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Increment of ambient exposure to fine particles and the reduced human fertility rate in China, 2000–2010

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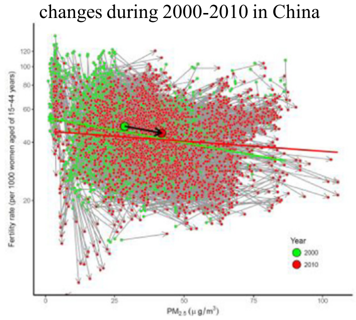
HIGHLIGHTS

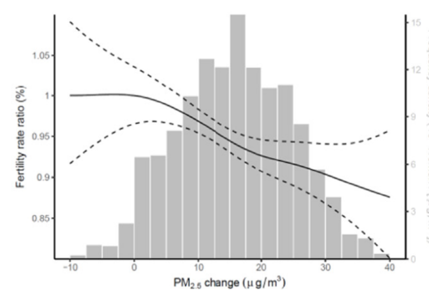
- A few studies indicate air pollution can reduce human reproductive capacities.
- We link $PM_{2.5}$ increment to fertility rate reduction from 2000 to 2010 in China.
- This study adds to new evidence of the infertility effect of $PM_{2.5}$ in China.
- For the first time, we quantify $PM_{2.5}$-attributed burdens of childlessness in China.

GRAPHICAL ABSTRACT

Observed $PM_{2.5}$, fertility rate and their changes during 2000-2010 in China



Estimated exposure-response function between $PM_{2.5}$ and fertility rate in China



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ABSTRACT

Epidemiological and toxicological studies suggest that exposure to ambient fine particles ($PM_{2.5}$) can reduce human reproductive capacity. We previously reported, based on spatial epidemiology, that higher levels of $PM_{2.5}$ exposure were associated with a lower fertility rate (FR) in China. However, that study was limited by a lack of temporal variation. Using first-difference regression, we linked temporal changes in FR and $PM_{2.5}$ with adjustment for ecological covariates across 2806 counties in China during 2000–2010. Next, we performed a sensitivity analysis of the variation in the $PM_{2.5}$–FR association according to (1) geographic region, (2) indicators of the level of development, and (3) $PM_{2.5}$ concentrations. Also, we quantified the reduction in the FR attributable to ambient $PM_{2.5}$ in China for the first time. The FR decreased by 3.3% (1.2%, 5.3%) for each 10 $\mu g/m^3$ increment in $PM_{2.5}$. The association varied significantly among the geographic regions, but not with the level of development. Nonlinearity analysis suggested a linear exposure–response function with an effect threshold of ~8 $\mu g/m^3$. We also found that comparing to the 2000 scenario, increment of $PM_{2.5}$ in 2010 might result in a reduction of 2.50 (2.44, 2.60) infants per 1000 women aged 15–44 years per year in China. Our results confirm the statistical association between ambient particles and FR and suggest that poor air quality may contribute to childlessness in China.

1. Introduction

Low fertility leads to an aging population, which is a major economic and social issue globally (Butler, 1997; Dummer et al., 2011). Low fertility can be caused by demographic policies (Mcdonald, 2006), socioeconomic dynamics [e.g., urbanization (Guo et al., 2012) and gender

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inequality (Galor and Weil, 1969)], and unknown factors. Although a major reason of low fertility is delayed marriage and childbearing in face of social stress, environmental exposure to toxic chemicals has also been identified to harm natural fertility by triggering reproductive abnormalities, such as low sperm quality (Carlsen et al., 1992; Diamantikandarakis et al., 2009). Recently, epidemiological and toxicological studies suggest that long-term exposure to ambient particles, including fine particles with diameters <2.5 μm ($PM_{2.5}$), may decrease human fertility by reducing sperm quality (Hammoud et al., 2010; Han et al., 2011; Hansen et al., 2010), fecundability (Dejmek et al., 2000), and fertilization (Bloom et al., 2017; Carré et al., 2017b), and by increased incidence of stillbirth (Faiz et al., 2012; Faiz et al., 2013). Thus, increasing concentrations of $PM_{2.5}$ may be associated with a reduced fertility rate (FR) (Carré et al., 2017a; Mahalingaiah et al., 2016; Vizcaino et al., 2016). Actually, some pathological pathways underlying the adverse effects of ambient pollutants, such as disruptions of the endocrine system (Carré et al., 2017a) also make the negative correlation between $PM_{2.5}$ and FR biologically possible. Indeed, this association has been examined by several spatial epidemiological studies (Nieuwenhuijsen et al., 2014; Xue and Zhang, 2018). Strictly speaking, spatial epidemiology like ours (Xue and Zhang, 2018), which evaluates the association between health outcomes and environmental exposures by exploring their spatial concordance, tests the hypothesis that the FR in a geographic unit with higher ambient pollutant levels tends to be lower than the FR elsewhere. Due to the lack of temporal variation, such spatial epidemiology in ecological level does not directly determine the variation in the FR caused by changes in long-term exposure to air pollutants.

