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ABSTRACT

Light Pollution, Sleep Deprivation, and Infant Health at Birth*

This is the first study that uses a direct measure of skyglow, an important aspect of light pollution, to examine its impact on infant health at birth. We find evidence of reduced birth weight, shortened gestational length and even preterm births. Specifically, increased nighttime brightness, characterized by being able to see only one-third to one-fourth of the stars that are visible in the absence of artificial light, is associated with an increase in the likelihood of a preterm birth by as much as 12.8 percent, or an increase of approximately 45,000 preterm births nationwide annually. Our findings add to the literature on the impact of in utero and early-life exposure to pollution, which thus far has focused primarily on air pollution. The unique feature of our identification strategy to determine a causal effect is the application of Walker's Law in physics, which provides a scientific basis to estimate skyglow. We use estimated skyglow as an instrumental variable to address the endogeneity problem associated with the skyglow variable. In addition, our study shows that increased skyglow is associated with less sleep, indicating a likely biological mechanism that links sleep deprivation to light-pollution induced circadian disruption. This result, combined with the literature on the adverse effects of sleep disorders, completes the causal chain underlying our finding on the adverse health impact of skyglow. Our study has important policy implications for current installation of LED streetlights in many U.S. municipalities, highlighting the necessity of minimizing skyglow contributed by streetlights.

JEL Classification: I10, I12, I18, Q59, R11

Keywords: light pollution, skyglow, sleep deprivation, birth outcomes

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"The nighttime environment is a crucial natural resource for all life on Earth, but the glow of uncontrolled outdoor lighting has hidden the stars, radically changing the nighttime environment."

International Dark Sky Week 2018 (April 15–21), *The International Dark-Sky Association*

1 Introduction

In nature the light-dark cycle is determined by the solar day, and the biological clock of life on Earth regulates physiological functions, such as sleep, in accordance with the natural rhythm of a day.[1] However, for humans the transformation into a 24-hour society is not only jeopardizing that synchronization but also making sleep an expensive "good" to consume. To date, a small but growing literature in economics has shown adverse effects of sleep loss due to misalignment between circadian rhythm and social time (i.e., social jet lag) on health and economic performance (e.g., Giuntella and Mazzonna, 2017). Our study expands that literature by examining another source of social jet lag—artificial lighting at night.

While light is essential to a modern society and also indicative of economic growth (Henderson, Storeygard and Weil, 2012), artificial lighting at night can disrupt a human body's circadian rhythm (Skeldon, Phillips and Dijk, 2017). In this regard, artificial light is a "pollutant," and its contribution to "the alteration of night natural lighting levels" is often referred to as light pollution (Falchi et al., 2016, p. 1), which has been dramatically increasing throughout the 20th century and into the 21st. Today, nearly 80 percent of the world's population and 99 percent of individuals in the United States and Europe experience light pollution. In many cities in North America, artificial light at night is nearly 10 times brighter than natural nighttime light (Chepesiuk, 2009).[2]

Like air pollution, light pollution can be viewed as a negative externality of modern so-

[1] For more details, see the press release of the 2017 Nobel Prize in Physiology/Medicine available at https://www.nobelprize.org/nobel_prizes/medicine/laureates/2017/press.html (accessed on February 19, 2018).

[2] To increase public awareness about light pollution, the International Dark-Sky Association has been holding events such as International Dark Sky Week annually since 2003. For details, see http://www.darksky.org/dark-sky-week-2018 (accessed on April 16, 2018).

ciety. There is a vast literature on the effects of early-life exposure to pollution summarized in Currie et al. (2014). However, as they note, the majority of that literature has focused on air pollution, largely due to data availability, and economists have made significant contributions to that literature by utilizing natural or quasi-experiments to obtain causal estimates that have policy implications.

In this paper we aim to make contributions in two important areas. First, we examine effects on birth weight and gestational length of *in utero* exposure to light pollution, a type of pollution that has not received much attention in the economics literature. Second, we estimate an instrumental variable (IV) model based on a law in physics used for predicting light pollution. This law has not yet been used for identifying causal effects of light pollution on human health. While the medical literature has suggested a potential impact of circadian rhythm disruptions (e.g., through shift work) on human reproductive function (Casper and Gladanac, 2014), causal estimates of that impact are still lacking. Such estimates are not only important for shaping public policies, but also necessary for understanding the long-term impact of those policies, given that there is a robust association between early-life health indicators, such as birth weight, and long-run outcomes including adult health, educational attainment and earnings (Currie and Rossin-Slater, 2015).

Specifically, our study focuses on one important and visible aspect of light pollution—skyglow, which is an artificial brightening of the night sky in a built-up area, such as a city. To the best of our knowledge, this is the first study that uses a direct measure of skyglow and examines the impact of skyglow on birth outcomes. This line of research so far has been limited to studies on the health impact of night shift work (e.g., Lunn et al., 2017), in which exposure to nighttime light is only inferred, not measured. In contrast, we obtain a direct measure of skyglow from the Loss of the Night (LON) project.[3] LON is a project using citizen science, that is, public participation in scientific research. A mobile app enables users to collect data on skyglow and submit the data to the LON website.

[3] For more information about this LON project, see http://www.myskyatnight.com.

To the best of our knowledge, our study is the first to use the LON data to examine the impact of skyglow on health in general and birth outcomes in particular. Although satellite images have been used in studies examining the health consequences of light exposure in urban areas, such as the occurrence of breast cancer (Kloog et al., 2008), our use of the LON skyglow data represents a significant improvement. Satellite images can reveal the degree of artificial lighting used on the earth. However, there are two important limitations for using satellite imagery to measure skyglow. First, satellites measure the light emitted upward from the ground, not the light that humans are exposed to on the ground. Second, satellites, even with the most advanced instrument (i.e., the Visible Infrared Imaging Radiometer Suite Day-Night Band), are not sensitive to the blue part of the visible spectrum of light (Kyba et al., 2017), such as that emitted by Light-Emitting Diode (LED) streetlights. As a result, satellite images may fail to capture the skyglow added by LED streetlights, a growing source of light pollution. In comparison, the LON mobile app uses human eyes as a sensor to detect the brightness of a night sky including that from LED sources.

Specifically, the LON mobile app collects data on the Naked Eye Limiting Magnitude (NELM) from each user's location. NELM is defined as the brightness of the faintest star that a human can see with naked eyes, which is introduced by astronomers as a measure for skyglow given that skyglow obscures stars. The higher the NELM measure is, the more stars a human can see with naked eyes, which indicates less skyglow and a darker night sky.

Linking data from the LON project to birth records from the New Jersey Department of Health, we find evidence of reduced birth weight, shortened gestational length and even preterm births due to increased skyglow. Specifically, the likelihood of a preterm birth (defined as gestational length shorter than 37 weeks) increases by as much as 12.8 percent, as a result of decreasing the NELM by one unit.[4] Furthermore, in keeping with other studies that have found male fetuses to be more vulnerable than female fetuses, we find that the

[4] A one-unit increase in NELM indicates approximately three or four times as many stars can be seen in a night sky, according to the design of NELM. Additional detail regarding the interpretation of NELM measures is provided in the data discussion.

adverse effects of maternal exposure to skyglow on birth outcomes are more pronounced for male babies than for female babies. In addition, we use data on sleep deprivation from the 500 Cities Project[5] to further confirm the relationship between higher skyglow and less sleep. Our finding is consistent with the literature showing that outdoor nighttime lighting is linked to sleep disorders (e.g., Ohayon and Milesi, 2016).[6]

Another important contribution of our study is the expansion of the toolkit that can be used for identifying causal effects of light pollution. In the vast economics literature on the effects of early-life exposure to air pollution, existing empirical strategies used for causal inference largely belong in two categories. One uses detailed longitudinal data that allow for the use of fixed effects to control for time-invariant unobserved heterogeneities, such as the use of maternal fixed effects to control for unobserved characteristics of mothers (Currie, Neidell and Schmieder, 2009). The other category uses exogenous variation in air pollution levels driven either by human activities, such as economic recessions (Chay and Greenstone, 2003) and traffic congestions (Currie and Walker, 2011; Knittel, Miller and Sanders, 2016; Schlenker and Walker 2016), or by natural forces such as temperature inversions (Arceo, Hanna and Oliva, 2016), wildfires (Jayachandran, 2009) and wind (Yang et al., 2017; Yang and Chou, 2018). In contrast, our study utilizes a law in physics—*Walker's Law* (Walker, 1977)—to construct an IV, based on which we propose a new way of addressing the endogeneity problem associated with light pollution in general and the skyglow variable in particular.[7]

Because skyglow is often associated with urbanization and higher urbanicity tends to correlate with higher income, the impact of skyglow on an adverse birth outcome can be under-estimated without controlling for income, given that higher income usually helps improve birth outcomes. The positive correlation between skyglow and income is emphasized

[5] See https://www.cdc.gov/500cities for more details about the 500 Cities Project.

[6] The awarding of the 2017 Nobel Prize in Physiology/Medicine to scientists who study the biological underpinnings of the circadian clock has drawn attention to determinants of sleep patterns and the role played by exposure to light. For more details about this 2017 Nobel Prize in Physiology/Medicine, see https://www.nobelprize.org/nobel_prizes/medicine/laureates/2017/press.html (accessed on February 19, 2018).

[7] We give more detailed descriptions about this identification strategy in Section 4.1.

by Henderson, Storeygard and Weil (2012), who propose estimating real income growth (or economic growth) by using changes in the intensity of night lights. The basis of this estimation is that artificial lighting used at night can reflect human economic activities, and the estimation proposed by Henderson, Storeygard and Weil (2012) can be particularly useful for evaluating the economic performance of a geographic area that is not defined by existing jurisdictional borders, where official data on economic activities (e.g., Gross Domestic Product) may be lacking. In our study we also emphasize the positive correlation between skyglow and income by stressing that without separating the health-promoting effect of income (by controlling for the income variable), the adverse impact of skyglow on birth outcomes can appear to be zero, when in fact a substantial effect exists. In our study the skyglow variable may be endogenous due to the fact that we do not observe mother's income.

The rest of the paper proceeds as follows. We discuss the background of our study and describe the data, followed by the explanation of our identification strategy and regression models. Finally, we discuss our findings and the associated policy implications.

2 Background

In the following sections we summarize two strands of literature that jointly suggest an impact of light pollution on adverse birth outcomes, possibly through sleep loss due to circadian rhythm disruptions that are caused by light pollution.

