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Do socioeconomic factors modify the effects of PM1 and SO2 on lung cancer incidence in China?

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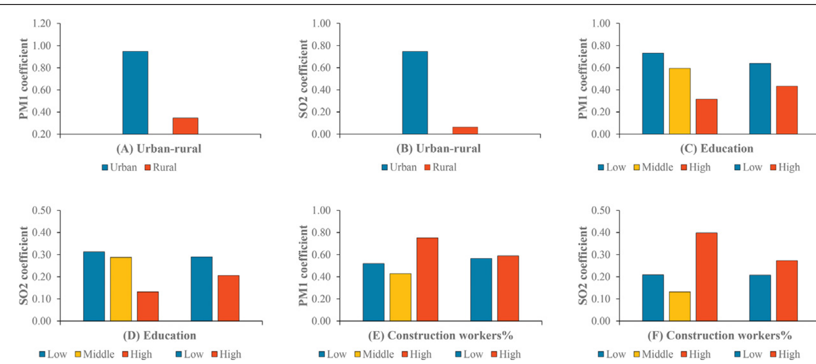
HIGHLIGHTS

- One of the earliest studies investigating socioeconomic modifying roles on the effect of PM1 in China
- Male residents in urban areas have a high risk of lung cancer incidence associated with ambient PM1.
- Male residents with low education levels suffer from larger effects of PM1 and SO2 on the incidence rate of lung cancer.
- There is no modification effect of the proportion of construction workers.

GRAPHICAL ABSTRACT



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ABSTRACT

Background: It remains uncertain whether socioeconomic factors modify the effect of air pollution on human health. Moreover, studies investigating socioeconomic modifying roles on the effect of PM1 are quite limited, especially in developing countries.
Objectives: The present study aims to investigate socioeconomic modification effects on the associations of the incidence rate of male lung cancer with ambient PM1 and SO2 in China.
Methods: We conducted a nationwide analysis in 345 Chinese counties (districts) between 2014 and 2015. In terms of multivariable linear regression models, we examined the modification effects of urban-rural division, education level and proportion of construction workers in the stratified and combined datasets according to the tertile and binary divisions of the three factors. Moreover, we performed three sensitivity analyses to test the robustness of socioeconomic modification effects.
Results: We found a larger effect of PM1 on the incidence rate of male lung cancer in urban areas than in rural areas. The association between PM1 (or SO2) and the incidence rate of male lung cancer was stronger in counties with low education levels than in those with high education levels. The findings of the significant modification effects of urban-rural division and education level were robust in the three sensitivity analyses. No significant modification effect was observed for the proportion of construction workers.

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Conclusions: Male residents in urban areas have a high risk of lung cancer incidence associated with ambient PM1. Male residents with low education levels suffer from larger effects of PM1 and SO2 on the incidence rate of lung cancer. Area- and population-specific strategies should be developed to reduce the urban-rural and educational disparities in air pollution effects, which thereby alleviates air pollution-associated health disparities in China.

1. Introduction

Air pollution has been a great risk to human health. Numerous studies have indicated the detrimental effect of air pollution on human health (Pope III et al., 2002; International Agency for Research on Cancer, 2016b). However, there is substantial heterogeneity in effect estimates among these studies. One potential explanation for the differential estimates may be relevant to socioeconomic status which can modify the effect of air pollution. Theoretically, socioeconomic factors can modify the association between air pollution and health outcome mainly through three pathways, namely the differences in material resources, biological factors and psychological stress (Peters et al., 2001; Kan et al., 2008; Clougherty et al., 2014). A better understanding of socioeconomic modification effects is not only a key methodological issue (i.e. cofounder, modifier or both) in the field of air pollution, but also informative in policy making which aims to attenuate health disparities. Despite a few efforts (Kan et al., 2008; Chen et al., 2017; H. Guo et al., 2019), however, whether there are socioeconomic modification effects has not been well investigated in China.

Studies investigating socioeconomic modification effects are concentrated in developed countries. In general, there remains the debated hypothesis that people with low socioeconomic statuses are associated with greater effects of air pollution exposures. Several studies are in support of this hypothesis (Jerrett et al., 2004; Miller et al., 2007; Kan et al., 2008; Chi et al., 2016). In particular, a time-series study conducted in Hong Kong used the social deprivation index (SDI) to measure the socioeconomic status of each tertiary planning unit (i.e. TPU, the smallest analysis unit in Hong Kong) and indicted that residents living in areas (i.e. TPUs) with high SDI are faced with larger effects of NO2 and SO2 on all nonaccidental, cardiovascular and respiratory mortality (Wong et al., 2008a). Similarly, using mortality data collected from the National Centre for Health Statistics of United States, a case-crossover study suggested that educational level negatively modifies the association between PM10 and daily mortality (Zeka et al., 2006).

By contrast, some studies do not find socioeconomic modification effects (Samet et al., 2000; Schwartz, 2000; McGuinn et al., 2016). For example, O'Neill et al. (2004) examined the modification effects of six socioeconomic variables and a composite socioeconomic index and found that these factors do not significantly modify the association between exposure to ambient ozone and daily mortality in the city of Mexico. Ren et al. (2010) reported that there are no significant modification effects of socioeconomic factors on the relationship between ozone exposure and mortality in eastern Massachusetts, USA. However, there are few studies reporting the findings which are contrary to the proposed hypothesis (Atkinson et al., 2013; Bravo et al., 2017). With the data derived from a US cohort of 836,557 patients, Atkinson et al. (2013) reported that patients who are least deprived suffer from high risks of heart failure incidence associated with long-term exposure to PM10 and NO2.

Apart from inconsistent findings, efforts and improvements are required in previous studies. Firstly, studies examining socioeconomic modification effects are quite limited in developing counties (Zhou et al., 2015; Yin et al., 2017). Using data collected from 295 Chinese counties from 2006 to 2014, H. Guo et al. (2019) reported that male residents in rural areas or counties with low financial (or educational) levels are at a high risk of PM2.5-associated lung cancer incidence in China. A study conducted in Beijing, Tianjin and Hebei Province of China indicated that smog episodes and PM2.5 pollution have larger detrimental effects on mortality in rural areas than in urban areas in this region (Zhou et al., 2015). However, such studies are still limited. Moreover, the findings from the Western studies may not be applicable in China due to the great differences in air pollution levels (especially for PM2.5) and population characteristics (e.g. urban-rural disparity) between China and Western countries (World Health Organization, 2016; Yin et al., 2017). All of these highlight the significance of investigating socioeconomic modification effects in developing counties such as China, but such studies are still limited.

Secondly, little attention has been placed on air pollutants such as PM1. Most studies focus on PM10, PM2.5, SO2 (mostly conducted in developed countries), NO2 and O3 (Samet et al., 2000; Beelen et al., 2008; Yin et al., 2017), while other air pollutants have been seldom targeted, especially for PM1 (G. Chen et al., 2017). There are increasing evidences suggesting that compared with the severe PM2.5 (or coarser PMs) pollution in Chinese cities, PM1 pollution has a larger detrimental effect on human health (Brook, 2008; Lin et al., 2016; G. Chen et al., 2017; Hu et al., 2018). This mainly results from the smaller particle size of PM1, which can be inhaled more deeply into human lungs and thus causes a greater adverse effect on human health. However, studies examining socioeconomic modification effects on PM1 pollution-health outcome associations are quite limited, partly as a result of the unavailability of PM1 data (e.g. there are 91 PM1 monitoring stations in China).

