the *Hukou* system (residential registration system) is a fundamental reason for the existence of social deprivation in China. To assess the differences in ozone (O_3) exposure among social groups, especially groups divided by *Hukou* status, we assigned estimates of O_3 exposure to the latest census data of the Beijing urban area using a kriging interpolation model. We developed simultaneous autoregressive (SAR) models that account for spatial autocorrelation to identify the associations between O_3 exposure and social factors. Principal component regression was used to control the multicollinearity bias as well as explore the spatial structure of the social data. The census tracts (CTs) with higher proportions of persons living alone and migrants with non-local *Hukou* were characterized by greater exposure to ambient O_3. The areas with greater proportions of seniors had lower O_3 exposure. The spatial distribution patterns were similar among variables including migrants, agricultural population and household separation (population status with separation between *Hukou* and actual residences), which fit the demographic characteristics of the majority of migrants. Migrants bore a double burden of social deprivation and O_3 pollution exposure due to city development planning and the *Hukou* system.

1. Introduction

Environmental justice (EJ) first emerged in the United States and Canada where it is now an important part of environmental and public health policy assessments. The concept draws attention to the questions of whether certain social groups bear disproportionate burdens of environmental externalities, and whether policies and practices that are related to sources of nuisance and pollution or environmental resources are equitable and fair (Bowen, 2002; Fairburn et al., 2009; Jerrett et al., 2001). There are certain subgroups of the general population that are likely to suffer from higher exposure to air pollution, depending on social status, ethnic group, race, educational level, etc. For example, Pope found that O_3 concentrations increased with an increasing proportion of the Native American population in the Phoenix metropolitan region (Pope et al., 2016). Gray found that the average tract-level O_3 concentrations during the ozone season were significantly associated with socioeconomic variables (e.g., median household income, poverty percentage, percentage of the population with less than a high school education) (Gray et al., 2013).

In the past 35 years, China has experienced remarkable economic growth and rapid agricultural-to-industrial and rural-to-urban transitions. As a consequence, China now faces many daunting environmental challenges such as indoor and outdoor air pollution, which are significantly affecting human health and quality of life (Gong et al., 2012; Lü et al., 2015). Systematic and quantitative research on who is most affected by air pollution is relatively lacking in China. Ma (2010) examined the issue of environmental inequality through an analysis of the geographical distribution of industrial pollution sources in Henan Province and concluded that rural residents, especially rural migrants, are disproportionately exposed to industrial pollution. Schoolman and Ma (2012) analyzed locations of air and water emissions in Jiangsu Province and reported that communities with a higher proportion of rural migrants were likely to live near industrial emission sources.

The race or minority concept in EJ research, which is of great concern in western countries, does not fit well in the Chinese context. Ma (2010) argued that *Hukou* status might play the role that racial classification has historically played in America and Europe. To balance rural-urban development and control the growth of large cities, China

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implemented a *Hukou* system to restrict inter-regional and rural-urban migration in the 1950s (Chan et al., 1999). The *Hukou* system divides the urban population into four groups: local residents with non-agricultural *Hukou* (local urban residents), local residents with agricultural *Hukou* (suburban farmers), migrants with non-agricultural *Hukou* registered elsewhere (urban migrants), and migrants with agricultural *Hukou* registered elsewhere (rural migrants). Migrants in large and developed cities are generally characterized by relatively low social status in China (li, 2016). Migrants with agricultural *Hukou* undergo a slow citizenization process and face many obstacles such as access to adequate public services and social identity (Wei and Su, 2013). In addition to the local-migrant *Hukou* divide and the urban-rural *Hukou* divide, a collective-family *Hukou* divide is another important type of *Hukou* status. The population with collective *Hukou* refers to those who lack the conditions required to establish their own households and can register only in collective households, and this population is mainly composed of immigrant employees and businessmen (Zhou, 2015). Compared to migrants and the collective registered population, the local and family registered populations enjoy more adequate social welfare and rights (i.e., social security, job opportunities, educational opportunities, access to public resources) (Li et al., 2015; Li, 2015).

The *Hukou* system is one of the most important institutions in China as it defines a person's access to welfare benefits. The *Hukou* system is a fundamental reason for the existence of social deprivation (Ouyang et al., 2016). The discrimination phenomenon caused by *Hukou* status can be observed in Beijing where comprehensive social welfare packages are exclusively provided to the local residents (Shi et al., 2017).

