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Associations between prenatal sunshine exposure and birth outcomes in China

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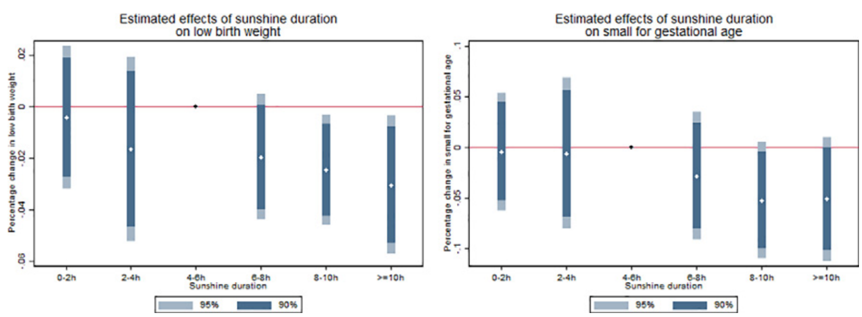
HIGHLIGHTS

- One of the first study using a nationally representative birth record dataset in China
- Prenatal exposure to increasing sunshine was associated with positive birth outcomes.
- The effect was more salient in the second trimester during pregnancy.
- Potential mechanisms include obtaining vitamin D and relieving maternal stress.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper is one of the first to examine the associations between prenatal sunshine exposure and birth outcomes, specifically the incidence of low birth weight (LBW) and small for gestational age (SGA), based on a nationally representative birth record dataset in China. During the sample period in the 1990s, migration was limited in rural China, allowing us to address the identification challenges, like residential sorting and avoidance behaviors. We found a nonlinear relationship between the length of sunlight and birth outcomes. In particular, prenatal exposure to increasing sunshine was associated with a reduction in the incidence of LBW and SGA, especially in the second trimester during pregnancy. This finding was consistent with the clinical evidence suggesting positive effects of sunshine on birth outcomes via obtaining vitamin D or relieving maternal stress.

1. Introduction

The effects of environmental factors on birth outcomes have received much attention in the literature. For example, humidity has been proven to be an important determinant of mortality (Barreca,

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2012). Air pollution can affect infant health and its cognitive condition, as well as the incidence of low birth weight and premature birth (Currie et al., 2009; Knittel et al., 2016; Bharadwaj et al., 2017). Hot weather can result in low birth weight (Deschênes et al., 2009) and preterm delivery (Basu et al., 2010; Andalón et al., 2016; Beltran et al., 2014). Extreme cold can also lead to adverse birth outcomes, such as mortality (Deschenes and Moretti, 2009; Deschenes, 2014) and low birth weight (Murray, 2000; Beltran et al., 2014).

Recent epidemiological studies revealed that certain metal elements and organic compounds could also affect birth weight. Rodosthenous et al. (2017) suggested that prenatal lead (Pb) exposure was negatively associated with infant birth weight. Hou et al. (2019) revealed that low level serum cobalt (Co) was positively correlated with low birth weight and showed a nonlinear dose relationship. Ding et al. (2015) found that prenatal exposure to pyrethroids was adversely correlated with birth weight. Rhee et al. (2015) reported that high caffeine intake during pregnancy increased the risk of low birth weight significantly. Additionally, maternal smoking behaviors and passive smoking were also associated with low birth weight (Lindbohm et al., 2002).

Compared to other environmental stressors, evidence on the effects of sunshine exposure on health-related outcomes is limited and inconclusive. Tustin et al. (2004) found that first trimester maternal exposure to sunlight increased birth weight in human infants in New Zealand. Trudeau et al. (2016) found that sunshine exposure had a negative effect on birth weight for white infants but a positive effect for black infants, potentially through different mechanisms of vitamin D and folic acid by race. Wernerfelt et al. (2017) suggested that increasing sunlight in the second trimester during pregnancy could lower the probability of asthma through the effect of vitamin D. Slusky and Zeckhauser (2018) revealed that sunlight in late summer and early fall would strongly protect newborns against influenza.

Sunshine can affect birth outcomes through two offsetting physiological channels. First, sunshine is associated with folate depletion because of ultraviolet (UV) radiation (Fukuwatari et al., 2009). Folate and folic acid are different forms of vitamin B9. The well-studied consequence of folic acid deficiency for newborns is neural tube defects (De-Regil et al., 2010; Blencowe et al., 2010; Chen et al., 2008; De Wals et al., 2007; Ray et al., 2002; Green, 2002; Scholl and Johnson, 2000; Hernández-Díaz et al., 2000; Berry et al., 1999; Milunsky et al., 1989). Folic acid deficiency can also lead to defective cellular growth (Hibbard, 1964; Scholl and Johnson, 2000; Sram et al., 2005) and negative birth outcomes, such as preterm delivery, fetal growth retardation, and low birth weight (Siega-Riz et al., 2004; Scholl et al., 1996; Scholl and Johnson, 2000; Butterworth and Bendich, 1996; Iyengar and Rajalakshmi, 1975).

Second, exposure to sunshine can allow obtaining vitamin D, which plays an important part in pregnancy and birth. Vitamin D comprises a group of fat-soluble secosteroids. The main sources of vitamin D in the human body are from photosynthesis within the skin under exposure to ultraviolet B (UVB) radiation and dietary intake. The effect of vitamin D in pregnancy has been examined quite thoroughly. Maternal and infant vitamin D levels are highly correlated (Ponsonby et al., 2010). Appropriate vitamin D supplements can reduce the risk of low birth weight (Gernand et al., 2013; Scholl and Chen, 2009; Mannion et al., 2006) and small for gestational age (Bodnar et al., 2010). Vitamin D deficiency, on the other hand, can cause fertility impairment (Lewis et al., 2010), maternal skeletal preservation, and infant skeletal formation impairment, which raise the risk of chronical diseases for fetuses (Lapillonne, 2010).