Apart from PM1, few studies pay attention to the severe sulfur dioxide (SO2) pollution in developing countries, especially for China. China is the first order SO2 emitter in the world, with the value of annual mean concentration of SO2 in 338 Chinese cites ranging from 3 to 87 $\mu g/m^3$ in 2015 (Ministry of Environment Protection, 2015). Moreover, SO2 not only contributes to the formulations of coal-smoke air pollution and the secondary PMs, but also can adversely affect human health through systemic inflammation and oxidative stress (Routledge et al., 2006; Deng et al., 2017; Wang et al., 2018). Despite the severity of SO2 and its detrimental health effect, however, little attention has been paid to SO2 pollution in developing counties, especially for the socioeconomic modifying role on the effect of SO2.

To fill the gaps above, with the data collected from 345 Chinese cancer registries (counties/districts) from 2014 to 2015, the present study aims to investigate whether the effects of PM1 and SO2 on the incidence rate of male lung cancer vary among populations with different socioeconomic statuses. We used the multivariable linear regression model to examine socioeconomic modification effects in the stratified and combined datasets according to the tertile and binary divisions of socioeconomic indicators. We also tested whether the findings of socioeconomic modification effects are robust to the control of smoking and additional air pollutants, and exposure to air pollution with different lag structures (i.e. single and moving-average lags).

2. Materials and methods

2.1. Research area

The present study aims to investigate the modifying roles of socioeconomic factors in 345 Chinese cancer registries. As shown in Fig. 1, there are 259 rural registries (counties) and 86 urban registries (districts). The 345 registries were selected primarily as a result of the available lung cancer (2006–2015) and PM1 concentration data (2014–2015). They are dispersed over 31 of 34 Chinese provinces, autonomous regions and municipalities and are home to around 221.59

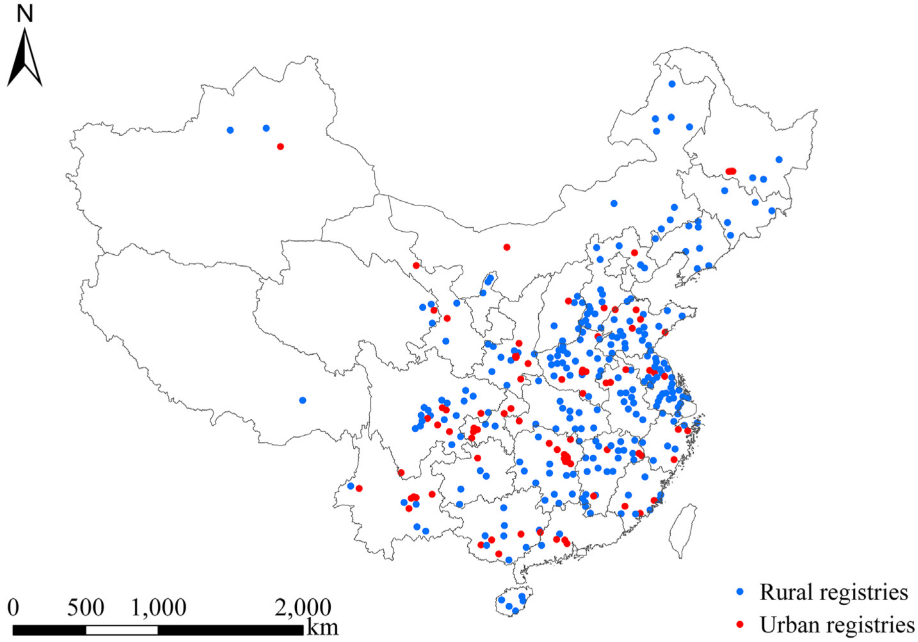

Fig. 1. Spatial distributions of the 345 cancer registries in China.

million residents in 2015 (China Statistical Yearbook (County level), 2016). The annual mean PM1 of the 345 Chinese cancer registries between 2014 and 2015 was 38.86 μg/m^3. The annual mean SO2 was 27.40 μg/m^3, which is higher than the 24-hour average value stated in the WHO air quality guideline at 20 μg/m^3 (World Health Organization, 2006).

2.2. Data collection

2.2.1. Health outcome (i.e. age-standardized incidence rate of male lung cancer)

The variable of health outcome is the annual age-standardized incidence rate of trachea, bronchus and lung cancer (ICD-code: C33–34) for males in each county (or district) (i.e. the incidence rate of male lung cancer hereinafter). It is defined as the number of incidents of lung cancer for males per 100,000 people per year in a registry (e.g. county and district), which is age-standardized according to the Segi's world population (He and Chen, 2018, 2019). Hence, the data source of health outcome has excluded the effects of age and sex. We focus on lung cancer in the present study, primarily because lung cancer represents the most popular cause of cancer incidences in China (Chen et al., 2016; He and Chen, 2018, 2019). Moreover, the incidence rate of lung cancer is more than two times higher for males than for females, with the values of 50.07 per 100,000 people and 23.60 per 100,000 people, respectively, according to the 2017 China Cancer Registry Annual Report (He and Chen, 2018). Therefore, we select the incidence rate of male lung cancer as health outcome in the present study.

Data on the incidence rate of male lung cancer between 2014 and 2015 were derived from the 2017–2018 China Cancer Registry Annual Report (He and Chen, 2018, 2019). The causes of incidences have been specified in the report according to the International Classification of Diseases version 10. These annual reports were released by the Chinese Cancer Registry of the National Cancer Centre, China. The establishment of the Chinese Cancer Registry is to provide the timely information, such as the number and rate of cancer incidence, which is considerably comprehensive and representative at the national scale. The 2017 annual report released the data of cause-specific cancer incidence for 339 cancer registries in 2014. The 339 cancer registries are located in 31 of 34 Chinese provinces, autonomous regions and municipalities and are home to more than 288 million residents in 2014 (He and Chen, 2018). Fig. 2(A–B) presents the spatial distributions of the incidence rate of male lung cancer in 2014 and 2015, respectively.

2.2.2. Air pollution (i.e. PM1 and SO2)

The variable of air pollution is the annual mean PM1 (or SO2) concentration in each county (or district). According to the volume 109 of the International Agency for Research on Cancer Monographs on the Evaluation of Carcinogenic Risks to Humans (International Agency for Research on Cancer, 2016b), outdoor air pollutants, including PM2.5 and SO2, have been identified as the Group I carcinogenic factor to lung cancer. In particular, ambient particular matter (e.g. PM1, PM2.5 and PM10) has become one of the most important risk factors to lung cancer diseases in the world (Wang et al., 2020a). From the biological perspective, air pollution exposure can increase cancer risks in human beings through the increase in genetic damage, such as cytogenetic abnormalities, altered gene expression and mutations happening in somatic and germ cells (International Agency for Research on Cancer, 2016b). Empirically, several studies have suggested the adverse effects of air pollution on lung cancer diseases (Pope III et al., 2002; Hamra et al., 2014; Guo et al., 2016; Guo et al., 2020). Moreover, it has been suggested that PM1 has the largest effect on human health among the three prominent PM pollutants (i.e. PM1, PM2.5 and PM10) in Chinese cities (Lin et al., 2016; G. Chen et al., 2017; Hu et al., 2018). Furthermore, the impacts of PM1 pollution and its interactions with socioeconomic factors on human health are not yet well understood in China, partly because of the few ground observations of PM1 data in nationwide China (i.e. 91 monitoring stations). Therefore, PM1 and SO2 are selected as the targeted air pollutants in the present study.