2.1 Light Pollution and Health

Light exposure has long been linked to the timing and duration of sleep. Nighttime exposure to light reduces melatonin production, which is important in the regulation of the biological clock and is associated with increased sleep. There has been substantial documentation of the role of bright indoor lighting, television watching and use of electronic devices in sleep reduction (Gradisar et al., 2013; Heo et al., 2017; LeGates, Fernandez and Hattar, 2014;

Wood et al., 2013), but outdoor lighting is also increasingly implicated in sleep disorders. In an observational study that links recordings of nighttime light emission from the Defense Meteorological Satellite Program with survey data, Ohayon and Milesi (2016) find that higher levels of nighttime light are strongly associated with later sleep initiation, shorter sleep duration and increased daytime sleepiness. These results remain even after controlling for indoor lighting behavior, noise, and sleep location in addition to personal characteristics such as age, work, housing and family structure.

These well-documented changes to sleep and hormonal balance in response to increased artificial light at night have raised concerns about the impact of light pollution on health. Researchers have taken a variety of approaches to try to disentangle the impact of light exposure on a number of biological outcomes. Ecological studies have linked increases in nighttime light exposure to disrupted behavior in animals. In studies of animals as diverse as sea turtles, mice, birds and frogs, artificial light at night has been found to disrupt migration, foraging, and reproduction. It has also been found to lead to increased anxiety and suppressed immune function (Navara and Nelson, 2007). These effects are most pronounced in nocturnal animals near urban areas. Many of these results are confirmed in laboratory studies.

Adverse health effects of nighttime light exposure extend to humans (Chepesiuk, 2009). Nighttime light has been found to be associated with health consequences including cancers, metabolic dysfunction and mood disorders. These studies take different approaches, one by identifying variation in light exposure among shift workers and a second based on population studies exploiting variation in environmental light. Health outcomes examined include cancers (Conlon, Lightfoot and Kreiger, 2007; Davis, Mirick and Stevens, 2001; Kloog et al., 2008; Schernhammer et al., 2001), diabetes (Pan et al., 2011), obesity (Fonken et al., 2010), heart disease (Cho et al., 2015), and anxiety and depression (Bedrosian and Nelson, 2017).

Explanations of the mechanism through which increased exposure to light at night negatively affects health typically focus on changes in melatonin and its importance in maintaining circadian rhythm. Disruption in early evening melatonin secretion leads to disrupted sleep and also alters the production of estrogen. These changes in hormones and healthy sleep patterns have been implicated in adverse health outcomes (Chepesiuk, 2009), and are also linked to disrupted fertility (Goldstein and Smith, 2016; Kloss et al., 2015; Reiter et al., 2014). For example, Reiter et al. (2014) note the importance of the nocturnal secretion of melatonin for fetal health stating that regular circadian rhythms and sufficient melatonin are conducive to successful reproduction and suggesting that artificial light at night be avoided particularly in the third trimester of pregnancy.

The most substantial work in this area is comprised of studies examining the link between light exposure and health among shift workers. Recognizing the dramatic change in light exposure at night for evening and nighttime employees, a number of studies have found sizable increases in the risk of breast cancer among samples of nurses and other shift workers (Davis, Mirick and Stevens, 2001; Schernhammer et al., 2001). Similar approaches have found somewhat more mixed results linking shift work to an increased incidence of colorectal cancer (Schernhammer, et al., 2003) and prostate cancer (Conlon, Lightfoot and Kreiger, 2007). Studies using similar populations have found links between shift work and obesity, cardiovascular symptoms and diabetes (Antunes et al., 2010; Kim et al., 2013; Pan et al., 2011). Most closely related to this study, there is also evidence that female shift workers, who have disrupted circadian rhythms and sleep cycles, have a higher risk of having premature and low birth weight babies (Mahoney, 2010).

In addition to the substantial literature using shift work to identify exposure to light, researchers also have used population data to understand the health consequences of light exposure, exploiting data available on measurements of light exposure in urban areas. One notable study used satellite photos to measure nighttime artificial light in Israel (Kloog et al., 2008). Light data from 147 communities were linked to community-level breast cancer. Controlling for population density, socioeconomic status and air pollution, this study suggests a significant relationship between outdoor light at night and breast cancer: women living in brighter neighborhoods had a 73 percent higher risk of developing breast cancer compared to their counterparts living in areas with the least outdoor artificial lighting. This same methodology found no such link to the risk of lung cancer.

Kloog et al. (2010) extended this work by using data on light at night from 164 countries. They found a significant positive correlation between light at night and the incidence of breast cancer, controlling for country characteristics that include the fertility rate, per capita income, urbanicity and electricity consumption. Simulations of the increased rate of breast cancer between a country experiencing the highest level of light pollution and the lowest suggests a 30–50 percent higher incidence of breast cancer.

2.2 Sleep and Birth Outcomes

Sleep disorders during pregnancy are an important and widespread problem. Pregnancy requires sufficient sleep for fetal development and the stamina needed for the labor and delivery process (Chang et al., 2010). There are a number of studies showing a strong correlation between sleep and birth outcomes. In particular, sleep deprivation during pregnancy has been identified as a risk factor for preterm delivery, which is important since even today unknown causes still account for 50 percent of preterm births (Chang et al., 2010).

Li et al. (2017) conduct a prospective study of nearly 700 women in several hospitals in China. After controlling for potential confounders, Li et al. (2017) find that women who self-report poor sleep quality during the second and third trimesters were at greater risk of having a preterm birth. Micheli et al. (2011) analyze a prospective cohort of approximately 1,000 women in Greece. They have complete self-reports of the mother's sleep during the third trimester linked to birth outcomes. After adjusting for other factors, they find that women with sleep deprivation (defined as sleeping no more than five hours) were at higher risk for preterm births. Okun, Dunkel Schetter and Glynn (2011) also use observational data on 166 pregnant women, and they find those who report poor sleep (as measured by the Pittsburgh Sleep Quality Index) are more likely to have a preterm birth.

In one of the best identified studies, Felder et al. (2017) had a sample of more than three million pregnant women in California. Of this sample, 2,265 had diagnosed sleep disorders. Using propensity-score matching to provide a control group (and matching on a wide array of potential confounders), the researchers reported that pregnant women with diagnosed sleep disorders (insomnia and sleep apnea) were approximately two times more likely to have an early preterm birth (defined as gestational length less than 34 weeks) than comparable pregnant women without sleep disorders. The mechanism behind these poor birth outcomes is hypothesized to be inflammation that results from poor sleep.

Inflammation that results from sleep deprivation is still under study as a link between poor sleep and preterm birth (Blair et al., 2015; Chang et al., 2010; Felder et al., 2017). In particular, Blair et al. (2015) focus on racial differences in the association between poor sleep quality and shortened gestational length as well as increased risk of preterm delivery. Blair et al. (2015) suggest that their study provides new evidence that African-American women exhibit greater inflammation in response to sleep disturbance than European-American women, and that these effects correspond with length of gestation. They conclude that such racial differences may contribute to the marked racial disparities in preterm births observed in the United States.

3 Data

3.1 Data Sources

Our study uses data from three sources: birth records collected by the New Jersey Department of Health (NJDOH), the 500 Cities Project, and the Loss of the Night (LON) citizen science project. Our main analysis is focused on birth records obtained from the NJDOH, which include all live births that occurred in New Jersey between 2011 and 2015. These data provide information on birth weight (measured in grams), low birth weight (LBW, defined as birth weight under 2,500 grams), gestational length (measured in weeks), and the sex of the baby; as well as information on the mother's age, race and ethnicity, education, marital status, the number of prenatal visits, and smoking status. In addition, these data include the zip code of the mother's residence during pregnancy, and the associated latitude and longitude of that zip code's centroid. In our study we focus on singleton births, which constitute approximately 96 percent of the birth records collected by the NJDOH, to avoid cases in which adverse birth outcomes occur not because of maternal sleep loss due to light pollution, but because of factors that are related to carrying multiple fetuses.

We obtained a measure of sleep deprivation from the 500 Cities Project, which was launched in 2015 by the Robert Wood Johnson Foundation and CDC Foundation in partnership with the Centers for Disease Control and Prevention (CDC).[8] Sleep deprivation in these data is defined as sleeping less than 7 hours among adults aged 18 or older. In our analyses we use a variable measuring the annual prevalence (percentage) at the city level.[9] Data are available for the year 2014 for the 500 largest U.S. cities, covering all 50 states plus the District of Columbia.[10] We also use data directly provided by the 500 Cities Project on city population as well as the latitude and longitude of each city's centroid.

Skyglow data are obtained from the LON citizen science project. In 2012, the German Federal Ministry of Education and Research funded the development of a mobile app for measuring skyglow, which was released to the public in April 2013.[11] This mobile app collects skyglow data submitted by users around the world to be published on the LON project's website.[12]

[8] See https://www.cdc.gov/500cities for more details about the 500 Cities Project.

[9] The 500 Cities data include measures of sleep deprivation at both the city and census tract levels. We use the variable on the prevalence of sleep deprivation measured at the city level rather than the census tract level because there can be insufficient variation in light pollution within a small area.

[10] For the list of these 500 cities, see https://www.cdc.gov/500cities/pdf/500-Cities-Listed-by-State.pdf.

[11] Source: http://lossofthenight.blogspot.de/2013/08/first-blog-post-welcome-to-official.html (accessed on February 9, 2018).

[12] For more information about this LON project, see http://www.myskyatnight.com.

3.2 NELM Measures of Skyglow and Their Interpretation

The LON mobile app utilizes Google's Sky Map to ask its users to look for specific stars in the sky. If a star can be seen, then the app asks the user to find a dimmer star. If it cannot be found, then the app asks the user to find a brighter star. By repeating this exercise, the LON mobile app records and reports to the user the value of the NELM for the user's location. As noted earlier, the higher NELM is, the more stars a human can see with naked eyes, indicating less skyglow.[13]

The NELM can also be interpreted to indicate the number of stars a human can see with the naked eye. According to the scale used, an NELM of 2 indicates that approximately 25 stars can be seen with naked eyes, and is regarded as heavily light polluted (e.g., Manhattan). In contrast, in a night sky entirely clear of light pollution humans can see approximately 6,000 stars, which corresponds to an NELM value of 6.8.[14]

A simple rule of thumb is that an increase in NELM by one unit indicates that approximately three or four times as many stars could be seen with the naked eye. So, an NELM of 3 (increased from 2) indicates that approximately 75 to 100 stars can be seen with naked eyes (50–75 more stars visible than at an NELM of 2). This increase in the number of visible stars indicates a reduction in skyglow and reduced light pollution.