Beijing is severely polluted by O_3, which is a major secondary air pollutant after $PM_{2.5}$ and has exceeded the national ambient air quality standards for four consecutive years since 2013 with an increasing trend (Cheng et al., 2017). The well-documented adverse health effects caused by O_3 include premature death, asthma and increased hospitalization rates (Bell et al., 2005; Stieb et al., 1996; Wong et al., 1999). Jerrett et al. (2009) examined the effect of long-term exposure to ozone on air pollution–related mortality and demonstrated a significant increase in the risk of death from respiratory causes in association with an increase in ozone concentration. Adverse health outcomes, including mortality, cardiovascular morbidity and pregnancy outcomes have been attributed to both short term and long term exposure to ozone (Brunekreef and Holgate, 2002). Our study primarily intended to test the hypothesis that the *Hukou* system has caused inequality in O_3 (daily 8-h maximum) exposure at the CT scale in the Beijing urban area.

2. Methodology

2.1. Study area and census data

The Beijing urban area was selected as the study site given the availability of air pollution monitoring data and its representativeness as a large and developed city in China. The study area includes six districts (county level): Xicheng, Dongcheng, Haidian, Chaoyang, Shijingshan, and Fengtai. The study area is 1378 km^2, accounting for 8.4% of the total area of Beijing. The sixth National census revealed that the official population of the Beijing urban area is 11,950,124, constituting 60.9% of the total population in Beijing (National Bureau of Statistics of China, 2010). We matched the census data from the urban area of Beijing to the administrative map of 2010. In total, 129 census geographic units (street level) were formulated after the data were processed and merged in Microsoft Excel software and ArcGIS software, version 10.0 (Supplementary Table 1).

We selected a series of variables from the census indicators to obtain a comprehensive view of social deprivation. Those variables included *Hukou* status, educational attainment, family size, age and gender. Educational attainment and age were included in the research by Ma on environmental inequality in Henan Province of China (Ma, 2010). The other variables except for *Hukou* status were selected based on previous studies in western countries (Crouse et al., 2009; Goodman et al., 2011; Padilla et al., 2014; Pinault et al., 2016; Zou et al., 2014). The *Hukou* status variable included migrants (vs. locals), agricultural population (vs. urban population), collective registered population (vs. family registered population), collective household population (vs. family household population), which is composed of collective registered individuals. Since the actual residences of all migrants and almost one-third of the local population were different from their *Hukou* locations in Beijing (Wang, 2011), a population status with separation between *Hukou* and actual residences (household separation) was also included in the study. The educational attainment indicators included college graduates, postgraduates or above, and illiterate. Seniors over 60 and children under 14 were used as indicators of vulnerable populations. One-person family (living alone), large family (family composed of four or more people) and extended family (family with three or more generations living together) were used as indicators of special family structures. All variables are expressed as proportions; that is, the amount of the population with a certain characteristic divided by the total population within the census tract.

2.2. Air pollution exposure

At the end of September 2012, immediately after the publication of the 'Environmental Air Quality Standards', the Beijing Environmental Protection Bureau gradually released real-time air pollution data to the public. We calculated the daily 8-h maximum O_3 concentrations from March of 2013 to February of 2014 for each air quality monitoring station using hourly O_3 data. Then we averaged the daily 8-h maximum O_3 concentrations to generate an annual average concentration estimate. The missing and abnormal data that might affect the accuracy of pollution simulation account for 11.12% of initial hourly data. Considering cases with missing or abnormal data have very scattered distribution, we directly deleted them before calculating daily O_3 8-h maximums. A total of 35 monitoring sites are unequally distributed over Beijing, dense in the urban area and sparse in the suburban area (Fig. 1). Then, we used GIS-based spatial analysis techniques to estimate the air pollution levels of the locations between air monitoring stations.

Kriging models are considered optimal interpolators because they supply the best linear unbiased estimate of the value of the variable at any point in the coverage (Lloyd et al., 1998). Among the various forms of kriging, ordinary kriging (OK) is frequently and widely used. OK assumes a constant but unknown mean, which allows for the construction of an unbiased estimator that does not require prior knowledge of the stationary mean of the observed values (Pang et al., 2010). As a complement to the OK method, we used a universal kriging model that considered the obvious concentration trend of ambient O_3 in the study area. Other interpolation methods, including spline and inverse distance weighted (IDW) interpolation, are considered more appropriate for areas where monitoring stations are sparsely distributed or where a certain kind of dominant trend in pollution concentration exists (Ding et al., 2016; Xu, 2016). All three of these interpolation methods were applied to generate the O_3 surfaces of the Beijing urban area. The validation indexes used in this study are average error (AE), average absolute error (ABE), average relative error (ARE) and mean square root (MSR). The interpolation model with the smallest values of those indexes was selected and applied to the field. Finally, the annual CT-scale O_3 concentrations were generated using the partition statistics module. The interpolation and partition statistics methods were implemented in ArcGIS 10.0.

3. Statistical analyses

All variables were transformed to their closest approximation of the normal distribution (Supplementary Table 3) and analyzed. Pearson