We collected PM1 data from our previous study (Wei et al., 2019). The previous study estimated daily PM1 concentrations at 1 km^2 spatial resolution from 2014 to 2018 in China. In this dataset, a space-time extremely randomized trees (STET) model was developed to estimate the near-surface PM1 concentrations using MAIAC (Multi-Angle Implementation of Atmospheric Correction) AOD (aerosol optical depth) data, in combination with data of meteorology, MEIC (multi-resolution emission inventory for China) pollution emission, land use, topography, road, population, and the spatiotemporal information. One of the strengths of the STET model relies on that similar to some prior studies

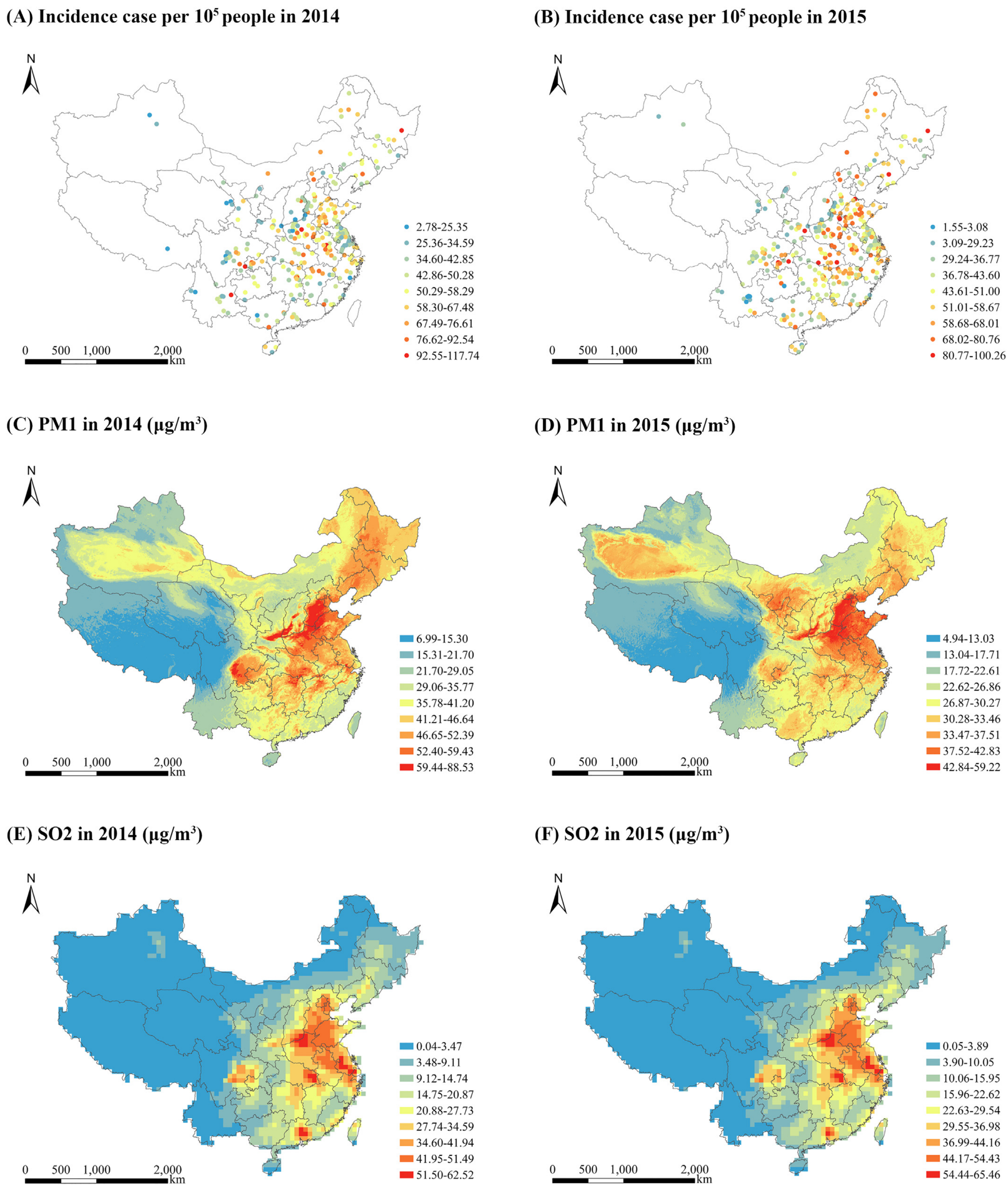

Fig. 2. Spatial distributions of the incidence rate of male lung cancer and air pollutions.

(Di et al., 2016; Wei et al., 2020, 2021), this model incorporates the spatial and temporal autocorrelations of PM1 concentrations as model inputs, which has significantly improved the accuracy of PM1 estimates (Wei et al., 2019). Moreover, given that different variables as model input can produce different efficiency and accuracy of PM1 estimates, Wei et al. (2019) excluded variables that show less contributions through calculating and ranking the importance scores of all variables in the STET model. According to the results of the ten-fold crossvalidation, there is high consistency between the predicted daily PM1 concentrations and ground-level measurements, with R^2 and root-mean-square error (RMSE) equal to 0.77 and 14.6 μg/m^3, respectively (Wei et al., 2019). Regarding the monthly mean PM1 concentrations across China, they were calculated through averaging PM1 concentrations for each grid where has sufficient daily PM1 values in a month. Seasonal and annual maps of PM1 concentrations are thereby produced in terms of the calculated monthly PM1 maps. According to the results of the evaluation based on 1650 matched data samples, the estimated seasonal and annual PM1 concentrations are highly in line with ground-level measurements, with R^2 equal to 0.97 and RMSE less than 4.1 μg/m^3 (Wei et al., 2019).

We collected SO2 data from the monthly time-series dataset of M2TMNXAER (V5.12.4) at 0.5° × 0.625° grid (https://disc.gsfc.nasa.gov/datasets/M2TMNXAER_5.12.4/summary). This dataset is one of the products of the Modern-Era Retrospective analysis for Research and Applications version 2 (Merra-2: the latest global atmospheric reanalysis dataset), released by the Global Modelling and Assimilation Office of the National Aeronautics and Space Administration, USA. More details of the Merra-2 dataset can refer to Randles et al. (2017) and Buchard et al. (2017). Briefly, the Merra-2 reanalysis dataset was produced using the GEOS (i.e. Goddard Earth Observing System Model) Atmospheric Data Assimilation System (version 5.12.4). Considering the bias between the observations and background forecast, a 3DVAR algorithm was used to correct such bias, which thereby produced the time series dataset from 1980 to the present including the targeted variable (i.e. SO2 surface mass concentration) in the present study (Gelaro et al., 2017). To date, the SO2 data derived from the Merra-2 dataset have been widely used in Chinese and Western studies, such as examining the spatiotemporal variations of SO2 (Eltahan and Magooda, 2018) and the associations of SO2 with environmental factors and migration (S. Chen et al., 2017). Moreover, some variables acquired from the Merra-2 dataset, especially for AOD (i.e. Aerosol Optical Depth), have also been widely used in air pollution studies (Liu et al., 2019; Ghosh et al., 2019; J. Guo et al., 2019; Wang et al., 2020b). Fig. 2(C–F) shows the spatial distributions of PM1 and SO2 concentrations in 2014 and 2015 in China.

2.2.3. Socioeconomic variables, location and time

Seven socioeconomic variables are included as covariates. They are average education years (years), finance per capita (10^8 RMB), proportion of construction workers (%), employment rate (%), proportion of manufacturing workers (%), urban–rural dummy variable, and population size (10^4 people). These variables are selected to control the differences in health outcome caused by economic status, education level, occupation, and socioeconomic status (i.e. a comprehensive measure) based on some previous studies (Wong et al., 2008b; Elo, 2009; Zhou et al., 2015; Bravo et al., 2017). We extracted socioeconomic data from the China Statistical Yearbook (County level), Tabulation of the 2010 Population Census of the People's Republic of China, Report on the Work of the Government, and the Statistical Communique on National Economic and Social Development. Consistent with some prior studies (Ebenstein et al., 2017; H. Guo et al., 2019), degrees of longitude and latitude are used to control the effect of location, while the time dummy variable is selected to control the effect of time.