Figure 1 is a screenshot taken from the LON website illustrating the collection of skyglow data by the mobile app. The number in the raindrop shaped circle (2) shown at a location in Upper Manhattan (near Columbia University in New York City) is the NELM value for that location. The chart (on the right) shows which stars, based on Google's Sky Map, were observed by the LON mobile app user. Using this user's observation, the LON mobile app calculates the NELM value, which is represented by the white horizontal line in this chart.[15]

[13] For humans, the faintest object that can be seen with naked eyes has an apparent magnitude of about 8 (source: https://darkskydiary.wordpress.com/2011/01/07/limiting-magnitude/, accessed on May 15, 2018).

[14] See the Sky Brightness Nomogram for details, in which the NELM is called "approximate visible magnitude" (http://www.darkskiesawareness.org/img/sky-brightness-nomogram.gif, accessed on February 12, 2018).

[15] The associated shaded rectangular area shows the range over which this user was self-consistent when making multiple observations. This diagnostic check is required for each user of the LON mobile app as a

In addition to the skyglow data collected directly by the LON mobile app, the LON project publishes observations on skyglow that are obtained from three additional sources: the Globe at Night (GAN) project,[16] a sky quality meter (SQM),[17] and the dark sky meter (DSM) mobile app.[18] Because the sleep deprivation variable we obtained from the 500 Cities Project is only available for the year 2014, to match it we extract from the LON project the skyglow data also for the year 2014. In the data we extracted, 41.60 percent of the observations are obtained from the LON mobile app, 28.12 percent from the DSM mobile app, 25.93 percent from the GAN project, and 4.35 percent from the SQM.

3.3 Estimation Sample

Figure 2 is a screenshot taken from the LON website showing the data on NELM collected in the year 2014. In this figure the number shown in a circle in a geographic area is the number of NELM values obtained by the LON mobile app users in that geographic area. The number shown in a raindrop shaped circle is the NELM value obtained at a geographic location that has a single NELM value. The left panel shows the spatial distribution of the NELM data for the lower 48 U.S. states; the right panel zooms in on New Jersey, the state from which we obtained birth records. Figure 2 shows that more NELM data are generally collected in more populous regions, since the number of the LON mobile app's users in an area is likely to increase with population.

Birth data from the NJDOH contain the mother's residential zip code. To obtain a zip code level variable on skyglow, we use the following procedure. First, we calculate the average of the NELM values that are obtained in 2014 for each latitude and longitude of the mother's residential zip code. These NELM values may have been obtained by (the

way of ensuring data quality. The narrower (or wider) the band is, the more (or less) self-consistent the observations are. For a more detailed (step-by-step) instruction on how to use the LON mobile app, please see http://lossofthenight.blogspot.de/2017/02/a-step-by-step-guide-to-using-loss-of.html (accessed on February 10, 2018).

[16] The GAN project is another international citizen science project, which is similar to LON. For more information about the GAN project, see https://www.globeatnight.org.

[17] For more details, see http://www.unihedron.com/projects/sqm-l.

[18] For more details, see http://www.darkskymeter.com/app.html.

same or different) users of the LON mobile app on different dates. By averaging multiple NELM values obtained at the same location, we sacrifice the time dimension of the NELM data for at least two important reasons. First, in addition to skyglow, other atmospheric conditions affect the number of stars that can be seen by humans with naked eyes (e.g., higher humidity makes it harder to see stars). Second, the number of stars seen with naked eyes depends on a number of factors that are specific to that observer, such as age, sharpness of vision, and even the size of the eye's pupil. Averaging multiple NELM values obtained at the same location, possibly under different atmospheric conditions or by different observers, can reduce measurement error in the NELM variable.

Next, we calculate the distance[19] between the centroid of the New Jersey zip code where the mother lives and the location of each of the averaged NELM values. We calculate the zip code-level NELM value by averaging all NELM values measured at locations that are within 10 miles of each mother's zip code centroid to ensure sufficient sample size. The average number of NELM values that are within 10 miles of a zip code centroid is 4.6 and the median is 3.

The large New Jersey cities used in our study are those selected by the 500 Cities Project,[20] from which we extract the information on the city's latitude, longitude, and population. These data are required for our identification strategy and so the sample used for our main analysis includes 33 zip codes in the following eight New Jersey cities: Camden, Clifton, Elizabeth, Jersey City, Newark, Passaic, Trenton, and Union City.[21]

Table 1 reports the summary statistics (in columns 1 and 2) for the variables for our

[19] Throughout our study we use geodetic distance (a.k.a. geodesic distance) as the distance between two locations. Geodetic distance represents the length of the shortest curve between two points on the earth. The calculation of this distance uses the latitudes and longitudes of those two points.

[20] The 500 Cities Project is a collaboration between the Centers for Disease Control and Prevention (CDC), the Robert Wood Johnson Foundation, and the CDC Foundation to collect data that provide city- and census tract-level estimates of chronic disease risk factors, health outcomes, and clinical preventive service use for the largest 500 cities in the United States. See https://www.cdc.gov/500cities for detailed information.

[21] The city of Paterson, which appears in the 500 Cities Project, is not included in the sample used for our main analysis because of the 10-mile radius (previously explained) we used in calculating the zip code level average NELM value.

estimation sample.[22] The LBW and preterm rates among live singleton births that occurred in New Jersey during 2011–2015 are 6.9% and 11.5%, respectively. The LBW rate (6.9%) is roughly similar to the national average among all live singleton births during 2011–2015, which is 6.29%. However, the preterm rate (11.5%) is higher than the national average among all live singleton births during 2011–2015, which is 9.78%.[23] One possible reason for this higher preterm rate is that the eight large cities in New Jersey that make up our estimation sample include a greater proportion of African-American women than in the U.S. general population. The medical literature has shown that pregnant African-American women are at greater risk of having preterm babies (e.g., Blair et al., 2015).[24]

Table 1 also shows that the average NELM value in our estimation sample is 2.473, which indicates a darker night sky than that associated with an NELM of 2 in Upper Manhattan (Figure 1). For comparison, a value of 2 indicates that approximately 25 stars can be seen, and an NELM of about 2.5 means that 38 to 50 stars can be seen in the night sky. In the rest of the paper and for the purpose of brevity, we will refer to an NELM of 2.5 as being able to see approximately 50 stars in a night sky. This interpretation, although being an approximation, is consistent with the Sky Brightness Nomogram used by the "Dark Skies Awareness" project.[25]

Since skyglow is an artificial brightening of the night sky in a built-up area, it can be viewed as a by-product of urbanization. To examine whether our measure of skyglow is correlated with characteristics of urbanized areas, we regress the NELM (measured at the zip code level) on a set of zip code level characteristics. In Table 1, column (3) we see that at the zip code level higher population, higher housing values and higher household

[22] The zip code level variables (e.g., the variable on the zip code level average household income) are obtained from a zip code database purchased at https://www.zip-codes.com/zip-code-database.asp.

[23] The national LBW and preterm rates among all live singleton births are obtained from the CDC WONDER Online Database (https://wonder.cdc.gov/natality.html, accessed on February 12, 2018).

[24] In the NJDOH birth data information on whether the mother is non-Hispanic White was not collected. As a result, in Table 1 these two categories—mother being White and mother being Hispanic—are not mutually exclusive.

[25] For more details about the Sky Brightness Nomogram, see http://www.darkskiesawareness.org/img/sky-brightness-nomogram.gif (accessed on February 12, 2018), in which the NELM is called "approximate visible magnitude."

income are all associated with lower NELM, that is, a brighter night sky. The association between NELM and household income is particularly strong. This result is consistent with Henderson, Storeygard and Weil (2012), who propose estimating real income growth (or economic growth) by using changes in the intensity of night lights based on the positive correlation between artificial lighting at night and income. Furthermore, our estimation result reported in column (3) of Table 1 is reassuring in the sense that the NELM variable used in our study indeed captures an important aspect of skyglow, which is the generally positive correlation between the brightness of an area's sky and the income level of that area.

4 Methods

4.1 Identification Strategy

Because skyglow can be viewed as a by-product of urbanization and correlated with higher income, the impact of skyglow on an adverse birth outcome is expected to be an under-estimate of the true effect in the absence of controlling for mother's income. The bias is likely downward because higher income is associated with better birth outcomes (possibly through improved access to health care), and higher income is also often observed in more urbanized areas, where skyglow is higher. Therefore, without controlling for income, the impact of skyglow on an adverse birth outcome may appear to be small or zero, when in fact the effect is substantially positive. The birth data that we obtained from the NJDOH do not include information on the mother's income. As a result, our identification strategy focuses on the correction of an under-estimated impact of skyglow on an adverse birth outcome.[26]

To address the possible estimation bias due to the lack of information on mother's income, we use an instrumental variable (IV), which should be uncorrelated with a mother's income but predictive of the mother's skyglow exposure. The construction of this IV follows a

[26] Note that because NELM is inversely related to skyglow, the aforementioned under-estimation problem with respect to skyglow will be called an over-estimation problem with respect to NELM.

scientifically proven relationship called *Walker's Law* (Walker, 1977). This law has been used as a rule of thumb for estimating light pollution that is contributed by a city (e.g., Albers and Duriscoe, 2001; Elsahragty and Kim, 2015). Specifically, this law states that the skyglow at a location (A) in or near a city is linearly positively related to the product of the city's population and the inverse of $d^{2.5}$, where d is the distance between A and the center of the city (measured in kilometers). That is,

$$\text{skyglow at A} \propto \text{city's population} \times \frac{1}{d^{2.5}}.$$

Walker's Law is a variant of the *inverse-square law* in physics, which states that the intensity of a physical quantity is inversely proportional to the square of the distance from the source of that physical quantity. Walker's Law treats a city as the light-emitting source and revises the exponent of the distance in the inverse-square law from 2 to 2.5. Walker's Law can only be applied locally across areas where the levels of economic development or the degrees of urbanicity are similar. That is, this law cannot be used for predicting light pollution, for example, in an area that has a significant urban-rural divide. The empirical setting of our study is suitable for the application of this law, because the focal areas are the eight large cities of New Jersey, and New Jersey has the second highest percentage of urban residents in the United States, according to the U.S. 2010 Census.[27]

We employ Walker's Law to predict skyglow at the mother's residential zip code and use it as the IV for the skyglow represented by the NELM. Specifically, our IV is constructed as follows:

$$\begin{aligned} \text{IV} &= \text{predicted skyglow at the mother's residential zip code} \\ &= k \times \frac{1}{\text{distance}^{2.5}} \times \text{city's population}, \end{aligned} \tag{1}$$

[27] "Of the 50 states, California was the most urban, with nearly 95 percent of its population residing within urban areas. New Jersey followed closely with 94.7 percent of its population residing in urban areas. New Jersey is the most heavily urbanized state, with 92.2 percent of its population residing within urbanized areas of 50,000 or more population." (source: https://www.census.gov/newsroom/releases/archives/2010_census/cb12-50.html, accessed on March 19, 2018).

where k is a positive constant (which we choose to be 0.00001 in order to scale the IV to the NELM values). In equation (1) the variable "distance" is the distance (measured in kilometers) between the mother's residential zip code centroid and the centroid of the city which the zip code belongs to. City population is obtained from the 500 Cities Project. Prior to our IV estimation and as a diagnostic check, we computed the correlation coefficient between the IV and the NELM, and we found it to be -0.4456. The negative sign is consistent with Walker's Law, since NELM is inversely related to skyglow.