Sunshine may also affect birth outcomes via a psychological channel. As documented in the literature, sunshine enhances happiness and mental well-being (Kämpfer and Mutz, 2013; Hirshleifer and Shumway, 2003; Keller et al., 2005), while prenatal exposure to stressful events (e.g., natural disasters, violence, and family loss) has detrimental effects on birth outcomes, such as low birth weight and preterm (Persson and Rossin-Slater, 2018; Aizer et al., 2016; Koppensteiner and Manacorda, 2016; Torche, 2011). Therefore, a long-time window of sunlight exposure may promote positive birth outcomes through alleviating maternal stress during pregnancy. However, too much sunshine may also be a stressor and result in negative birth outcomes.

The existing literature details mixed conclusions on the influence of prenatal exposure to sunshine on birth outcomes, and reports that the effect differs by race. The goal of the present study was to examine how and to which extent birth outcomes, i.e., low birth weight (LBW) and small for gestational age (SGA), were related to in utero exposure to sunshine for a Chinese population using a nationally representative birth record dataset. Taking advantage of the unique aspects of rural China in the 1990s, we were able to address the identification challenges, like residential sorting and avoidance behaviors.

Early life has been well recognized as a critical period that shapes long-term health and well-being (Barker, 1990). For example, the Fetal Origins Hypothesis shows that the nine months in utero could have a substantial effect on future outcomes (e.g., Almond and Currie, 2011). As birth weight strongly predicts adult health and earnings (Bharadwaj et al., 2018; Black et al., 2007; Behrman and Rosenzweig, 2004), this study may help effectively target newborns more vulnerable to inadequate sunshine to promote their health as well as shedding light on other labor and fertility policies in China.

2. Data and methods

2.1. Study design and population

The birth record data were obtained from the China's National Disease Surveillance Points (DSP) system, which contained data from 145 counties in 31 provinces (autonomous regions and municipalities), using multistage cluster probability sampling to cover a 1% nationally representative sample of the Chinese population. The system was established by the Chinese Academy of Preventive Medicine, with the "Disease Prevention Unit" of the township hospitals in each DSP site responsible for the vital registration within the DSP system; see Yang et al. (2005) for a detailed introduction. The data included detailed information on each birth, including birth weight, gender, birth order, date and county of birth, gestational week, and parents' age at birth and education years. We obtained permission from the Chinese Center for Disease Control and Prevention to use data from the Disease Surveillance Point System. Data were de-identified, and informed consent was not required.

The gestational week information was recorded according to the exact date of the mother's last menstrual period. As displayed in Fig. A1, the gestational age ranged from 28 to 45 weeks, with 93.76% of the gestational age concentrated between 37 and 41 weeks. Infants born before 37 weeks were considered preterm and infants born after 42 weeks were considered postterm, which accounted for 2.97% and 3.28% of our sample observations, respectively. The distribution of gestational age in our sample was similar to that in Dai et al. (2014), which confirmed the accuracy of the gestational age measurement. We interpolated the missing gestational age by 39 weeks in the analysis.

We used two binary indicators to represent the incidences of low birth weight (LBW) and small for gestational age (SGA), respectively. LBW refers to infants whose birth weights were below 2500 g, regardless of gestational age. SGA refers to babies whose birth weights were below the 10th percentile for each gestational age by gender using data from the National Population-based Birth Defects Surveillance System; see Table 2 in Dai et al. (2014) for the gestational age-specific birth weight percentiles for Chinese babies. Based on the information on gestational age and birth date, we calculated the conception date and identified the three trimesters of the pregnancy accordingly. In particular, we assigned weeks 1–13 after conception to the first trimester, weeks 14–26 to the second trimester, and weeks 27–39 to the third trimester.

2.2. Weather data

The daily weather data came from the China National Meteorological Data Service Center (CMDC) under the National Meteorological Information Center of China. The dataset contained data from 824 monitoring stations along with information on their longitudes and latitudes. The key variable in our analysis was the sunshine duration. Sunshine duration is defined as the total hours in a given period during which direct solar irradiance exceeds a threshold value of 120 W/m^2 (World Meteorological Organization, 2008). It accounts for cloudiness, and thus differs from insolation, which measures the total energy delivered by sunlight over a given period. Other weather controls included temperature, precipitation, wind speed, and relative humidity. The distribution of weather monitoring stations and DSPs is shown in Fig. 1.

As displayed in Fig. 1, birth record data from the DSPs and weather data from the CMDC could be well matched. We calculated the weighted average values from the monitoring stations within a 60 km radius to the centroid of each DSP county, where the weights equaled the inverse distance between the county centroids and the weather monitoring stations. If there were no monitoring stations within 60 km, we extended the radius to 100 km. The average matching distance in our sample was 32 km. Only 4.1% of the observations were matched to weather stations beyond 60 km. This specification allowed us to capture the effect of sunshine on birth outcomes in a nonlinear and semiparametric way. In our subsequent analyses, we separated the number of days falling in each sunshine duration interval in the gestation period by trimester.