2.2.4. Smoking factors

As in some prior studies (Raaschou-Nielsen et al., 2013; Hart et al., 2015; International Agency for Research on Cancer, 2016a), smoking prevalence and the number of cigarettes smoked per day are used to adjust for the effect of smoking on lung cancer diseases. The smoking data were derived from the 2015 China Health and Retirement Longitudinal Study (CHARLS) wave3 (specifically, the module of health status and functioning of the CHARLS survey), which were publicly released by the National School of Development of Peking University (http://charls.pku.edu.cn/en/page/data/2015-charls-wave4). The CHARLS survey is mainly to evaluate the social, economic and health conditions of Chinese residents with ages 45 and older. As a high-quality nationally representative survey, the CHARLS recruited the respondents (i.e. 10,257 households and 17,708 individuals) from 28 of 30 Chinese province-level administrative units (except Tibet, Hong Kong, Taiwan and Macao) (Zhao et al., 2020).

2.3. Statistical analysis

We examined socioeconomic modification effects in two steps. The first one was relevant to data stratification according to socioeconomic factors. Similar to studies examining modification effects (Wong et al., 2008a; Chen et al., 2018), the whole data were firstly stratified into three categories in accordance with the tertile split of socioeconomic factor. We then divided the whole data into two categories according to the binary division of the same factor. The multiple divisions adopted in the present study is to investigate the modification effects of socioeconomic factors in a robust way instead of the solely three- or two-category division used in most prior studies (Ren et al., 2008; Ostro et al., 2014; Qin et al., 2017).

In the second step, we developed a multivariable linear regression model to determine socioeconomic modification effects in terms of the stratified and combined datasets. For the estimate in the stratified datasets, we included annual mean PM1 (or SO2) concentration, time dummy variable, degrees of longitude and latitude (location factors), average education years, finance per capita, proportion of construction workers, employment rate, proportion of manufacturing workers, urban–rural dummy variable and population size (composite socioeconomic variables) in the regression model. We compared the estimated effects of PM1 (or SO2) among socioeconomic subgroups (for tertile division: low, middle and high; for binary division: low and high) in the stratified datasets. Then, we combined the stratified data and added the interaction (s) between PM1 (or SO2) and socioeconomic dummy variable to the regression model. This is to determine whether socioeconomic factors significantly modify the association between air pollution and the incidence rate of male lung cancer. Given that socioeconomic dummy variable has high collinearities with not only PM1 (or SO2) but also its interaction (s), we did not include socioeconomic dummy variable in the regression model. We investigated the modification effects of three socioeconomic factors, namely urban-rural division, education level and proportion of construction workers.

Finally, three sensitivity analyses were conducted. Firstly, we investigated whether the findings of socioeconomic modification effects are sensitive to the control of smoking factors. Following some prior studies (Raaschou-Nielsen et al., 2013; Hart et al., 2015; International Agency for Research on Cancer, 2016a), smoking prevalence and the number of cigarettes smoked per day are selected. The smoking data that we can derive from the CHARLS survey are available at city level, so we attributed districts/counties belonging to the same city with the same smoking behaviours. Also, because the smoking data obtained from the CHARLS survey are not available for all counties/districts of the present study, we kept the samples of counties/districts located in the cities of the CHARLS survey, which left approximately 45% of the original number (i.e. 345) of counties/districts for the sensitivity analysis. Secondly, we examined whether the findings of socioeconomic factors with significant modification effects are robust to the inclusion of additional air pollutants. For PM1, we tested whether our findings are sensitive to the inclusion of SO2 in the regression model and vice versa. Thirdly, we investigated whether the findings of socioeconomic modification effects are sensitive to air pollution exposures with different lag structures. We considered both the single (lag1–lag8) and moving-average (lag01–lag08) lags. As our PM1 data sources are only available from 2014 to 2015, we tested the sensitiveness of socioeconomic modification effects to SO2 exposures with different lag structures in the present study. The statistical analyses were conducted using IBM SPSS Statistics 26.

Table 1
Descriptive statistics of air pollution, socioeconomic factors and incidence rate of male lung cancer.

Variables	Mean	SD	Min	Median	Max
Incidence rate of male lung cancer (per 100,000 people)	50.16	17.21	1.55	48.63	117.74
PM1 ($\mu g/m^3$)	38.86	10.21	12.51	37.52	72.17
SO2 ($\mu g/m^3$)	27.40	14.42	0.09	28.86	64.11
Finance per capita (10^8 RMB)	23.04	29.58	0.81	13.18	284.76
Average education year (year)	9.35	1.02	6.90	9.12	13.39
Employment rate (%)	69.71	8.23	40.92	71.29	86.15
Proportion of construction workers (%)[a]	32.02	21.20	4.25	27.82	314.47
Proportion of manufacturing workers (%)[a]	82.99	78.86	2.48	58.94	421.04
Population size (10,000 people)	64.48	34.59	4.00	59.00	186.23

[a] For value = original value×100.

Table 2
Modifying role of urban-rural division on PM1 and SO2 effects.

	PM1		SO2	
	β	95% CI	β	95% CI
PM1	10.66%***	(6.88%, 14.44%)	3.54%***	(1.33%, 5.74%)
Log	0.64***	(0.39, 0.89)	0.73***	(0.48, 0.97)
Lat	−0.25**	(−0.51, 0.02)	−0.11	(−0.37, 0.15)
Year 2015	4.40***	(1.04, 7.77)	−2.19*	(−4.80, 0.42)
Finance	0.03	(−0.03, 0.10)	0.02	(−0.04, 0.09)
Education	−2.55**	(−4.77, −0.32)	−1.61	(−3.70, 0.48)
Employment	−0.28**	(−0.52, −0.04)	−0.16	(−0.39, 0.08)
Construction	0.01	(−0.06, 0.08)	0.00	(−0.07, 0.07)
Manufacturing	−0.03**	(−0.06, −0.01)	−0.04***	(−0.07, −0.01)
Population	0.02	(−0.03, 0.06)	0.03	(−0.02, 0.08)
PM1×Urban-rural	2.47%**	(0.38%, 4.55%)	5.44%***	(2.80%, 8.08%)

With a 10 $\mu g/m^3$ change in PM1 (or SO2), the change in incidence rate relative to its mean = (10 ×coefficient for PM1 (or SO2) or its interaction terms) / mean incidence rate.
* For $p < 0.1$.
** For $p < 0.05$.
*** For $p < 0.01$.

3. Results

3.1. Descriptive analysis

Table 1 presents the descriptive analysis of health outcome, air pollutions and socioeconomic factors. The mean incidence rate of male lung cancer was 50.16 per 100,000 people, with the standard deviation of 17.21. This indicates that there is a substantial variation in the incidence rate of male lung cancer across counties (districts). The considerable variation can also be observed for PM1 and SO2, with the standard deviations of 10.21 and 14.42, respectively (Table 1). With regard to socioeconomic factors (Table 1), the mean and standard deviation of average education year were 9.35 years and 1.02, respectively, which demonstrates the substantial difference in education level among counties (districts). A similar pattern of results can also be observed for other socioeconomic factors (Table 1).