Our use of the IV is motivated by the need to correct the under-estimation of the impact of skyglow on adverse birth outcomes due to the lack of information on mother's income. This requires the independence between mother's income and the two components that are used in Walker's Law (i.e., the distance and the city's population). Here, we present some suggestive evidence in Table 2, showing the results of the two components regressed on observed characteristics related to mother's income. Column (1) reports the results of regressing the city population of the mother's residence on the mother's demographic characteristics. In this column, the statistical insignificance of the coefficients, except the one for mother being Hispanic, provides some suggestive evidence that mothers' demographic characteristics are independent of the population of her city of residence. These results also suggest, to the extent that these demographic characteristics are predictive of her income, that higher-income mothers in our sample do not necessarily live in more populous cities.

Column (2) of Table 2 reports the results of regressing the distance between the mother's residential zip code centroid and the centroid of the city where the mother lives on the mother's demographic characteristics and her zip code characteristics. In this column all except one coefficient are statistically insignificant. The only exception is the coefficient for the mother being white, and the point estimate is small: being white is associated with an increase of 0.4184 kilometers between the mother's residential zip code's centroid and the centroid of the city where the mother lives. These results suggest that the distance between the zip code's centroid and the city's centroid, although being predictive of the light pollution at the zip code's centroid, is not predictive of either zip code characteristics or mothers' demographic characteristics, indicating that the mother's income is independent of the measure of distance used in Walker's Law. Taken together, these results strengthen our argument that our IV captures variation in skyglow that is unrelated to mother's income.

Furthermore, the IV uses the product of the population of the city and the distance between the mother's residential zip code's centroid and the centroid of the city where the mother lives raised to the power of -2.5. We argue that this nonlinear transformation (of the distance and the city's population), while being predictive of the skyglow at the mother's residential zip code, is unlikely to directly determine birth outcomes. That is, the exclusion restriction of this IV is likely to hold.

4.2 Regression Models

To examine the impact of light pollution on birth outcomes, we estimate the following regression model:

$$y_{ij} = \alpha_0 + \alpha_1 \text{NELM}_j + \mathbf{x}_i'\beta + \mathbf{w}_j'\gamma + \text{birth year fixed effects} + \text{error term}_{ij}. \qquad (2)$$

Here, y_{ij} denotes the birth outcomes of an infant born to mother i who lives in zip code j during her pregnancy. The definition and measurement of NELM are explained in Section 3.2. In equation (2) $\mathbf{x}$ is mother and child characteristics including the sex of the baby, mother's age, mother's race and ethnicity (1/0 dummy variables for White, Black, and Hispanic), mother having completed a four-year college education or higher (1/0), mother being married (1/0), the number of prenatal visits, and maternal smoking (1/0).[28] Our regression model also includes a set of zip code level control variables denoted by $\mathbf{w}$: the population size for each zip code based on the 2010 U.S. Census and the associated White,

[28] The exact wording of the question asked about maternal smoking in the NJDOH's birth records is this: "Did mother smoke cigarettes before or during pregnancy?" As a result, this variable on maternal smoking included in our regression model is not necessarily able to capture mothers' smoking behaviors that occurred only during pregnancy.

Black and Hispanic subpopulation sizes for that zip code, the number of households for each zip code based on the 2010 U.S. Census, the average number of individuals per household for each zip code based on the 2010 U.S. Census, the average house value for each zip code based on the American Community Survey five-year estimate, the average household income for each zip code based on the American Community Survey five-year estimate, and the median age among all individuals for each zip code based on the 2010 U.S. Census.

The estimation sample includes all birth records obtained from the NJDOH between 2011 and 2015, to provide the statistical power needed for subsample analysis, for example, estimation by the newborn's sex to investigate potential biological mechanisms. In our regression model we treat the skyglow at a zip code as a time-invariant variable, which is supported by the trend analysis conducted at the LON website and now reported in Figure 3. This figure shows that, based on the 95% confidence intervals, there is little change in skyglow (represented by NELM) in New Jersey and the nearby region during this time period. This is also consistent with the finding of Kyba et al. (2017), who show that over the period of 2012–2016 the earth's artificially lit outdoor surface and the radiance increased in most countries but remained stable in a few countries including the United States, Spain, Netherlands and Italy.

We estimate the regression model using the Walker's Law IV, and we also compare the IV estimates with the estimates obtained from ordinary least squares (OLS). Standard errors in both OLS and IV estimations are clustered at the zip code level, that is, at a level that is higher than the level at which the dependent variable (each infant's birth outcome) varies, and the zip code level is also the level at which the NELM varies.

To gain insight into a possible mechanism through which light pollution may affect birth outcomes, we estimate the following regression model at the city level:

$$\text{sleep deprivation}_k = \pi_0 + \pi_1 \text{NELM}_k + \mathbf{c}_k' \pi_2 + \text{error term}_k. \tag{3}$$

The definition and measurement of the "sleep deprivation" variable was detailed in Section 3.1, and k denotes the city included in the 500 Cities Project. The city-level NELM value is the average value of the NELMs measured at locations that are within 10 miles of the city centroid. As a result of this restriction, 330 out of the 500 cities are included in the estimation sample. The vector $\mathbf{c}_k$ in equation (3) includes a set of control variables for city k's demographic characteristics, which are average values of zip code level demographic variables (previously explained), with the zip code centroid located within 10 miles of the city centroid. The control variable city population size is obtained directly from the 500 Cities Project. We estimate equation (3) by OLS with standard errors clustered at the county level.

5 Results

5.1 Main Results

Table 3 reports the main results of our IV estimation. Indeed, Walker's Law works well in our empirical setting, evidenced by the first-stage results showing that the IV strongly predicts the skyglow represented by NELM (with partial F-statistics greater than 20).

Regarding adverse birth outcomes (Panels A and C), we find that the likelihood of preterm birth increases by about 1.47 percentage points or 12.8% (calculated by 0.0147/0.115, shown in Table 1) as a result of a one-unit decrease in the NELM, which indicates that approximately one-third to one-fourth of the stars can be seen with the naked eye.[29] This effect implies that approximately 45,000 preterm births among all live singleton births nationwide could be averted annually.[30] Overall, the results in Panels A and C suggest adverse effects

[29] See the Sky Brightness Nomogram for details, in which the NELM is called "approximate visible magnitude" (http://www.darkskiesawareness.org/img/sky-brightness-nomogram.gif, accessed on February 12, 2018). In our estimation sample the average value of NELM is around 2.5 (shown in Table 1), which according to the Sky Brightness Nomogram corresponds to being able to see approximately 50 stars in the night sky with the naked eye. Thus, an NELM of 3.5 (i.e., a one-unit increase from 2.5) indicates approximately 150 to 200 stars can be seen in the night sky with the naked eye.

[30] According to the CDC's natality data (https://wonder.cdc.gov/natality.html, accessed on February

on infant health of having a brighter night sky (indicated by a lower NELM value).[31] These adverse infant health effects are further confirmed in Panels B and D in terms of continuous measures of birth weight and gestational length: a brighter night sky (indicated by a lower NELM value) reduces birth weight and gestational length.

The adverse effects of maternal exposure to skyglow on birth outcomes differ by child sex. The impacts of NELM on birth weight and gestational length are greater for sons (column 2) than for daughters (column 3). This finding is consistent with the sex difference predicted by theory (Aiken and Ozanne, 2013), and provides evidence supporting the "fragile male" hypothesis that male fetuses are more vulnerable than female fetuses to *in utero* environmental insults (Eriksson et al., 2010). This hypothesis is also supported by Currie and Schwandt (2016), who show that the adverse effects on birth outcomes of *in utero* exposure to the dust cloud caused by the 9/11 terrorist attacks are concentrated among males.

In contrast, OLS estimates reported in Table 4 are inconsistent with the "fragile male" hypothesis. Furthermore, in comparison with the IV estimates (reported in Table 3), the OLS estimates exhibit the under-estimation problem (which is the focal point of our identification strategy) regarding the impact of skyglow on adverse birth outcomes. This endogeneity problem would be reflected in an estimate of smaller magnitude in the OLS than in the IV. For example, the IV estimate reported in Table 3 (column 1) shows that an increase in skyglow, represented by a one-unit decrease in NELM, could increase the probability of

12, 2018), the annual live singleton births averaged over 2011–2015 is around 3,820,000. Thus, a reduction of 1.47 percentage points in the probability of preterm births for a single year means a reduction of 56,154 preterm births (i.e., the product of 3,820,000 and 1.47%). Note that our study is focused on urban areas, and four-fifths of the U.S. population lived in urban areas during 2011–2015 (https://www.cdc.gov/nchs/data/databriefs/db297.pdf, accessed on July 16, 2018). Assuming four-fifths of the newborns lived in urban areas, we infer that approximately 45,000 preterm births (roughly 80 percent of the 56,154 preterm births) among all live singleton births could be averted annually.

[31] In Appendix Table A1 we report the full set of coefficient estimates, and the results are consistent with stylized facts. For example, female babies are more likely to be LBW than male babies (since on average females are lighter than males at birth); preterm births are more likely to occur among male babies (in part due to male fetuses' greater susceptibility to complications of pregnancy); pregnant African-American women are at greater risk of having preterm babies (e.g., Blair et al., 2015); mothers with higher levels of education are at lower risks of having LBW and preterm babies; and maternal smoking is associated with increased risks of having LBW and preterm babies.

having a preterm birth by 1.47 percentage points, which is greater than the corresponding OLS estimate showing that the probability of having a preterm birth could increase by 0.63 percentage points (column 1 of Table 4).[32]

5.2 Further Checks on the Validity of the Main Results

Table 5 checks the exclusion restriction of the IV, a nonlinear transformation of the distance and the city's population based on the Walker's Law. We previously argued that this nonlinear transformation, while being predictive of skyglow in the mother's residential zip code, is unlikely to determine birth outcomes. Indeed, in column (2) of Table 5, where we regress low birth weight on both the NELM and the IV while controlling for our full set of covariates, we see that the coefficient of the IV is statistically insignificant and the estimate is also close to zero (i.e., 0.00007). Furthermore, the differences in all other coefficient estimates between column (1) without the IV and column (2) with the IV are extremely small, suggesting that the IV is uncorrelated with those covariates. These results, although not a direct proof, are nonetheless consistent with a valid exclusion restriction.