We conducted a spatial epidemiological study of the county-level FR in China using satellite-based estimates of $PM_{2.5}$ with adjustment for area-level covariates using the 2010 census data (Xue and Zhang, 2018). We reported that the FR decreased by 2.0% (95% confidence interval [CI]: 1.8%, 2.1%) for each 10 μg/m^3 increment in $PM_{2.5}$ assuming that the spatial association was a good approximation of the effect of $PM_{2.5}$ on fertility. In current study, we incorporated the temporal variations in FR and $PM_{2.5}$ from 2000 to 2010 in China, and re-examined their association using the method of first-difference regression. The model linked changes in the FR to $PM_{2.5}$ changes between the 2 years across a variety of county-level units. First-difference regression has been applied to analysis of life expectancy, particularly the association between life expectancy and ambient particles (Correia et al., 2013; Pope 3rd et al., 2009) and their chemical components (Dominici et al., 2015).

Driven by the economic growth and rapid urbanization of China, the anthropogenic emissions of particulate matter considerably increased during 2000–2010 (Guan et al., 2014), which increased the ambient concentrations of $PM_{2.5}$ (Liu et al., 2017; Ma et al., 2016). According to a recent study that reconstructed a historical $PM_{2.5}$ time series from records of visibility (Liu et al., 2017) during 1996–2004, the annual mean population-weighted exposure to $PM_{2.5}$ increased by 0.24 μg/m^3/year (95% CI: 0.14, 0.34). Ma et al. (2016) estimated the historical $PM_{2.5}$ from satellite measurements of aerosol optical depth (AOD), and reported a comparable trend of 1.97 μg/m^3/year (1.32, 2.72) during 2004–2007 across China. The anthropogenic-emission-driven increment of $PM_{2.5}$ provided a quasi-experimental scenario through which to study how health indicators vary after a dramatic change in air quality.

Making use of two cross-sectional censuses of China in 2000 and 2010 and satellite-based estimates of $PM_{2.5}$ during 1999–2010, we first derived the temporal variations in FR, exposure to ambient $PM_{2.5}$, and several county-level covariates, and then estimated the FR–$PM_{2.5}$ association using a log-linear model with adjustment for covariates and a spatial trend. Using sensitivity analysis, we explored the geographic variation of, effect modifications on, and nonlinearity of the FR–$PM_{2.5}$ association. Finally, we quantified the reduction in the FR attributable to $PM_{2.5}$ increment from 2000 to 2010 in China.

2. Methods

2.1. Data source

The study is based on publicly available data. Censuses data can be acquired from the related publications (National Bureau of Statistics of China, 2003; National Bureau of Statistics of China, 2012) or the website of National Bureau of Statistics of China (http://www.stats.gov.cn/). $PM_{2.5}$ exposure data can be freely obtained from the link: http://fizz.phys.dal.ca/~atmos/martin/?page_id=140 (accessed Jan. 23, 2018).

2.2. Study population

The study domain was selected as the mainland of China (excluding Hong Kong, Macro, Taiwan, and some islands in the North China Sea) (Fig. 1). We selected the year 2000 and 2010 for the study, when the most recent two censuses including surveys on human fertility were conducted. We first geocoded the 2000 and 2010 county-level censuses separately, and then matched the geographic units from the two datasets using administrative codes and boundaries. For the counties whose administrative boundaries changed during the period, we split the 2010 census data according to the weights of their areas overlapping with the map of 2000. In total, we matched 2806 county-level areas (Fig. 1) and obtained the 2000 and 2010 census data for each of them. Based on the two census databases, we derived the following variables: (1) fertility rate (FR), the ratio of the number of newborns (N_B; i.e., the population aged less 1 year) to the number of women 15 to 44 years old (N_F); (2) percentage of urban residents (Urban [%], calculated as the number of urban residents divided by the number of total population); (3) sex ratio (F/M, calculated as the ratio of the total number of females to the total number of males); (4) percentage of college-educated females (CollegeF [%], calculated as the number of female with education attainment equal to or above college level divided by the number of total population); (5) percentage of minority nationalities (Minority [%], calculated as the number of non-Han people divided by the number of total population); and (6) percentage of immigrants (Immigrants [%], calculated as the number of immigrant residents divided by the number of total population). The original variables, such as the number of newborns and the number of urban residents can be directly obtained from the census databases. For reasons of data availability, we used the percentage of immigrants as a surrogate for the level of development of a county instead of the gross regional product *per capita* (which was used in our previous study). Internal migration in China has been evidenced to contribute to the economic growth (Ping and Shaohua, 2005), and the two variables were significantly correlated with a Pearson coefficient of 0.65 (95% CI: 0.63, 0.67) in the 2010 database. Because the willingness of childbearing cannot be measured directly, we utilized several socioeconomic factors (i.e., Urban, F/M, CollegeF, Minority and Immigrants) as surrogates. For instance, CollegeF indicates the percentage of women who may putting off having children in favor of their careers.

2.3. $PM_{2.5}$ exposure

The long-term exposure to $PM_{2.5}$ was derived from published annual and global estimates with a spatial resolution of 0.1° (approximately 10 km) based on satellite-measured AOD (Van Donkelaar et al., 2016). Satellites with equipped sensors can retrieve the column concentration of aerosol (i.e., AOD) from the ground surface to the top of atmosphere from the electromagnetic signals. Since earth observing satellites (e.g., Terra and Aqua) finish a global scan every one or two days, the satellite-retrieved AOD has been evidenced as a good predictor with global coverage for ground surface $PM_{2.5}$. During 2008–2013, the satellite-based estimates were shown to be in good agreement with annual averages of *in-situ* observations ($R^2 = 0.81$), according to the cross-validation results (Van Donkelaar et al., 2016). Due to the lack of *in-situ*