2.3. Statistical methods

The following equation describes the primary estimation equation:

$$Y_{icyd} = \sum_{j=1}^{6} \alpha_j SSD_{cydj} + \beta W_{cyd} + \varphi X_{icyd} + \eta_y + \delta_{cd} + \varepsilon_{icyd} \quad (1)$$

The outcome variable Y_{icyd} stands for birth outcomes of child i born in county c on day d of year y. Here the birth outcomes could either be an indicator for LBW or SGA. SSD_{cydj} represents the number of days of the sunshine duration bin j (from 1 to 6) among the 39 weeks after the conception for child i born in county c on day d of year y. We set the 4–6 h sunshine duration bin as the reference group in all the

Fig. 1. Distribution of DSP sites and monitoring stations. Source: China's National Disease Surveillance Points system and China Meteorological Data Service Center. Note: This figure was plotted using ArcMap 10.5.1.

exercises. W_{cyd} stands for a set of weather variables, including the number of days falling in each temperature bin (<−4 °C, −4–0 °C, 0–24 °C, 24–28 °C, ≥28 °C), mean wind speed, precipitation, and relative humidity in polynomial forms. A growing body of literature has shown negative effects of exposure to extreme temperatures on birth outcomes (Ha et al., 2016; Andalón et al., 2016; Deschenes and Moretti, 2009). Hence, we divided the daily temperature into five bins as proposed by Isen et al. (2017) and calculated the number of days falling in each bin to fully capture the nonlinear relationship. X_{icyd} represents a vector of the demographic characteristics, including the children's gender, birth order, maternal age when giving birth, and its quadratic term, as well as indicators for the mother's education levels. η_y is the birth year fixed effect, which captures common time shocks across years. To control for county-specific seasonality, we included δ_{cd}, for the county × day of birth year fixed effects following Isen et al. (2017). The error term is ε_{icyd}. Taking the correlation of sunshine duration within each county into account, the standard errors were clustered at the county level.

To examine the heterogeneous effects of sunshine on birth outcomes by trimester, we expanded our model like this:

$$Y_{icyd} = \sum_{j=1}^{6} \alpha_j^{TR1} SSD_{cydj}^{TR1} + \sum_{j=1}^{6} \alpha_j^{TR2} SSD_{cydj}^{TR2} + \sum_{j=1}^{6} \alpha_j^{TR3} SSD_{cydj}^{TR3} + \beta^{TR1} W_{cyd}^{TR1} + \beta^{TR2} W_{cyd}^{TR2} + \beta^{TR3} W_{cyd}^{TR3} + \varphi X_{icyd} + \eta_y + \delta_{cd} + \varepsilon_{icyd} \tag{2}$$

TR1, *TR2*, and *TR3* correspond to the first, second, and third trimesters during the pregnancy. This model specification enabled us to detect how sunshine exposure in different trimesters affects birth outcomes differently and whether the overall effect was driven by a particular period, like the first trimester, when the fetus might be more sensitive to environmental factors.

After controlling for the fixed effects described above, we compared children born in the same county on the same day of the year but in different years, after excluding annual shocks. The key identifying assumption was that by holding constant the county of birth and birth day of the year of an individual, there would be no unobserved factors that were systematically correlated with both prenatal sunshine exposure and birth outcomes. As this assumption was inherently untestable, the results should be interpreted as associations.

3. Results

3.1. Characteristics of the study population

In our main analyses we concentrated on live singleton births in rural China during 1991–2000. Since there were 181,139 missing values for birth weight and 53,300 missing values for other demographic controls, the final dataset included 637,033 observations. Table 1 summarizes the characteristics of the study population in our sample. The average LBW rate was 2.9% and 4.0% for male and female infants, respectively, and the average rate for SGA was 7.0% and 7.1% for the males and females, respectively. 55.2% of the babies were male and the mean gestational age was 39.17 weeks. The average value for maternal age when giving birth was 25.28 years old and 52.8% of the mothers had a middle school education level.

Table 1
Characteristics summary of the study population.

Variable	All		Male		Female	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Birth weight (grams)	3318.7	406.5	3357.7	407.3	3287.2	400.3
Low birth weight (LBW)	0.035	0.183	0.029	0.166	0.040	0.195
Small for gestational age (SGA)	0.070	0.256	0.070	0.254	0.071	0.258
Male	0.552	0.497	–	–	–	–
Birth order	1.432	0.744	1.451	0.748	1.407	0.742
Gestational age	39.170	1.047	39.183	1.045	39.169	1.097
Maternal age	25.275	3.449	25.354	3.470	25.207	3.438
Mother's education						
Primary school or below	0.301	0.459	0.280	0.449	0.284	0.451
Middle school	0.528	0.499	0.547	0.498	0.544	0.498
High school or above	0.171	0.376	0.173	0.378	0.172	0.378

Source: China's National Disease Surveillance Points system.

3.2. Summary statistics for sunshine exposure and other weather covariates

Table 2 further summarizes the statistics for sunshine exposure and other weather covariates. The average length of daily sunshine duration an expectant woman was exposed to during the gestation period was 5.26 h. The mean values for daily temperature, wind speed, precipitation, and relative humidity were 15.12 °C, 2.08 m/s, 2.89 mm, and 72.31%, respectively. Fig. 2 further shows the distribution of daily sunshine duration in the 6 bins (i.e., 0–2, 2–4, 4–6, 6–8, 8–10, and ≥10 h) during the gestation period. The average number of days was 86.74 for the 0–2 h range, 27.78 for the 4–6 h bin, and 35.23 for the above 10 h bin.