As a robustness check, we construct an alternative IV based on the inverse-square law, in which case the IV is equal to the inverse of the distance between the mother's residential zip code centroid and the centroid of the city which the zip code belongs to. The results of using this alternative IV are reported in column (2) of Table 6. Compared with the results in column (1) where the IV is based on Walker's Law, we see that the two sets of IV estimates are very similar. This finding is reasonable, since Walker's Law applied to predicting light pollution is a revised version of the inverse-square law in physics that is more generally applicable.

[32] Taken together, the results in Tables 3 and 4 demonstrate that the IV, constructed based on Walker's Law, is able to correct the under-estimation problem in estimating the impact of skyglow on an adverse birth outcome, when the under-estimation problem is caused by the omission of the variable on mother's income. By the same logic, omission of the variable on mother's income would cause an over-estimation problem in estimating the impact of skyglow on a positive birth outcome (e.g., birth weight and gestational length). The correction of this over-estimation problem by our IV is also confirmed in Tables 3 and 4.

5.3 Potential Biological Mechanism

Table 7 (Panel A) reports estimates of equation (3). In this estimation sample there are 330 U.S. cities, from 43 U.S. states plus the District of Columbia. Both sleep deprivation and NELM are measured in 2014.[33] Consistent with the literature, we find that a brighter night sky is associated with greater sleep loss. Specifically, the results in Panel A show that a one-unit decrease in NELM is associated with an increase of 0.46 percentage points or 1.3% (calculated by 0.46/35.5) in sleep deprivation among adults aged 18 or older.[34]

In Panel B we conduct a robustness check by replacing the sleep deprivation variable in equation (3) with a variable measuring current asthma among adults aged 18 or older, which is also measured in 2014. Because asthma is affected by air pollution, and air pollution is often associated with urbanicity, we use this check to see whether the NELM variable actually captures these two aspects of urbanicity simultaneously—skyglow and air pollution. A zero coefficient for NELM in the regression of city-level prevalence of current asthma would provide suggestive evidence that the variable NELM represents skyglow, not air pollution, since asthma is not directly affected by light pollution. Indeed, in Panel B we find the coefficient to be very small and statistically insignificant.

In addition, we examine whether the effects of skyglow on gestational length and preterm birth differ by race. To explain the effects that are found to be different by race, we rely on the results reported in Table 7 (Panel A), and also the link suggested by the literature between sleep deprivation and preterm birth (Blair et al., 2015; Chang et al., 2010; Felder et al., 2017; Li et al., 2017; Micheli et al., 2011; Okun, Dunkel Schetter and Glynn, 2011). Our results,

[33] The average value of NELM for this nationwide sample of cities is 3.6, which according to the Sky Brightness Nomogram (http://www.darkskiesawareness.org/img/sky-brightness-nomogram.gif , accessed on February 12, 2018) can be interpreted as seeing approximately 150 stars in a night sky with naked eyes.

[34] According to the Sky Brightness Nomogram (in which the NELM is called "approximate visible magnitude, http://www.darkskiesawareness.org/img/sky-brightness-nomogram.gif, accessed on February 12, 2018), an NELM of 4.6 (increased from 3.6) indicates that approximately 500 stars can be seen with naked eyes. The increase in the number of stars (from 150 stars for an NELM of 3.6 to 500 stars for an NELM of 4.6) indicates a reduction in skyglow given that a less light polluted night sky reveals more stars that can be seen with naked eyes. However, this reduction in skyglow is far from removing all light pollution. According to the Sky Brightness Nomogram, in a night sky clear of light pollution humans can see approximately 6,000 stars with naked eyes.

reported in Table 8, suggest that the effects of light pollution on preterm and gestational length are concentrated among mothers who are black, but not among mothers who are white. This difference between the two racial groups might be explained by inflammation, which is a potential biological mechanism underlying the link between sleep deprivation and preterm birth found in the literature. For example, Blair et al.'s (2015) study suggests that African-American women exhibit greater inflammation in response to sleep disturbance than European-American women, and these effects correspond with length of gestation.

5.4 Limitations

The biological mechanisms underlying these findings include two steps: the first links sleep deprivation to skyglow through circadian rhythm disruptions, and the second links adverse birth outcomes to sleep deprivation through inflammation. The existing medical literature thus far has consistently found that sleep deprivation is linked to preterm birth, but not low birth weight (Blair et al., 2015; Chang et al., 2010; Felder et al., 2017; Li et al., 2017; Micheli et al., 2011; Okun, Dunkel Schetter and Glynn, 2011). Therefore, we regard our findings on the increased risks of having preterm births due to light pollution as consistent with the biological mechanisms most supported by the existing medical literature.

However, our estimates of the impact of skyglow on preterm birth may still be biased, despite the use of an IV shown to be a strong predictor of light pollution. Given the large literature showing a positive association between maternal stress during pregnancy and preterm births (e.g., studies summarized in Bussières et al., 2015), the direction of the bias will depend on whether there is a positive or negative correlation between skyglow and maternal stress. On one hand, skyglow and stress leading to poor birth outcomes can both result from urban living; on the other hand, skyglow can increase perceived safety at night, thereby reducing stress and poor birth outcomes. Indeed, Doleac and Sanders (2015) show that increased ambient light could reduce crimes, and their study supports the presence of an association between increased skyglow and decreased maternal stress through exposure to fewer crimes.

To assess the direction of the bias in estimating the impact of skyglow on preterm birth, we control for possible correlates of urbanicity and skyglow that could be related to maternal stress. In particular, we focus on crime and noise. From New Jersey's annual Uniform Crime Reports (UCR) between 2011 and 2015, we obtained two crime variables measured at the city level: the yearly number of violent crimes (murder, rape, robbery, and aggravated assault) per 1,000 residents and the yearly number of non-violent crimes (burglary, larceny-theft, and motor vehicle theft) per 1,000 residents in the eight New Jersey cities included in our study. We use these two annual city-level crime variables as proxy variables for maternal stress caused by higher levels of crime. In addition to crime, noise pollution is also likely to be positively correlated with skyglow due to urbanicity, and may lead to an over-estimate of the impact of skyglow on the probability of having a preterm birth, since noise pollution is found to be associated with adverse birth outcomes (Gehring et al., 2014). To deal with this confounding factor, we obtain data on aviation and road noise from the U.S. Department of Transportation, where the noise data are available for year 2014 and vary by zip code.[35]

These three variables were added to the IV regression model described by equation (2), and the estimates of the impact of skyglow on preterm birth when we control for them are reported in Table 9. We see that an increase in skyglow, represented by a one-unit decrease in NELM, increases the probability of having a preterm birth by 2.10 percentage points (column 1), which is greater than the magnitude (1.47 percentage points) reported in Table 3. Again, the adverse impact seems to be concentrated among male babies (column 2), not among female babies (column 3). Taken together, these results suggest that our finding on the impact of skyglow on preterm birth, without controlling for maternal stress (through crime) and noise, appears to under-estimate the actual impact of skyglow on the probability of having a preterm birth.

[35] At the time of our study, only the 2014 data are available. For detailed information about the noise data, see https://www.transportation.gov/highlights/national-transportation-noise-map (accessed on May 31, 2018).

5.5 Policy Implications

While skyglow appears to be an inevitable by-product of economic development, a study by Kyba et al. (2015) shows that there are actually "cultural footprints" in the use of artificial lighting at night: cities in the United States use many times more artificial lighting at night per capita than cities in Germany. Some of the difference in lighting usage could be explained by the fact that highways in Germany are rarely lit at night, and cities and towns are lit conservatively.[36] This suggests that it is possible to reduce light pollution even in prosperous countries without sacrificing economic development. In this spirit, we conduct a case study to investigate whether the type of lighting matters. This case study draws attention to an unforeseen cost of LED streetlights: their contribution to light pollution and adverse health effects.

In a recent study, Jones (2018) used the 2009 Streetlight Efficiency Program that introduced LED streetlighting in Los Angeles to understand the impact of alternative lighting technology on breast cancer rates. This program resulted in the installation of more than 140,000 LED streetlights in the Los Angeles area. Using a synthetic control method, this study finds that exposure to LED streetlighting is associated with an increase in breast cancer mortality by nearly 0.5 deaths per 100,000 population. This finding is consistent with the warnings about adverse health impacts of LED lighting by the 2016 American Medical Association report and recommendations that their use be limited. Jones's (2018) estimates suggest that the negative health consequences more than outweigh the benefits of energy efficiency.

Again, using birth data obtained from the NJDOH, we focus on two specific cities in this case study: Camden and Newark. In November 2009 the city of Camden began preparing for the installation of LED streetlights.[37] To analyze this change, we turn to a standard

[36] Source: http://www.darksky.org/night-lights-and-prosperity-dont-always-go-hand-in-hand (accessed on February 17, 2018).

[37] For a more detailed description about the initiation of the LED streetlight installation in the city of Camden, please see https://www.menendez.senate.gov/news-and-events/press/menendez-announces-750-000-for-energy-efficiency-in-camden-city-through-program-he-created (accessed

difference-in-differences (DID) model to measure the impact of LED streetlighting on birth outcomes. Specifically, we use five birth years from 2011 to 2015 as the post-period, and five birth years from 2004 to 2008 as the pre-period. We exclude births from 2009 to 2010 because we have imprecise information on exactly when the city of Camden completed the LED streetlight installation. By excluding birth years 2009 and 2010, we have a clear delineation between pregnancies in Camden that were not exposed to LED streetlights and births resulting from pregnancies that occurred after the large scale switch to LED streetlights. We choose Newark as the comparison city for Camden because these cities are similar across a number of dimensions. Comparing every city and town in New Jersey with more than 10,000 people based on data from the 2013 American Community Survey, Yelp and Area Vibes, Camden and Newark are ranked lowest and second lowest, respectively, in 2018, according to criteria including household income levels, high school graduation rates, number of convenience stores, number of drug stores, number of discount stores, and crime.[38]

Table 10 reports the DID results of this case study, showing that maternal exposure to LED streetlight is associated with lower birth weight, shorter gestational length, and even LBW and preterm births (indicated by the coefficients for "Camden (1/0) × Post (1/0)" in Table 10). The estimates are robust across columns (1) through (3), whether controlling for zip-code level time-invariant observables (column 1 vs. column 2) or also for time-invariant unobservables by using zip code fixed effects (column 2 vs. column 3).[39] As before, the DID estimates (of the coefficients for "Camden (1/0) × Post (1/0)") become larger in magnitude in column (4) when we control for yearly city-level crimes. Admittedly, the causal inference in this case study is suggestive given the lack of an extensive set of control variables, and also the lack of exact information on the start and end dates of the LED streetlight installation in Camden. Nevertheless, the results reported in Table 10 may still be useful for considering

on February 17, 2018).