3.2. Socioeconomic modification effects

3.2.1. Urban-rural division

The results of urban-rural modifying role on PM1 effects are shown in Fig. 3(A) and Table 2. In general, urban-rural division positively modified the association between PM1 and the incidence rate of male lung cancer. In the stratified datasets, there was a significant effect of PM1 in urban and rural areas, with a higher effect observed in urban groups (Fig. 3(A)). In the combined dataset, if PM1 changes by 10 $\mu g/m^3$, then the change in incidence rate relative to its mean was higher by 2.47% (95% CI: 0.38%, 4.55%) in urban groups than in rural groups (Table 2). With regard to SO2, there was no significant modification effect of urban-rural division. Specifically, a significant association between SO2 and the incidence rate of male lung cancer was observed in urban groups but not in rural groups in the stratified datasets (Fig. 3(B)), although there was a significant effect of the interaction between SO2 and urban-rural dummy variable in the combined dataset (Table 2).

3.2.2. Education level

Fig. 3(C) and Table 3 present the results of the modifying role of education level on PM1 effects. In general, there was a statistically negative modification effect of education level. In the stratified datasets according to the tertile division, PM1 was positively associated with the incidence rate of male lung cancer in the low, middle and high education groups (Fig. 3(C)). In the combined dataset according to the tertile division, if there is a 10 $\mu g/m^3$ change in PM1, then the shift in incidence rate relative to its mean was lower by 3.00% (95% CI: −4.66%, −1.34%) and 3.79% (95% CI: −5.89%, −1.69%) in the middle and high education groups than in the low education group, respectively (Table 3). A similar

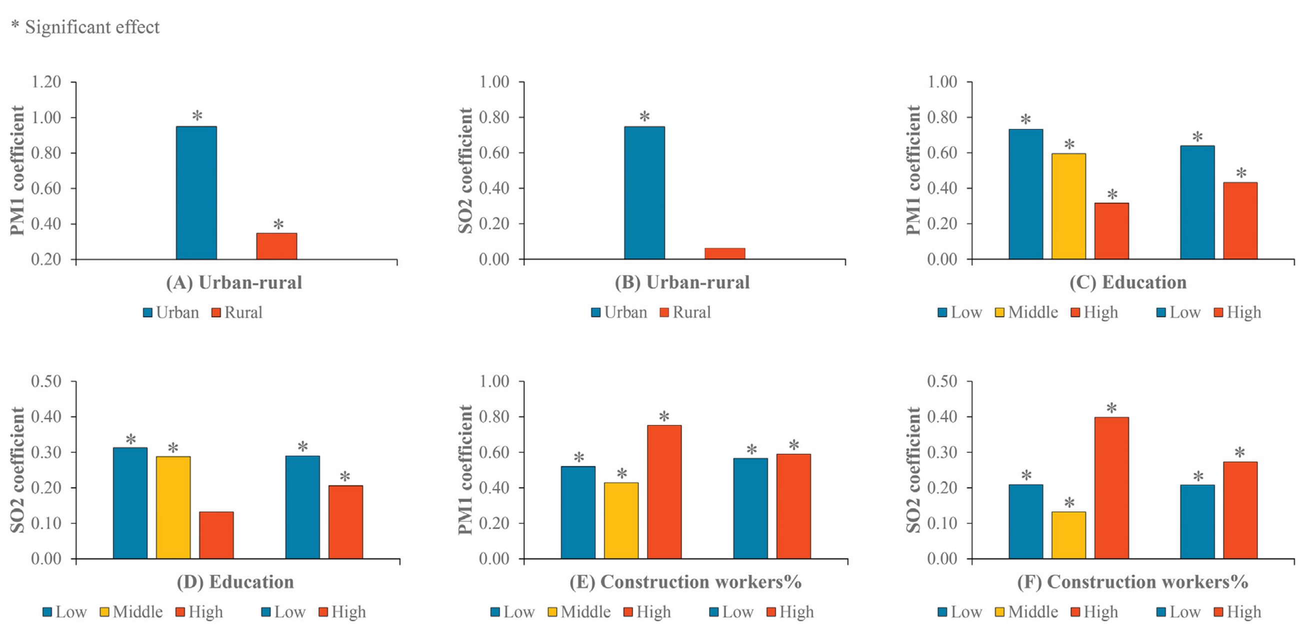

Fig. 3. Stratified analysis of air pollution (PM1 and SO2) effects according to socioeconomic factors.

Table 3
Modifying role of education level on PM1 effects.

	Tertile division		Binary division	
	β	95% CI	β	95% CI
PM1	13.94%***	(10.00%, 17.88%)	12.59%***	(8.80%, 16.38%)
Log	0.61***	(0.37, 0.86)	0.60***	(0.35, 0.85)
Lat	−0.27**	(−0.54, −0.01)	−0.28**	(−0.54, −0.01)
Year 2015	4.64***	(1.34, 7.93)	4.44***	(1.13, 7.74)
Finance	0.04	(−0.03, 0.11)	0.03	(−0.03, 0.10)
Employment	−0.29***	(−0.5, −0.08)	−0.25**	(−0.46, −0.05)
Construction	0.03	(−0.04, 0.10)	0.02	(−0.05, 0.08)
Manufacturing	−0.03**	(−0.05, 0.00)	−0.03**	(−0.05, 0.00)
Population	0.01	(−0.04, 0.06)	0.01	(−0.04, 0.06)
Urban-rural	2.88	(−1.13, 6.89)	2.90	(−1.00, 6.81)
PM1×Education2	−3.00%***	(−4.66%, −1.34%)	−2.56%***	(−4.12%, −1.01%)
PM1×Education3	−3.79%***	(−5.89%, −1.69%)		

With a 10 μg/m^3 change in PM1 (or SO2), the change in incidence rate relative to its mean = (10×coefficient for PM1 (or SO2) or its interaction terms) / mean incidence rate.
** For $p < 0.05$.
*** For $p < 0.01$.

pattern of results was observed in the examinations according to the binary division. Specifically, a significant effect was discovered in the low and high education groups in the stratified datasets, with a larger effect discovered in the former group (Fig. 3(C)). The interaction between PM1 and education dummy variable was negatively associated with the incidence rate of male lung cancer in the combined dataset (Table 3).

Education level was negatively related to the association between SO2 and the incidence rate of male lung cancer. Specifically, a significant effect of SO2 was observed in the low and middle education groups but not in the high education group in the stratified datasets according to the tertile division (Fig. 3(D)). In the combined dataset according to the tertile division, when SO2 changed by 10 μg/m^3, the change in incidence rate relative to its mean was lower by 3.95% (95% CI: −6.16%, −1.73%) and 4.47% (95% CI: −7.10%, −1.83%) in the middle and high education groups compared with the low education group, respectively (Table 4). With respect to the binary division, we observed the significant effect of SO2 in each education subgroup in the stratified datasets (Fig. 3(D)); moreover, as shown in Table 4, there was a negative effect of the interaction between SO2 and education dummy variable in the combined dataset (=−3.03%, 95% CI: −5.00%, −1.06%).

Table 4
Modifying role of education level on SO2 effects.