3.3. Effects of sunshine on birth outcomes

Fig. 3 visualizes the estimates reported in columns (2), (4), and (6) of Table A1. Panel A of Fig. 3 reveals the results for LBW; panel B corresponds to SGA, while panel C refers to the log form of birth weight. Each figure plots the estimated coefficients for six sunshine duration bins (0–2, 2–4, 4–6, 6–8, 8–10, and >10 h) in Eq. (1), together with their 90% and 95% confidence intervals. The reference bin in all figures is 4–6 h. The coefficients represent the marginal effect of one more day in the corresponding sunshine duration bin in the gestation period on birth outcomes compared with the reference bin 4–6 h.

First, we focused on LBW. Column (1) of Table A1 indicates the length of sunlight and the incidence of LBW were negatively correlated. Panel A of Fig. 3 indicates a nonlinear relationship between LBW and sunshine duration, where daily sunshine exceeding 8 h during the gestation period has a significant negative effect on the probability of being LBW. Specifically, spending an additional day with 8–10 h of sunshine, relative to the reference bin, reduced LBW by 0.023 percentage points (0.66% of mean occurrence in our sample), and an additional day with over 10 h of sunshine was associated with a decrease in LBW by 0.030 percentage points (0.86% of mean occurrence of LBW).

Because being of low birth weight might be caused by a preterm birth or growth restriction conditioned on gestation (i.e., being lighter than normal infants given the same gestational age), we employed

Table 2
Summary statistics for sunshine exposure and other weather covariates.

Variable	Mean	Std. Dev.
Mean sunshine duration (hour)	5.259	1.529
The number of days in sunshine duration bins:		
0–2 h	86.739	41.482
2–4 h	24.252	7.628
4–6 h	27.781	7.370
6–8 h	41.998	14.089
8–10 h	57.005	21.680
≥10 h	35.225	23.785
Mean temperature (°C)	15.122	4.878
The number of days in temperature bins:		
<−4 °C	9.532	23.616
−4–0 °C	10.567	14.572
0–24 °C	192.789	40.712
24–28 °C	41.897	28.062
≥28 °C	18.215	20.207
Mean wind speed (m/s)	2.075	0.758
Mean precipitation (mm)	2.889	1.609
Mean relative humidity (%)	72.306	9.572

Source: China's National Disease Surveillance Points system.

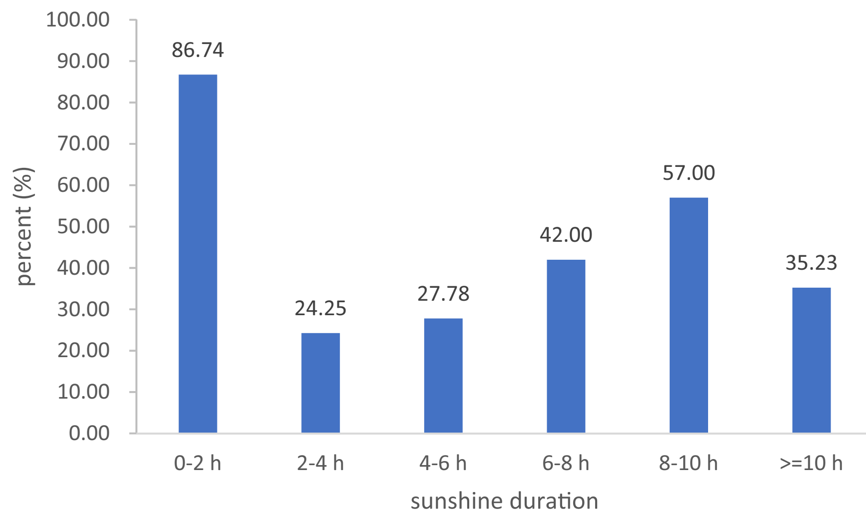

Fig. 2. Distribution of daily sunshine duration in the gestation period. Source: China's National Disease Surveillance Points system and China Meteorological Data Service Center.

SGA to represent small for gestational age. Column (3) of Table A1 shows that increasing sunshine during the gestation period was correlated with a decrease in SGA. Panel B of Fig. 3 further suggests that spending one more day with 8–10 h of sunshine was associated with a decrease in SGA by 0.049 percentage points (0.70% of mean occurrence in our sample).

As displayed in columns (5) through (6) in Table A1 and panel C in Fig. 3, we did not find any significant effects of sunshine on the log form of birth weight. We also examined the effect of sunshine on term LBW, preterm, and gestational age in columns (5) through (7) of Table A4. Term LBW refers to infants whose birth weights were below 2500 g with a gestational age above 37 weeks. Preterm is defined as gestational age below 37 weeks. Similar to SGA, spending one more day with 8–10 h of sunshine was associated with a decrease in term LBW by 0.017 percentage points. However, sunshine did not affect gestational age or the probability of being preterm. Thus, we found that the effect of sunlight on LBW was mainly caused by growth restriction conditioned on gestation.

We examined if the impact of prenatal exposure to sunshine on birth outcomes differed by trimester. Fig. 4 visualizes the estimated coefficients on the sunshine duration bins in each trimester for LBW and SGA, respectively. Table A2 shows the corresponding numeric results. We found a similar pattern, i.e., the length of sunlight was negatively correlated with the probability of being LBW or SGA. For both LBW and SGA, the point estimates suggested that sunshine played an important role in the second and third trimesters, especially in the second trimester. Specifically, spending an additional day with over 10 h of sunshine in the second trimester, relative to the reference bin, was associated with a reduction in LBW by 0.049 percentage points (1.40% of mean occurrence of LBW), and a decrease in SGA by 0.069 percentage points (0.99% of mean occurrence of SGA). This finding was in line with that of Wernerfelt et al. (2017), who showed that the second trimester mattered more as increasing sunlight exposure helped lower the probability of asthma.