[38] For more details, see https://www.roadsnacks.net/these-are-the-10-most-ghetto-cities-in-new-jersey (accessed on March 7, 2018).

[39] The use of zip code fixed effect takes into account the effect of the noise variable (which is time-invariant and varying by zip code) used in Table 9.

policies regarding how to install LED streetlights properly in order to minimize their impacts on light pollution (e.g., through proper shielding), given the presence of health impact of light pollution.

6 Conclusion

In this study we use a direct measure of skyglow to examine its impact on infant health at birth. We find evidence of reduced birth weight, shortened gestational length and even preterm births. Specifically, the likelihood of a preterm birth could increase by approximately 12.8 percent, as a result of increased nighttime brightness, which is characterized by being able to see only one-third to one-fourth of the stars that are visible in the absence of artificial light. Our findings add to the literature on the impact of early-life exposure to pollution, which thus far has focused mainly on air pollution.

To the best of our knowledge, this is the first study that uses direct measures of skyglow to examine its impact on health in general and infant health at birth in particular. The use of such direct measures distinguishes our study from the existing literature that predominately focuses on night shift work, in which the light pollution is only inferred, not measured. The causal inference of our study is bolstered by the use of Walker's Law to create an instrumental variable. This law, rooted in the inverse-square law in physics, provides a scientific basis for us to generate an estimated variable representing skyglow, and we use this estimated skyglow as the IV to address the endogeneity problem associated with the skyglow variable. We further confirm a likely biological mechanism well-documented in the medical literature, linking sleep deprivation to light-pollution-induced circadian disruption, by showing that less sleep is associated with increased skyglow. This finding, combined with the well-established literature on the negative health impact of sleep disorders, completes the causal chain underlying our finding regarding the adverse health impact of skyglow.

The results of our study have important policy implications, particularly in light of the case study indicating adverse birth outcomes following the installation of LED streetlights in Camden, New Jersey. While intended to support the public good by reducing crime and accidents and increasing safety (Painter, 1996), streetlights do contribute to skyglow, particularly LED streetlights which are rising in popularity.[40] Touting its energy efficiency and long lasting equipment, municipalities have been installing LED streetlights to reduce operating expenses as new streetlights are added or older fixtures are replaced. Between 2012 and 2014, applications for LED lighting more than quadrupled, resulting in an estimated energy saving of $1.4 billion compared to installation of conventional lighting, according to a report prepared by Navigant Consulting (2015). This report cites an estimate given by the Department of Energy's 2014 study that LED solid-state lighting will make up 84 percent of all lighting purchases by the year 2030.

Given the causal effect of skyglow on birth outcomes identified in our study, minimizing the contribution to skyglow by LED streetlights, for example by the use of shielding LED, can be of vital importance.[41] As the study by Kyba et al. (2015) shows, the use of artificial lighting at night includes a cultural element: cities in the United States use many times more artificial lighting at night per capita than cities in Germany. In particular, cities and towns in Germany are lit conservatively. This comparison between the two equally prosperous countries highlights a possibility that light pollution does not have to be the "price" that always must be paid for economic development. In this sense, light pollution is a public policy choice, made after careful consideration of all of its potential costs and benefits.

[40] See the 2014 Nobel Prize in Physics regarding the energy efficiency of LED lights: https://www.nobelprize.org/nobel_prizes/physics/laureates/2014/press.html (accessed on February 20, 2018).

[41] While light exposure in general matters, the type of light is also important. The eyes of mammals are most sensitive to short-wavelength (blue and blue-green) light present in many LEDs, "so night-time exposure to LEDs is typically more disruptive to circadian rhythms, melatonin secretion and sleep than incandescent lighting" (Czeisler, 2013).

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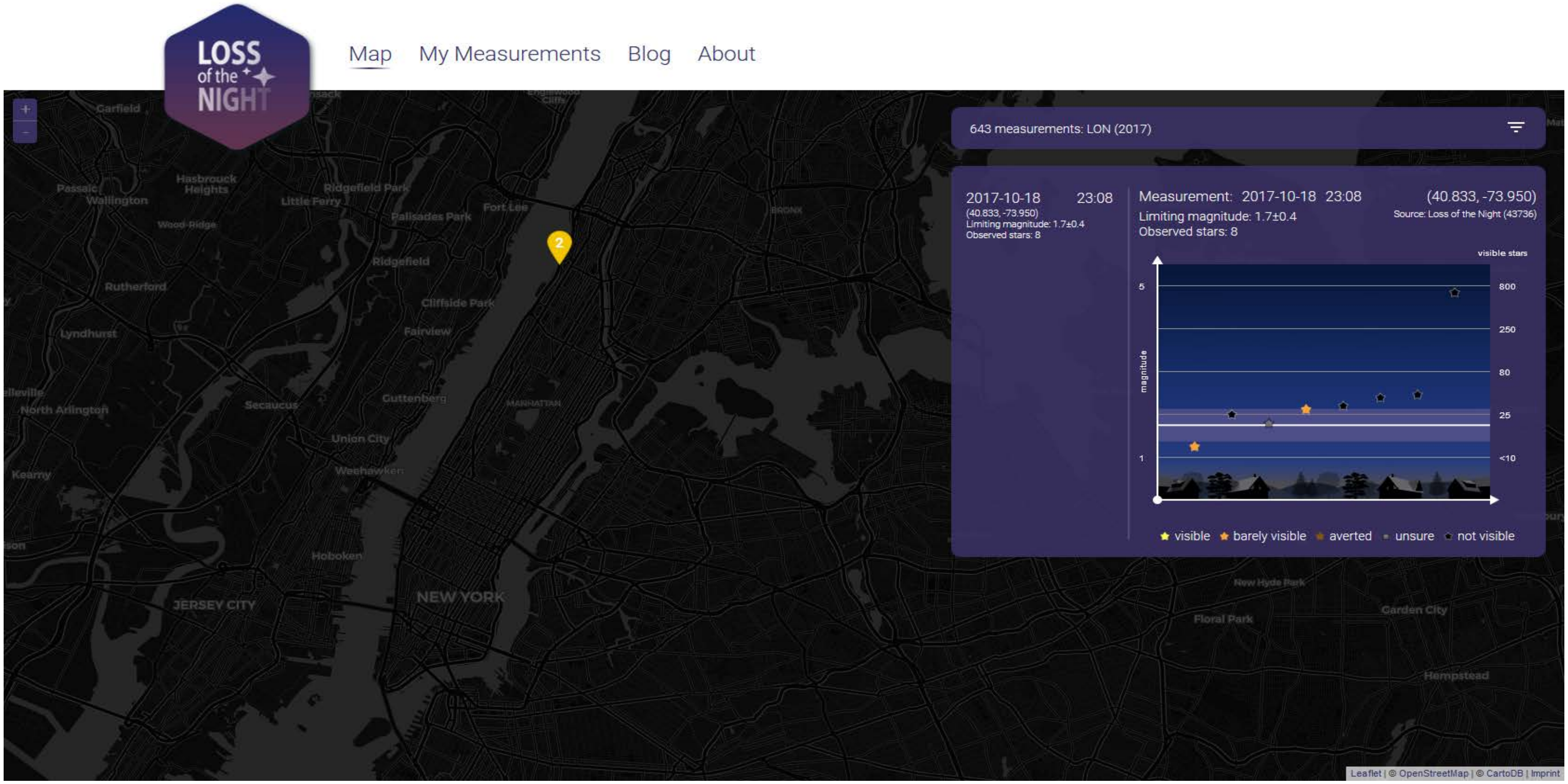

Figure 1: Data on Skyglow Collected by the Loss of the Night (LON) Mobile App and the Reported Naked Eye Limiting Magnitude (NELM)

Notes: This is a screenshot taken from the LON website showing how data on skyglow are collected by the LON mobile app. The number (which is “2”) in the raindrop shaped circle shown at a location in Upper Manhattan (near Columbia University in New York City) is the NELM value for that location. The NELM is defined as the brightness of the faintest star that a human can see with naked eyes. The higher an NELM is, the more stars a human can see with naked eyes, which indicates less skyglow. The chart (on the right) shows which stars (based on Google’s Sky Map) a user of the LON mobile app observed. Using this user’s observation, the LON mobile app calculated the NELM value, which is represented by the white horizontal line in this chart. The associated shaded rectangular area shows the range over which this user was self-consistent when making multiple observations, a diagnostic check made by this LON mobile app and also required for each user of this app to conduct, as a way of ensuring data quality: the narrower (or wider) the band is, the more (or less) self-consistent the observations are.

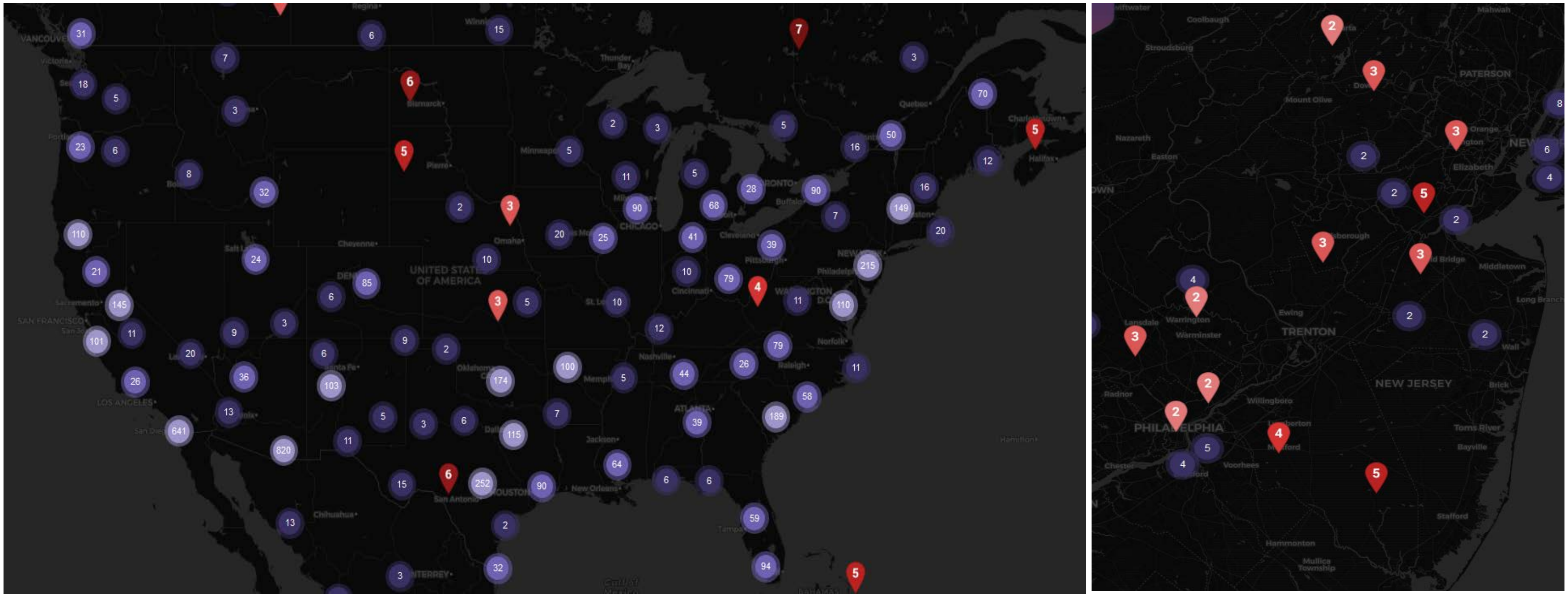

Figure 2: Spatial Distribution of the Measurements of Skyglow Represented by the Naked Eye Limiting Magnitude (NELM)