	Tertile division		Binary division	
	β	95% CI	β	95% CI
SO2	7.90%***	(5.10%, 10.70%)	6.56%***	(4.01%, 9.11%)
Log	0.72***	(0.47, 0.97)	0.71***	(0.46, 0.96)
Lat	−0.15	(−0.41, 0.12)	−0.15	(−0.41, 0.11)
Year 2015	−2.30*	(−4.91, 0.31)	−2.29*	(−4.92, 0.33)
Finance	0.05	(−0.02, 0.11)	0.04	(−0.03, 0.11)
Employment	−0.22**	(−0.43, −0.02)	−0.21**	(−0.41, 0.00)
Construction	0.01	(−0.06, 0.08)	−0.01	(−0.08, 0.06)
Manufacturing	−0.04***	(−0.07, −0.01)	−0.04***	(−0.07, −0.01)
Population	0.00	(−0.05, 0.05)	0.01	(−0.04, 0.06)
Urban-rural	4.25**	(0.24, 8.26)	4.33**	(0.39, 8.27)
SO2×Education2	−3.95%***	(−6.16%, −1.73%)	−3.03%***	(−5.00%, −1.06%)
SO2×Education3	−4.47%***	(−7.10%, −1.83%)		

With a 10 μg/m^3 change in PM1 (or SO2), the change in incidence rate relative to its mean = (10×coefficient for PM1 (or SO2) or its interaction terms) / mean incidence rate.
* For $p < 0.1$.
** For $p < 0.05$.
*** For $p < 0.01$.

Table 5
Modifying role of proportion of construction workers (i.e. occupation) on PM1 effects.

	Tertile division		Binary division	
	β	95% CI	β	95% CI
PM1	11.14%***	(7.23%, 15.06%)	11.50%***	(7.69%, 15.32%)
Log	0.62***	(0.36, 0.87)	0.61***	(0.36, 0.87)
Lat	−0.26**	(−0.53, 0.00)	−0.26**	(−0.53, 0.00)
Year 2015	4.45***	(1.06, 7.83)	4.46***	(1.08, 7.84)
Finance	0.03	(−0.04, 0.10)	0.03	(−0.04, 0.10)
Education	−2.08**	(−4.31, 0.14)	−2.18**	(−4.40, 0.04)
Employment	−0.29**	(−0.54, −0.05)	−0.31**	(−0.55, −0.07)
Manufacturing	−0.03**	(−0.06, −0.01)	−0.03**	(−0.05, 0.00)
Population	0.02	(−0.03, 0.06)	0.02	(−0.03, 0.07)
Urban-rural	3.14	(−1.07, 7.35)	3.22	(−0.98, 7.43)
PM1×Construction 2	0.11%	(−1.55%, 1.77%)	−0.11%	(−1.48%, 1.25%)
PM1×Construction 3	0.73%	(−0.97%, 2.43%)		

With a 10 μg/m^3 change in PM1 (or SO2), the change in incidence rate relative to its mean = (10×coefficient for PM1 (or SO2) or its interaction terms) / mean incidence rate.
** For $p < 0.05$.
*** For $p < 0.01$.

3.2.3. Proportion of construction workers

Fig. 3(E–F) and Tables 5 and 6 show the results of the modifying role of proportion of construction workers (i.e. occupation) on air pollution effects. In general, there was no significant modification effect of occupation. Despite the significant effect of PM1 observed in the stratified datasets according to the tertile division (Fig. 3(E)), the interaction between PM1 and occupation (i.e. proportion of construction workers) dummy variable was not significantly associated with the incidence rate of male lung cancer (Table 5). A similar pattern of results was discovered in the examinations in accordance with the binary division (Fig. 3(E) and Table 5). With regard to SO2, we observed the significant effect of SO2 in each occupation subgroup in the stratified datasets according to the tertile division (Fig. 3(F)). However, there was no significant effect of the interaction between SO2 and occupation (i.e. proportion of construction workers) dummy variable in the combined dataset according to the tertile division (Table 6). Similarly, the interaction between SO2 and occupation dummy variable was not significantly correlated with the incidence rate of male lung cancer in the combined dataset according to the binary division (Table 6).

3.3. Sensitivity analysis

Fig. 4 shows the results of the sensitivity analysis of socioeconomic modification effects to the control of smoking factors. In general, the modification effect of urban-rural division on the association between

Table 6
Modifying role of proportion of construction workers (i.e. occupation) on SO2 effects.

	Tertile division		Binary division	
	β	95% CI	β	95% CI
SO2	4.76%***	(1.85%, 7.67%)	5.01%***	(2.53%, 7.48%)
Log	0.72***	(0.47, 0.97)	0.72***	(0.47, 0.98)
Lat	−0.15	(−0.42, 0.12)	−0.15	(−0.42, 0.11)
Year 2015	−2.27*	(−4.92, 0.37)	−2.27*	(−4.91, 0.37)
Finance	0.02	(−0.04, 0.09)	0.03	(−0.04, 0.09)
Education	−0.71	(−2.90, 1.47)	−0.81	(−2.98, 1.35)
Employment	−0.20	(−0.44, 0.04)	−0.21*	(−0.45, 0.03)
Manufacturing	−0.04***	(−0.07, −0.02)	−0.04***	(−0.07, −0.01)
Population	0.02	(−0.03, 0.07)	0.02	(−0.02, 0.07)
Urban-rural	3.64*	(−0.66, 7.94)	3.62*	(−0.67, 7.92)
SO2×Construction 2	−0.37%	(−2.76%, 2.02%)	−0.68%	(−2.50%, 1.14%)
SO2×Construction 3	−0.04%	(−2.42%, 2.35%)		

With a 10 μg/m^3 change in PM1 (or SO2), the change in incidence rate relative to its mean = (10×coefficient for PM1 (or SO2) or its interaction terms) / mean incidence rate.
* For $p < 0.1$.
*** For $p < 0.01$.

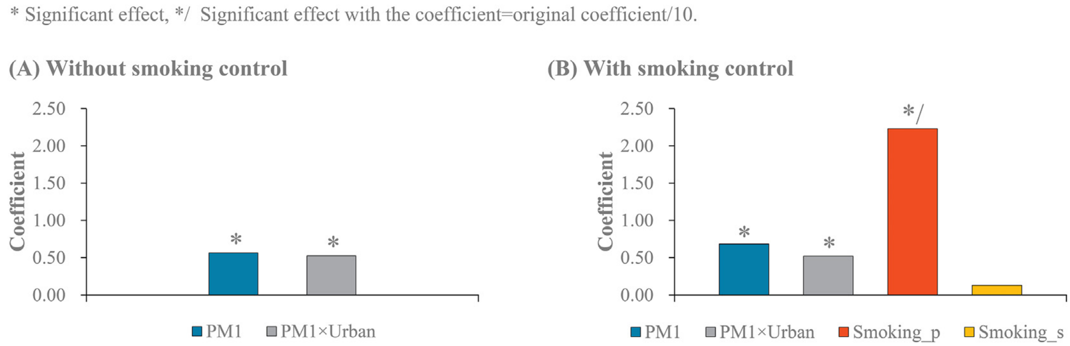

Fig. 4. Sensitivity analysis of socioeconomic modification effects to the adjustment of smoking factors.

PM1 and the incidence rate of male lung cancer was not sensitive to the adjustment of smoking. When smoking characteristics were not controlled (Fig. 4(A)), both PM1 and its interaction with urban-rural dummy variable were positively associated with the incidence rate of male lung cancer. When adjusting for smoking prevalence and smoking strength, as shown in Fig. 4(B), the effects of PM1 and its interaction term were still significant. Moreover, smoking factors were also significantly correlated to the incidence rate of male lung cancer (Fig. 4(B)).

The results of the sensitivity analysis including additional air pollutants in regression models are presented in Fig. 5. In general, the modification effects of urban-rural division and education level were robust to the adjustment of additional air pollutants. When SO2 was further included in the regression model, PM1 and its interaction with urban-rural dummy variable were all positively associated with the incidence rate of male lung cancer (Fig. 5(A)); we also observed the significant effect of the interaction between PM1 and education dummy variable according to the tertile division of education level (Fig. 5(B)); a significant effect of the interaction between PM1 and education dummy variable was also observed in accordance with the binary division of education level (Fig. 5(C)). When PM1 was further included in the regression model, as shown in Fig. 5(D–E), there was a significant association of the incidence rate of male lung cancer with the interaction between SO2 and education dummy variable according to each of the tertile and binary divisions of education level.