We conducted a Wald test to investigate whether the magnitude of coefficients on each sunshine duration bin differed across trimesters. For LBW, we found that the effect of sunshine between 0 and 2 h and over 10 h was significantly different between the first and second trimesters. However, this significance did not hold for SGA.

3.4. Dose-response relationship using the RCS method

In this section, we performed a restricted cubic spline (RCS) regression model (Desquilbet and Mariotti, 2010) to explore the dose–response relationship between sunshine duration and birth outcomes. Knots for RCS were placed at the 25th, 50th, and 75th percentiles of sunshine duration (i.e., 4.16, 5.32, and 6.36 h). We chose 5 h as the reference value, in line with the previous reference bin (4–6 h).

The dose–response relationships between sunshine duration and birth outcomes are plotted in Fig. 5. We observed a significant nonlinear relationship between sunshine duration and LBW (P-overall < 0.0001, and P-nonlinearity $= 0.0003$). Similarly, a nonlinear association was also found between sunshine duration and SGA (P-overall < 0.0001, and P-nonlinearity $= 0.0003$). The slopes of the lines showed that a longer length of sunlight was associated with smaller odds ratios for both LBW and SGA, which was consistent with our previous results.

4. Discussion

4.1. Placebo tests and alternative specifications

To assure our identifying assumptions were valid, we performed a placebo test following a similar strategy to that in Bharadwaj et al. (2017). In the placebo test, we matched the sunshine duration in three trimesters (39 weeks) before conception with each birth. Table A3 displays the results for LBW and SGA, respectively. As we expected, none of the coefficients on sunshine duration bins were significant, which suggested that the association between sunshine exposure and birth outcomes was not driven by the unobserved factors.

The results were also robust to a variety of alternative specifications. Columns (1) and (2) of Table A4 replicate the results in Fig. 3 for ease of comparison. In columns (3) and (4) of Table A4, we ran parsimonious specifications by dropping all the demographic controls. Columns (1) and (2) of Table A5 indicate that the estimates were robust to controlling for county × day of birth year × sex fixed effects instead of county × day of birth year fixed effects. Columns (3) through (4) of Table A5 show that migration was unlikely to bias our results significantly. Furthermore, while we used forward counting to match the sunshine duration in the above analysis, columns (7) through (8) of Table A5 show that the results remain robust if we use backward counting as per Currie and Rossin-Slater (2013).

4.2. Plausible behavior mechanisms and vulnerable subgroups

To examine whether the effect differed between male and female infants, we divided the sample by gender and ran regressions separately. Fig. 6 and Table A6 display the results visually and numerically. For both LBW and SGA, male children seemed to be more sensitive to a longer

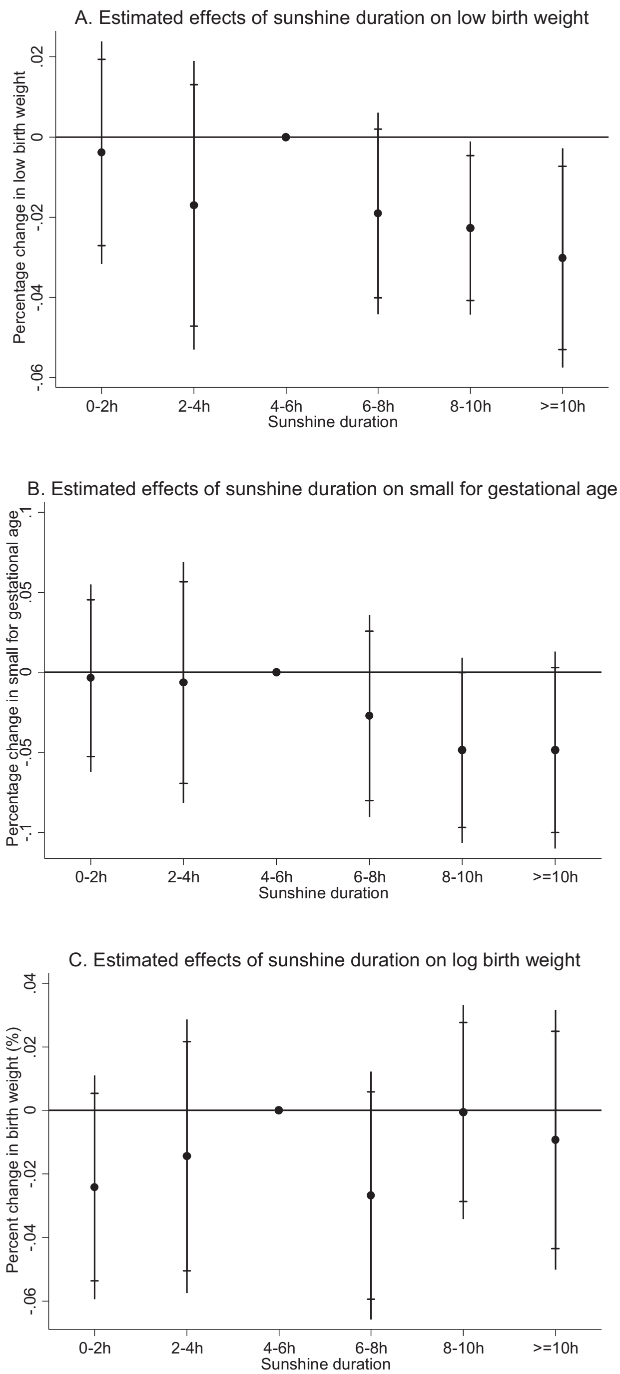

Fig. 3. Estimated effects of sunshine duration on birth outcomes in the gestation period. Source: China's National Disease Surveillance Points system and China Meteorological Data Service Center. Note: The figure plots the estimated coefficients with 90% and 95% confidence intervals associated with each sunshine duration bin identified from the regressions in Columns (2) and (4) of Table A1. Panels A, B and C correspond to the three birth outcomes, low birth weight (i.e., <2500 g), small for gestational age and log form of birth weight, respectively. The reference sunshine duration bin is 4–6 h. All the coefficients are scaled by 100 to make them more readable. The coefficients can be interpreted as effects of an additional day in the sunshine duration bin on birth outcomes relative to the reference sunshine duration category.

sunshine duration than their female counterparts, and this effect was significant at the 10% level when the sunshine duration was in the range of 8–10 h for SGA.