Notes: This is a screenshot taken from the Loss of the Night (LON) website at a particular zoom level for the year 2014. The geographic regions shown in the left and right panels are the lower 48 states of the United States and the State of New Jersey including the nearby regions, respectively. At the current zoom level, the number shown in a circle in a geographic area is the number of NELM values obtained by the LON mobile app users in that geographic area. This number will decrease when we zoom in that selected geographic area. The number shown in a raindrop shaped circle is the NELM value obtained at a geographic location that has a single observation, that is, a single NELM value.

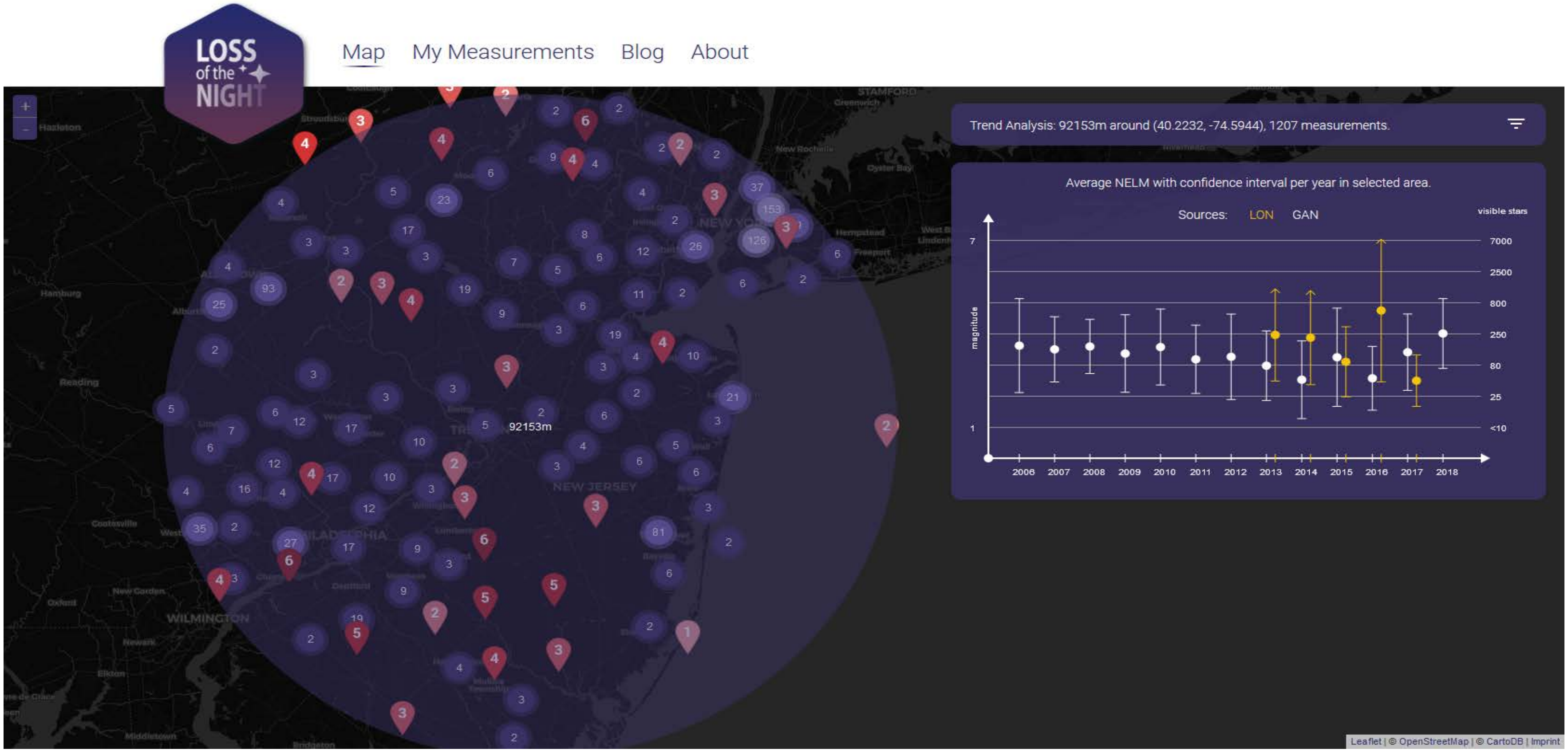

Figure 3: Trend Analysis on Skyglow Represented by the Naked Eye Limiting Magnitude (NELM)

Notes: This is a screenshot taken from the Loss of the Night (LON) website at a particular zoom level. Data are from the LON project with the following two sources for the NELM values: Globe at Night (GAN) and the Loss of the Night (LON). The geographic region selected here is the State of New Jersey including the nearby regions. At the current zoom level, the number shown in a circle in a geographic area is the number of NELM values obtained by the LON mobile app users in that geographic area. This number will decrease when we zoom in that selected geographic area. The number shown in a raindrop shaped circle is the NELM value obtained at a geographic location that has a single observation, that is, a single NELM value. The 95% confidence intervals are used for the trend analysis done by the LON project. The trend analysis uses all the NELM values that are available in the selected geographic area.

Table 1: Descriptive Statistics

	(1) Mean	(2) Std. Dev.	(3) Linear regression
Variables related to birth and pregnancy outcomes			
Birth weight (in grams), among singleton births	3,247.831	528.092	n/a
Low birth weight (1/0): birth weight < 2,500 grams, among singleton births	0.069	0.253	n/a
Gestational length (in weeks), among singleton births	39.120	2.380	n/a
Preterm (1/0): gestational length < 37 weeks, among singleton births	0.115	0.320	n/a
Female baby (1/0)	0.493	0.500	n/a
Variables related to mother's characteristics			n/a
Mother's age	28.400	6.087	n/a
Mother being White (1/0)	0.475	0.499	n/a
Mother being Black (1/0)	0.351	0.477	n/a
Mother being Hispanic (1/0)	0.493	0.500	n/a
Mother having completed a four-year college or higher (1/0)	0.227	0.419	n/a
Mother being married (1/0)	0.401	0.490	n/a
Number of prenatal visits	9.348	3.578	n/a
Mother smoked cigarettes before or during her pregnancy (1/0)	0.056	0.231	n/a
Variable on skyglow, measured at the zip code level, used as the dependent variable in column (3)			
Naked Eye Limiting Magnitude (NELM)	2.473	0.636	
Variables on mother's residential zip code's characteristics, used as the regressors in column (3)			
Population size for each zip code	42,572.515	16,942.188	-0.000095*
			(0.000048)
White subpopulation size for each zip code	17,543.885	12,359.125	0.000051
			(0.000039)
Black subopulation size for each zip code	12,480.857	8,570.687	0.000035
			(0.000021)
Hispanic subpopulation size for each zip code	20,647.318	16,786.382	0.000011
			(0.000027)
Number of households for each zip code	14,607.937	5,503.785	0.000137
			(0.000109)
Average number of individuals per household for each zip code	2.834	0.368	0.145073
			(0.324773)
Average house value for each zip code ($)	305,000.000	93,370.148	-0.000001*
			(0.000001)
Average household income for each zip code ($)	42,984.784	18,393.250	-0.000005**
			(0.000002)
Median age among all individuals for each zip code	32.208	2.830	0.021669
			(0.028410)
Number of zip codes	33		33
Number of observations	61,316		33

Notes: Summary statistics are based on the estimation sample including live and singleton births from 2011 to 2015. Birth records were collected and released by the New Jersey Department of Health. The zip code database was purchased from https://www.zip-codes.com/zip-code-statistics.asp. The NELM variable is obtained from the Loss of the Night citizen science project for the year 2014. An increase in NELM means a darker sky. The zip code level NELM value is the average value of the NELMs measured at locations that are within 10 miles of the zip code centroid. Zip code level control variables include the population size for each zip code based on the 2010 U.S. Census and the associated White, Black and Hispanic subpopulation sizes for that zip code, the number of households for each zip code based on the 2010 U.S. Census, the average number of individuals per household for each zip code based on the 2010 U.S. Census, the average house value for each zip code based on the American Community Survey five-year estimate, the average household income for each zip code based on the American Community Survey five-year estimate, and the median age among all individuals for each zip code based on the 2010 U.S. Census. Standard errors reported in parentheses are robust to zip code level heteroskedasticity. * p -value < 0.1; ** p -value < 0.05; *** p -value < 0.01.