Fig. 6 shows the sensitivity analysis of whether socioeconomic modification effects are robust to air pollution exposures with different lag structures. In general, the modification effect of education level was still significant. According to the tertile division of education level (Fig. 6(A)), there was a positive association between SO2 at each lag (i.e. lag1 to lag8, lag01 to lag 08) and the incidence rate of male lung cancer; the effect of SO2 at each lag was significantly lower in the middle and high education groups than in the low education group, respectively. With regard to the binary division of education level (Fig. 6(B)), a positive effect of SO2 at each lag was observed; there was a significant difference in SO2 effects between the low and high education groups, with a larger effect observed in the former group.

4. Discussion

The adverse effect of air pollution on human health has been reported in many studies. However, less is known about whether socioeconomic factors modify the association between air pollution and health outcome, especially in developing counties. Moreover, few studies focus on PM1 which has its health effect larger than PM2.5 and coarse PMs. Also, little attention has been placed on the severe SO2 pollution in developing countries, especially for China which is the first order SO2 emitter. As an attempt to remedy these issues, we performed a nationwide study linking socioeconomic indicators to the association between PM1 (or SO2) and the incidence rate of male lung cancer in China.

We found that the effect of PM1 on the incidence rate of male lung cancer is larger in urban areas than in rural areas in China, which is

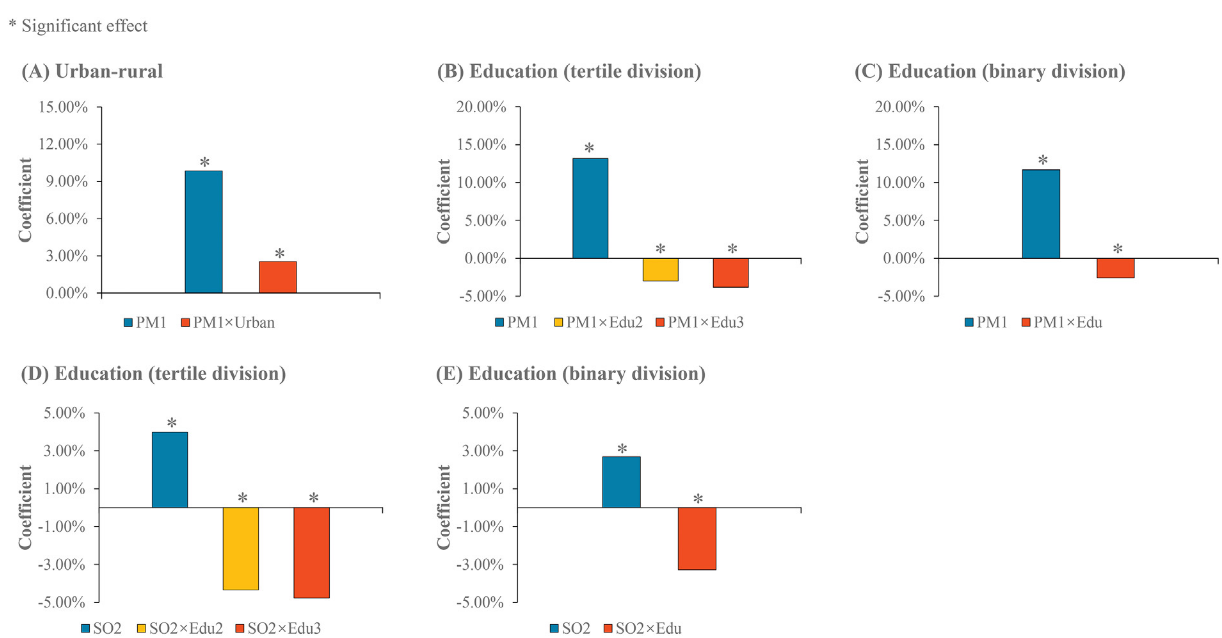

Fig. 5. Sensitivity analysis of socioeconomic modification effects to the adjustment of additional air pollutants.

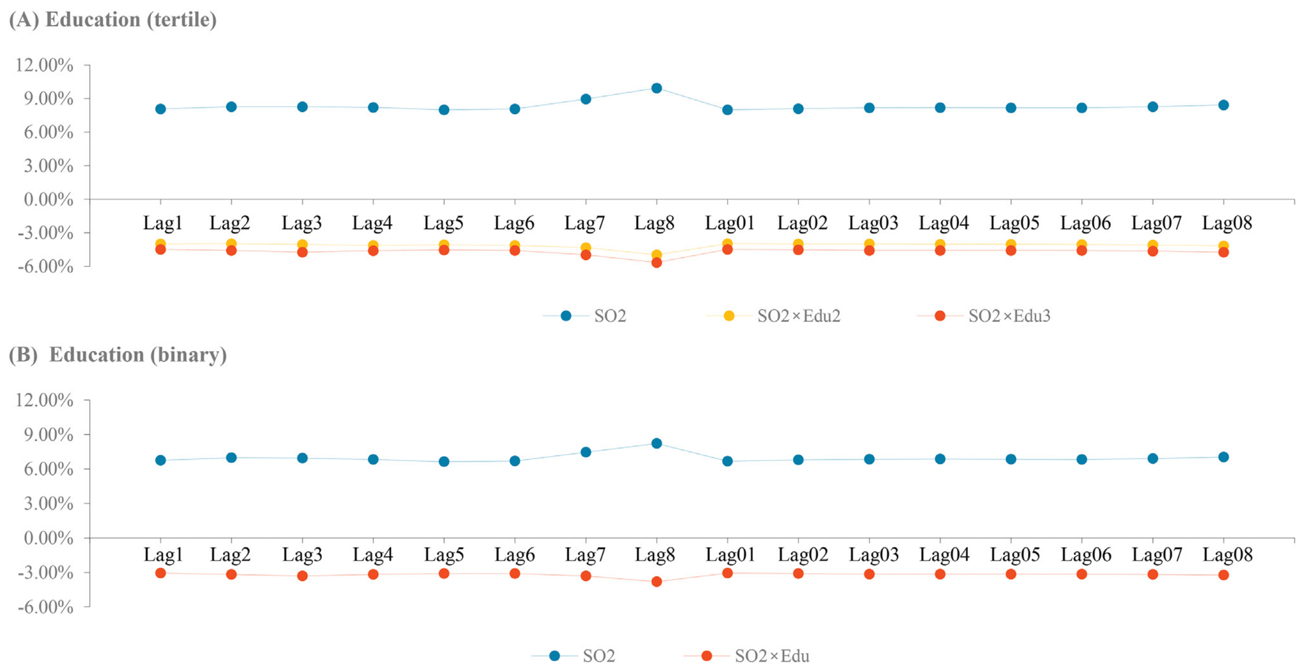

Fig. 6. Sensitivity analysis of socioeconomic modification effects to SO2 exposures with different lag structures.

seldom reported, especially for PM1. This finding is not expected but in line with those reported from some previous studies. In our previous study, we observed that the risk of male lung cancer incidence associated with ambient PM2.5 is stronger in urban areas than in rural areas (H. Guo et al., 2019). A recent Chinese study also reported the significant differences in the impacts of air pollution (e.g. PM10, SO2, NO2) on lung cancer incidence between urban and rural areas, with a larger effect observed in the former group (Zhou et al., 2017). Again, using the data of cause-specific hospitalization rate of 708 U.S. counties, Bravo et al. (2017) suggested the significant modifying role of urbanity on the association between PM2.5 and cardiovascular hospitalizations at the same day, with a greater effect observed in urban counties than in nonurban counties.