Following our discussion in Section 1 about two physiological mechanisms through which sunshine exposure affects birth outcomes, this section tests two behavior channels, including sorting into sunshine duration and mortality selection. The first channel involved sorting into longer sunlight exposure in terms of socioeconomic status (SES). If mothers from higher SES families tend to realize the importance of sunshine during pregnancy and therefore try to select into pregnancy when the length of daily sunlight is longer, newborns from higher SES families would be likely to have better birth outcomes when exposed to increasing sunshine duration.

Due to the data limitation on the income and social status of the parents, we used parental education years as proxies for SES. In the first two columns of Table 3, we examine the relationship between sunshine duration and parents' education years, respectively. As indicated in Table 3, we did not find any correlation between the number of days falling in the sunshine duration bins in the first month of pregnancy or the gestation period and parental SES.

The second channel is the mortality selection in utero as a result of sunshine exposure. We observed positive associations between an extremely long length of sunshine and birth outcomes when the weaker fetuses have a better chance to be screened out through the culling effect. Besides, boys are generally more vulnerable to negative shocks than girls. For instance, Valente (2015) found that, in terms of maternal stress, prenatal shocks resulted in a declined male-to-female sex ratio at birth. Column (3) of Table 3 shows that the number of days in the sunshine duration bins during the first month of pregnancy or the gestation period did not predict the gender of the child. As a result, the mortality selection mechanism is probably not feasible in our context.

4.3. Strengths and limitations

We merged a nationally representative birth record dataset with daily sunshine exposure during pregnancy in rural China and investigated how prenatal exposure to sunshine was related to birth outcomes, specifically the incidences of LBW and SGA. We contribute to the literature in several dimensions. First, we are among the first to examine the effect of prenatal exposure to sunshine on birth outcomes for a Chinese population. Due to the two offsetting channels linking sunshine and birth outcomes, the net effect of sunshine stimulation may become ambiguous and likely differs by race. Trudeau et al. (2016) found such a racial gap between White Americans and Black Americans, while the Asian population has not been tested. Our paper aimed to fill this gap by studying the effect of exposure to sunshine on birth outcomes based on a nationally representative birth record dataset in China.

Second, we took advantage of some unique features of rural China to address the identification challenges, like residential sorting and avoidance behaviors. One may be concerned about pregnant women migrating in response to sunshine exposure, but this is unlikely in our context. For one, people are less able to move during pregnancy, and those with rural registered residence have limited access to sanitation and other basic health facilities after outmigration. Two, unlike extreme weather or natural disasters, insolation is a relatively mild and long-lasting factor, while migration based on sunshine duration is too expensive, inconvenient, and unnecessary for rural families. Meanwhile, the household registration policy was stringent in a large part of the 1990s. It was not until 1997 that massive migration began (Meng, 2012). Furthermore, since most rural residents in China had to work outdoors during the daytime in the 1990s, sunshine duration nicely approximated sunshine exposure they actually received.

Third, we made use of more flexible model specifications than the previous literature, which mainly tested the effect of prenatal exposure to sunshine on health-related outcomes in linear or quadratic forms. We divided the sunshine duration into six bins to fully capture the nonlinear relationship between the length of sunlight and birth outcomes.

However, our study also has limitations. First, due to the ecological design of the study, some unobserved factors, like time-varying local shocks, may bias our estimates. Second, we did not have data on people's time outdoors, dietary intake, or avoidance behaviors, like wearing hats or sunscreens. Although we took advantage of some

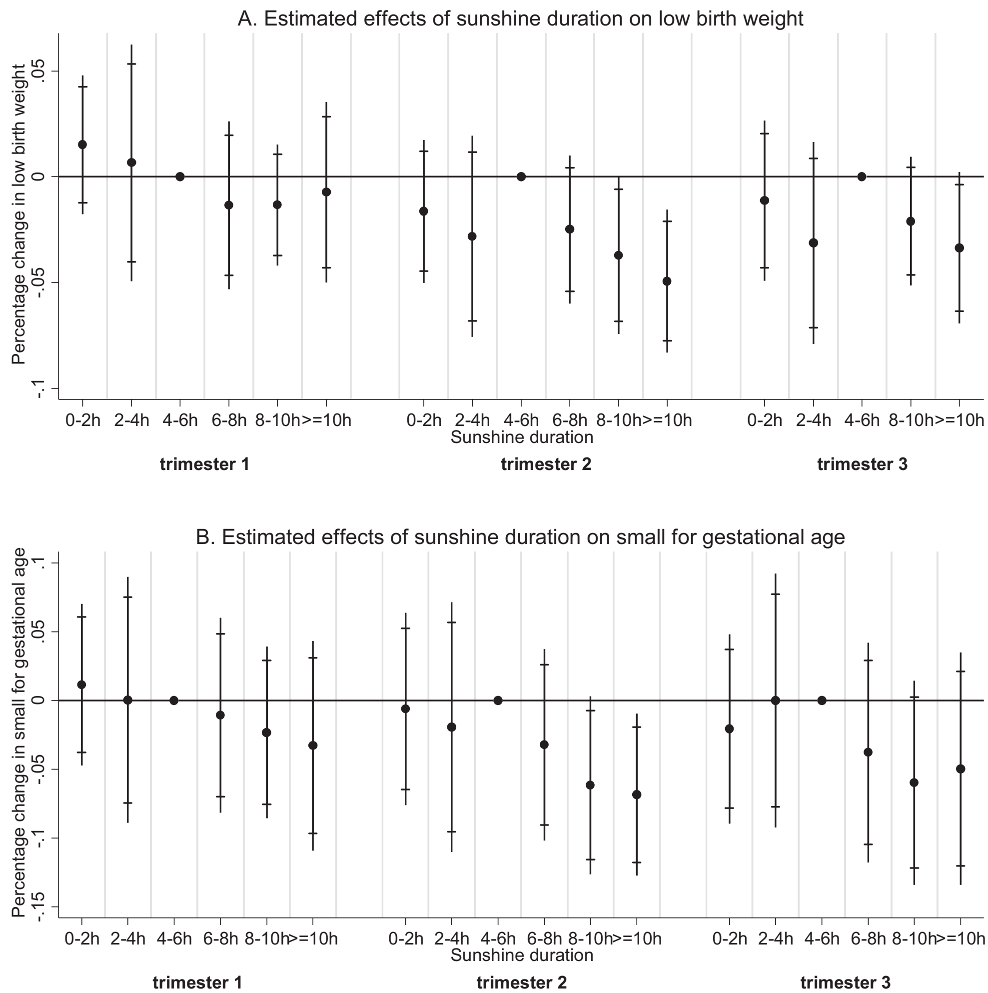

Fig. 4. Estimated effects of sunshine duration on birth outcomes in each trimester. Source: China's National Disease Surveillance Points system and China Meteorological Data Service Center. Note: The figure plots the estimated coefficients with 90% and 95% confidence intervals associated with each sunshine duration bin in each trimester from the regressions in Table A2. Panels A and B correspond to the two birth outcomes, low birth weight (i.e., <2500 g) and small for gestational age, respectively. The reference sunshine duration bin is 4–6 h. All the coefficients are scaled by 100 to make them more readable. The coefficients can be interpreted as effects of an additional day in the corresponding sunshine duration bin and trimester on birth outcomes relative to the reference sunshine duration category.

unique features of rural China in the 1990s to mitigate these confounders, pregnant women may have different farm work hours and schedules. Future research is encouraged to collect and incorporate this information. Third, sunshine exposure was likely to be measured with error due to the aggregation of sunshine duration data from sporadic outdoor monitoring stations at the county level. In addition, we

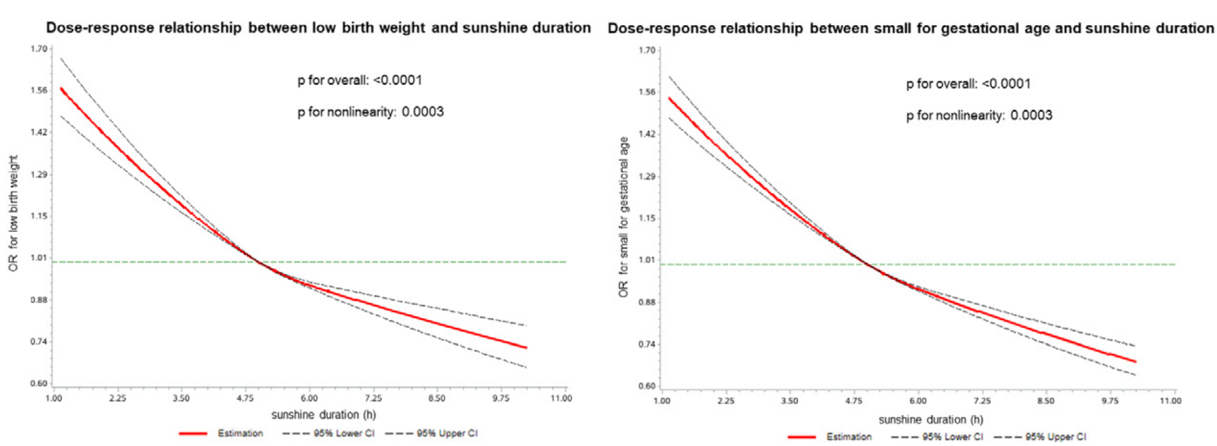

Fig. 5. Dose-response relationship between sunshine and birth outcomes using the RCS method. Source: China's National Disease Surveillance Points system and China Meteorological Data Service Center. Note: The x-axis is the mean of daily sunshine duration during pregnancy, and the y-axis is the odds ratios for both outcomes. The lines represent odds ratios based on the RCS method. The knots are placed at the 25th, 50th and 75th percentiles of the sunshine duration (i.e., 4.16, 5.32 and 6.36 h). The dashed lines represent the 95% confidence intervals. The horizontal dashed line represents the reference level (OR = 1), where the reference value is set at 5 h.