With regard to the mechanism, the differences in smoking behaviours may be responsible for the urban-rural disparity in PM1 effects in the present study. As reported, the effect of air pollution on human health differs among people with different smoking behaviours (Vena, 1982; Wong et al., 2007). In China, the prevalence of tobacco smoking alone may not be sufficient to understand the larger smoking-associated hazard (including lung cancer) in urban areas than in rural areas (Chen et al., 2015a). Despite the low prevalence of tobacco smoking (tobacco includes cigarettes and other tobaccos) in urban areas than in rural areas (Chen et al., 2015a,b), cigarette-related factors such as the number of cigarettes smoking per day as well as the prevalence of all smokers who used cigarettes, were larger in urban areas than in rural areas (Chen et al., 2015a). Meanwhile, the age started smoking regularly was smaller in urban areas than in rural areas (Chen et al., 2015a). Correspondingly, the effects of these cigarette-associated factors on lung cancer diseases were larger in urban areas than in rural areas (Chen et al., 2015a). For example, the relative risk of lung cancer disease associated with the number of cigarettes smoking per day (for smokers with the ages between 15 and 24) was 3.28 (95% CI: 2.82, 3.83) in urban areas, which is higher than the value of rural areas at 2.38 (95% CI: 2.14, 2.65) (Chen et al., 2015a). The differences in such smoking behaviours, in combination with the earlier occurring of both the widespread cigarette consumption and large intergenerational increase in cigarette smoking in urban areas than in rural areas, may be responsible for the difference in smoking-associated hazard risks (including lung cancer disease) between urban and rural areas with a higher risk in the former (Chen et al., 2015a). Such difference may thus make people in urban and rural areas have different vulnerability to exposure to air pollution with a larger effect of PM1 observed in urban areas in the present study.

We found that education level has a negative effect on the association between PM1 (or SO2) and the incidence rate of male lung cancer. Despite the proposed pathways of socioeconomic modification effects (Peters et al., 2001; Kan et al., 2008), it is still not clear how education level modifies the effect of air pollution on human health. The results reported from the present study are in line with those reported from some previous studies. Cakmak et al. (2011) indicated that the effects of ambient air pollutions (e.g. PM2.5 and SO2) on daily mortality are greater among individuals with a degree less than primary school than among university graduates. In a nationwide time-series analysis of 272 cities in China, Chen et al. (2017) reported that the associations between PM2.5 and daily cause-specific mortalities (e.g. cardiovascular diseases and stroke) are stronger in populations who are less educated. Ostro et al. (2008) suggested that compared with those with high education levels, individuals with low educational attainments suffer from a high risk of cardiovascular mortality associated with ambient exposure to PM2.5. Although these studies have reported the significant modification effect of education level, further investigations are highly required to determine how education level exerts its modifying role on the effect of air pollution in the future.

We found that the effects of PM1's interactions with socioeconomic factors are greater than those of PM2.5's interactions with the same factors, which is seldom reported. Previous PM1-related studies focus on determining the adverse effect of PM1 and then comparing the effects between PM1 and coarse PMs (Lin et al., 2016; G. Chen et al., 2017; Hu et al., 2018). As an extension of these studies, the present study is one of the earliest attempts to investigate and compare the effects between PM1's and PM2.5's interactions with socioeconomic factors. Specifically, with regard to the tertile division of education level, the absolute values of the shifts in the two interaction terms were 1.98% (95% CI: −3.18%, −0.79%) and 2.78% (95% CI: −4.17%, −1.39%) for PM2.5 in our previous study (H. Guo et al., 2019), which are lower than those of the same interaction terms at 3.00% (95% CI: −4.66%, −1.34%) and 3.79% (95% CI: −5.89%, −1.69%) for PM1 in the present study, when there was the same increase in PM2.5 and PM1. A similar pattern of results can be discovered according to the binary division of education level and urban-rural division.

Several limitations in the present study should be acknowledged. Firstly, the use of city-level smoking data as a surrogate to test the sensitiveness of urban-rural modification effect to the adjustment of smoking factors may neglect the variations of smoking conditions among counties/districts located in the same city. That is, such operation may be faced with the problem of ecological fallacy (Schwartz, 1994). Such limitation should be well considered and addressed in our future work if county-level smoking data are available. Secondly, as in most prior ecological studies (Kioumourtzoglou et al., 2016; Chen et al., 2019), there are inevitable errors in the estimate of air pollution exposure. Following these prior studies, we use the mean PM1 concentration aggregated in each county as the proxy of air pollution exposure. Such operationalization ignores the key determinants of the estimate of air pollution exposure (i.e. individual mobility and air pollution variations), which thus may produce the error in exposure estimate (Yoo et al., 2015; Shafran-Nathan et al., 2018; Guo et al., 2020).

Thirdly, it still remains unknown to what extent the SO2 data derived from the Merra-2 product can be used in China. Air pollution data (including SO2) acquired from the Merra-2 product have been widely used in many places including China (S. Chen et al., 2017; Eltahan and Magooda, 2018; J. Guo et al., 2019). However, it is not feasible to use the data collected from environmental monitoring stations to validate SO2 derived from the Merra-2 product in China, because of the great discrepancy in the resolution of SO2 data obtained between the Merra-2 product and monitoring stations (hourly VS monthly, $0.5° \times 0.625°$ grid VS station). If the Merra-2 product with the improved data resolution is available in the future, it should be required to validate SO2 data in China and thus test the robustness of the findings (i.e. socioeconomic modifying roles on SO2 effects) in the present study. Fourthly, with regard to the test of the sensitivity of socioeconomic modification effects to exposures to SO2 with different lag structures, as in many studies (Abbey et al., 1999; Guo et al., 2016; Guo et al., 2020), the up to 8-year lag used in the present study still may not be long enough to account for the unknown latency of lung cancer.

Fifthly, it should be noted that the accuracy of lung cancer incidence data released by the Chinese Cancer Registry, may be affected by the lack of the consideration of male migrant workers from rural areas to urban areas. If data on male migrant workers who have been diagnosed with lung cancer incidence are available in the future, the migration factor should be considered to improve the measurement of health outcome. Sixthly, as our PM1 data are available only from 2014 to 2015, the findings of socioeconomic modifying roles on PM1 effects may not be robust to PM1 exposures with different lag structures (i.e. single and moving-average lags). If data on PM1 concentration earlier than 2014 are available, such sensitivity analysis should be conducted in the future.

5. Conclusions

There is a high risk of PM1-associated lung cancer incidence for males in urban areas than in rural areas in China. Compared to those with high education levels, male residents with low education levels suffer from larger effects of PM1 and SO2 on the incidence rate of lung cancer in China. Area- and population-specific strategies should be developed to alleviate the urban-rural and educational disparities in the effects of air pollution on human health in China, such as reducing urban-rural disparities in access to high-quality healthcare resources and giving priority to counties with low education levels when promoting general education on air pollution effects.

CRediT authorship contribution statement

Huagui Guo: Conceptualization, Formal analysis, Methodology, Writing - original draft, Writing - review & editing. **Jing Wei:** Resources, Writing - review & editing. **Xin Li:** Writing - review & editing. **Hung Chak Ho:** Methodology, Writing - review & editing. **Yimeng Song:** Data curation, Visualization. **Jiansheng Wu:** Funding acquisition, Writing - review & editing. **Weifeng Li:** Investigation, Supervision, Writing - review & editing.

Declaration of competing interest

All authors declared no conflicts of interests.

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