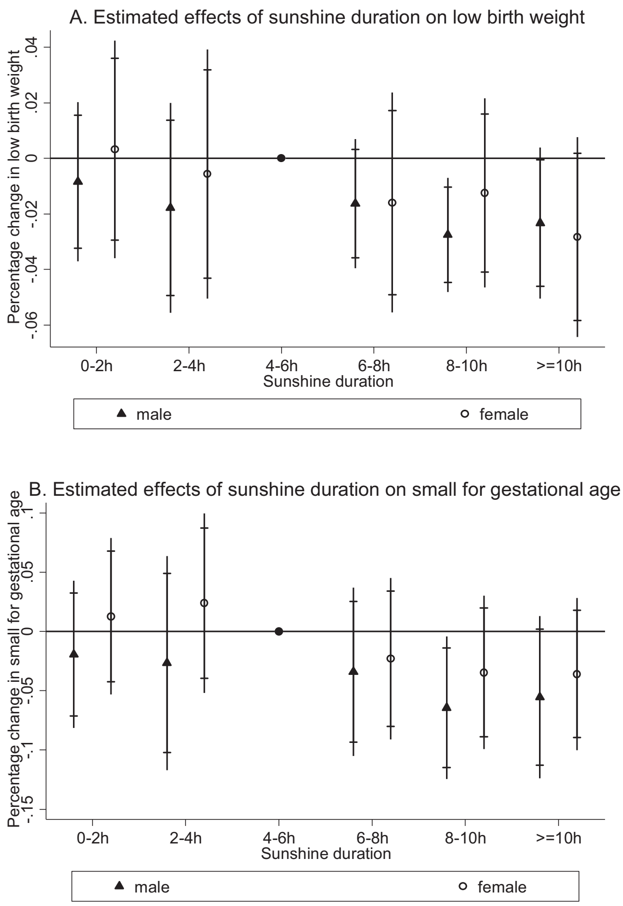

Fig. 6. Estimated effects of sunshine on birth outcomes, by gender. Source: China's National Disease Surveillance Points system and China Meteorological Data Service Center. Note: The figure plots the estimated coefficients with 90% and 95% confidence intervals associated with each sunshine duration bin identified from the regressions in Table A6. Panels A and B correspond to the two birth outcomes, low birth weight (i.e., <2500 g) and small for gestational age, respectively. The reference sunshine duration bin is 4–6 h. All the coefficients are scaled by 100 to make them more readable. The coefficients can be interpreted as effects of an additional day in the sunshine duration bin on birth outcomes relative to the reference sunshine category.

performed some tests on behavior mechanisms underlying the relationship between prenatal sunshine exposure and birth outcomes, but physiological and psychological channels still need to be examined using other data sources; this is also a further research direction.

5. Conclusion

Using matching data, we found a nonlinear relationship between the length of sunlight and birth outcomes, where increasing sunlight during the gestation period reduced the incidences of LBW and SGA. The effect was more salient in the second trimester during pregnancy. Specifically, spending an additional day with a sunlight length above 10 h in the second trimester, relative to a day in the 4–6 h range, was associated with a reduction in LBW by 0.049 percentage points (1.40% of mean occurrence of LBW), and a decrease in SGA by 0.069 percentage points (0.99% of mean occurrence of SGA). However, we found no significant detrimental effect on birth outcomes for newborns who were exposed to extremely short lengths of sunlight. Two behavioral channels, i.e., sorting into sunshine duration in terms of SES and mortality selection, could not fully explain our findings. The significant effect of the length of sunlight on birth outcomes was consistent with a physiological mechanism through vitamin D absorption or a psychological mechanism through relieving maternal stress.

Table 3
Behavior mechanism tests - sorting into sunshine duration and mortality selection.

Dependent variable	Father's years of education	Mother's years of education	Child being male
	(1)	(2)	(3)
A. number of days in the first 30 days of conception			
The number of days in the first 30 days of conception:			
0–2 h	−0.500	0.095	0.031
	(1.349)	(0.884)	(0.053)
2–4 h	−0.878	−0.462	−0.017
	(1.420)	(0.860)	(0.073)
4–6 h			
6–8 h	0.377	−0.316	−0.011
	(1.063)	(0.821)	(0.061)
8–10 h	−0.334	−0.616	0.002
	(1.087)	(0.750)	(0.055)
≥10 h	0.972	0.013	−0.083
	(0.942)	(0.933)	(0.056)
Number of observations	239,909	633,329	637,033
Adjusted-R^2	0.423	0.310	0.012
B. number of days in the gestation period			
The number of days in the gestation period:			
0–2 h	−0.275	1.147	−0.024
	(1.699)	(0.715)	(0.016)
2–4 h	−0.020	0.742	−0.049
	(1.368)	(0.662)	(0.033)
4–6 h			
6–8 h	0.239	0.723	−0.027
	(1.391)	(0.754)	(0.021)
8–10 h	−0.264	0.026	−0.014
	(1.342)	(0.567)	(0.022)
≥10 h	0.803	0.893	−0.019
	(1.093)	(0.609)	(0.022)
Number of observations	239,909	633,329	637,033
Adjusted-R^2	0.426	0.312	0.012

Source: China's National Disease Surveillance Points system and China Meteorological Data Service Center.
Note: *, **, and *** indicate significance level at 10%, 5%, and 1%, respectively. Robust standard errors, clustered at the county level, are presented in parentheses. The dependent variables are father's education years, mother's education years and child being male. The left-out sunshine duration bin is 4–6 h. All regressions include birth year fixed effects and county-by-day of year fixed effects. Demographic controls include gender, birth order, maternal age and its square term, and dummies for mother's education. Environmental controls include temperature bins (<−4 °C, −4–0 °C, 0–24 °C, 24–28 °C, ≥28 °C), as well as mean precipitation, mean wind speed and mean relative humidity in polynomial forms.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary figures and tables

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