Table 2: Check on the Exogeneity of the Two Components of the Instrumental Variable Constructed Based on the Walker's Law

Outcome variables:	Population of the city where the mother lives	distance between a zip code centroid and a city centroid
	(1)	(2)
Regressors listed below:		
Mother's age	0.3437	0.0037
	(0.4940)	(0.0029)
Mother's race and ethnicity:		
White (1/0)	-11.0535	0.4184*
	(19.8208)	(0.2140)
Black (1/0)	7.4420	0.1010
	(22.3105)	(0.0880)
Hispanic (1/0)	-39.2488*	-0.0082
	(18.1389)	(0.1516)
Mother having completed a four-year college education or higher (1/0)	6.0689	0.0323
	(11.6387)	(0.0801)
Mother being married (1/0)	-0.5853	0.0172
	(10.4316)	(0.0362)
Population size for each zip code (based on the 2010 U.S. Census)		0.0000
		(0.0002)
Associated White subpopulation sizes for that zip code		-0.0000
		(0.0001)
Associated Black subpopulation sizes for that zip code		0.0000
		(0.0000)
Associated Hispanic subpopulation sizes for that zip code		0.0000
		(0.0001)
Number of households for each zip code (based on the 2010 U.S. Census)		-0.0002
		(0.0004)
Average number of individuals per household for each zip code (based on the 2010 U.S. Census)		-0.3236
		(1.7397)
Average house value ($) for each zip code (based on the American Community Survey five-year estimate)		-0.0000
		(0.0000)
Average household income ($) for each zip code (based on the American Community Survey five-year estimate)		0.0000
		(0.0000)
Median age among all individuals for each zip code (based on the 2010 U.S. Census)		0.2615
		(0.1855)
Number of observations	61,316	61,316

Notes: The estimation sample includes live and singleton births from 2011 to 2015. The variables on city population (measured in 1,000 and for the year 2014), latitude and longitude of the city centroid are obtained from the 500 Cities Project. Latitude and longitude of the zip code centroid are obtained from the zip code database. The distance between a zip code centroid and the city centroid is the geodetic distance, measured in kilometers. Standard errors (reported in parentheses) are clustered at the city level (column 1) and at the zip code level (column 2), according to the level of variation of the dependent variable (varying at the city level in column 1 and varying at the zip code level in column 2). * p-value < 0.1; ** p-value < 0.05; *** p-value < 0.01.

Table 3: Effects of Light Pollution on Infant Birth Outcomes, IV Estimates

	(1) Full sample	(2) Male sample	(3) Female sample
Panel A: low birth weight (1/0, equal to 1 if birth weight < 2,500 grams)			
Naked Eye Limiting Magnitude (NELM)	-0.0039	-0.0087**	0.0012
	(0.0027)	(0.0042)	(0.0049)
Panel B: birth weight (measured in grams)			
Naked Eye Limiting Magnitude (NELM)	20.0540**	23.0941*	16.6447**
	(8.1138)	(13.1299)	(7.8618)
Panel C: preterm (1/0, equal to 1 if gestational length < 37 weeks)			
Naked Eye Limiting Magnitude (NELM)	-0.0147***	-0.0195***	-0.0099**
	(0.0041)	(0.0062)	(0.0041)
Panel D: gestational length (measured in weeks)			
Naked Eye Limiting Magnitude (NELM)	0.1101***	0.1141***	0.1082***
	(0.0292)	(0.0388)	(0.0316)
First-stage partial *F* statistics	22.37	21.95	22.80
Control variables used in Panels A through D			
Individual level demographic variables	Yes	Yes	Yes
Zip code level control variables	Yes	Yes	Yes
Birth year fixed effects	Yes	Yes	Yes
Number of observations	61,316	31,065	30,251

Notes: An increase in NELM means a darker sky. The estimation sample includes live and singleton births from 2011 to 2015. Individual level demographic variables controlled for are infant being female (1/0) except columns (2) and (3), mother's age, mother's race and ethnicity (1/0 dummy variables for White, Black, and Hispanic), mother having completed a four-year college education or higher (1/0), mother being married (1/0), the number of prenatal visits, and maternal smoking (1/0). Zip code level control variables include the population size for each zip code based on the 2010 U.S. Census and the associated White, Black and Hispanic subpopulation sizes for that zip code, the number of households for each zip code based on the 2010 U.S. Census, the average number of individuals per household for each zip code based on the 2010 U.S. Census, the average house value for each zip code based on the American Community Survey five-year estimate, the average household income for each zip code based on the American Community Survey five-year estimate, and the median age among all individuals for each zip code based on the 2010 U.S. Census. Standard errors (reported in parentheses) are clustered at the zip code level. * p-value < 0.1; ** p-value < 0.05; *** p-value < 0.01.

Table 4: Effects of Light Pollution on Infant Birth Outcomes, OLS Estimates

	(1) Full sample	(2) Male sample	(3) Female sample
Panel A: low birth weight (1/0, equal to 1 if birth weight < 2,500 grams)			
Naked Eye Limiting Magnitude (NELM)	-0.0026	-0.0027	-0.0026
	(0.0018)	(0.0023)	(0.0021)
Panel B: birth weight (measured in grams)			
Naked Eye Limiting Magnitude (NELM)	11.0137*	8.8466	13.5081***
	(5.4801)	(7.4748)	(4.7594)
Panel C: preterm (1/0, equal to 1 if gestational length < 37 weeks)			
Naked Eye Limiting Magnitude (NELM)	-0.0063*	-0.0070	-0.0055**
	(0.0035)	(0.0053)	(0.0026)
Panel D: gestational length (measured in weeks)			
Naked Eye Limiting Magnitude (NELM)	0.0498*	0.0315	0.0692***
	(0.0257)	(0.0310)	(0.0247)
Control variables used in Panels A through D			
Individual level demographic variables	Yes	Yes	Yes
Zip code level control variables	Yes	Yes	Yes
Birth year fixed effects	Yes	Yes	Yes
Number of observations	61,316	31,065	30,251

Notes: An increase in NELM means a darker sky. The estimation sample includes live and singleton births from 2011 to 2015. Individual level demographic variables controlled for are infant being female (1/0) except columns (2) and (3), mother's age, mother's race and ethnicity (1/0 dummy variables for White, Black, and Hispanic), mother having completed a four-year college education or higher (1/0), mother being married (1/0), the number of prenatal visits, and maternal smoking (1/0). Zip code level control variables include the population size for each zip code based on the 2010 U.S. Census and the associated White, Black and Hispanic subpopulation sizes for that zip code, the number of households for each zip code based on the 2010 U.S. Census, the average number of individuals per household for each zip code based on the 2010 U.S. Census, the average house value for each zip code based on the American Community Survey five-year estimate, the average household income for each zip code based on the American Community Survey five-year estimate, and the median age among all individuals for each zip code based on the 2010 U.S. Census. Standard errors (reported in parentheses) are clustered at the zip code level. * *p* -value < 0.1; ** *p* -value < 0.05; *** *p* -value < 0.01.

Table 5: Check on the Exclusion Restriction of the Instrumental Variable Constructed Based on the Walker's Law

Outcome variable: low birth weight (1/0, equal to 1 if birth weight < 2,500 grams)	(1)	(2)
Naked Eye Limiting Magnitude (NELM)	-0.00265	-0.00149
	(0.00183)	(0.00278)
IV used for NELM, constructed based on the Walker's Law		0.00007
		(0.00013)
Individual level demographic variables		
Female infant (1/0)	0.01192***	0.01192***
	(0.00197)	(0.00197)
Mother's age	0.00100***	0.00100***
	(0.00027)	(0.00027)
Mother's race and ethnicity:		
White (1/0)	-0.01492***	-0.01491***
	(0.00455)	(0.00457)
Black (1/0)	0.00365	0.00362
	(0.00371)	(0.00371)
Hispanic (1/0)	-0.01158***	-0.01143***
	(0.00268)	(0.00276)
Mother having completed a four-year college education or higher (1/0)	-0.00735***	-0.00742***
	(0.00252)	(0.00254)
Mother being married (1/0)	-0.01030***	-0.01030***
	(0.00262)	(0.00262)
Number of prenatal visits	-0.00790***	-0.00790***
	(0.00057)	(0.00057)
Maternal smoking (1/0)	0.04502***	0.04495***
	(0.00617)	(0.00618)
Zip code level control variables		
Population size for each zip code (based on the 2010 U.S. Census)	0.00000	0.00000
	(0.00000)	(0.00000)
Associated White subpopulation sizes for that zip code	-0.00000**	-0.00000**
	(0.00000)	(0.00000)
Associated Black subpopulation sizes for that zip code	-0.00000	-0.00000
	(0.00000)	(0.00000)
Associated Hispanic subpopulation sizes for that zip code	-0.00000	-0.00000
	(0.00000)	(0.00000)
Number of households for each zip code (based on the 2010 U.S. Census)	0.00000	0.00000
	(0.00000)	(0.00000)
Average number of individuals per household for each zip code (based on the 2010 U.S. Census)	0.00110 (0.00587)	0.00199 (0.00614)
Average house value ($) for each zip code (based on the American Community Survey five-year estimate)	0.00000 (0.00000)	0.00000 (0.00000)
Average household income ($) for each zip code (based on the American Community Survey five-year estimate)	-0.00000 (0.00000)	-0.00000 (0.00000)
Median age among all individuals for each zip code (based on the 2010 U.S. Census)	-0.00023 (0.00046)	-0.00025 (0.00045)
Birth year fixed effects	Yes	Yes
Number of observations	61,316	61,316

Notes: An increase in NELM means a darker sky. The estimation sample includes live and singleton births from 2011 to 2015. Standard errors (reported in parentheses) are clustered at the zip code level. * *p* -value < 0.1; ** *p* -value < 0.05; *** *p* -value < 0.01.

Table 6: IV Based on Walker's Law vs. IV Based on Inverse-Square Law

	(1)	(2)
Instrumental variable constructed based on:	Walker's Law	Inverse-Square Law
Panel A: low birth weight (1/0, equal to 1 if birth weight < 2,500 grams)		
Naked Eye Limiting Magnitude (NELM)	-0.0039	-0.0032
	(0.0027)	(0.0027)
Panel B: birth weight (measured in grams)		
Naked Eye Limiting Magnitude (NELM)	20.0540**	18.5254**
	(8.1138)	(7.9329)
Panel C: preterm (1/0, equal to 1 if gestational length < 37 weeks)		
Naked Eye Limiting Magnitude (NELM)	-0.0147***	-0.0145***
	(0.0041)	(0.0040)
Panel D: gestational length (measured in weeks)		
Naked Eye Limiting Magnitude (NELM)	0.1101***	0.1086***
	(0.0292)	(0.0284)
First-stage partial *F* statistics	22.37	23.99
Control variables used in Panels A through D		
Individual level demographic variables	Yes	Yes
Zip code level control variables	Yes	Yes
Birth year fixed effects	Yes	Yes
Number of observations	61,316	61,316

Notes: An increase in NELM means a darker sky. Column (1) shows the IV estimates, where the IV is constructed based on Walker's Law. Column (2) shows the IV estimates, where the IV is constructed based on the inverse-square law in physics. That is, the IV is equal to the inverse of the squared distance between a zip code centroid and a city centroid. The estimation sample includes live and singleton births from 2011 to 2015. Individual level demographic variables controlled for are infant being female (1/0), mother's age, mother's race and ethnicity (1/0 dummy variables for White, Black, and Hispanic), mother having completed a four-year college education or higher (1/0), mother being married (1/0), the number of prenatal visits, and maternal smoking (1/0). Zip code level control variables include the population size for each zip code based on the 2010 U.S. Census and the associated White, Black and Hispanic subpopulation sizes for that zip code, the number of households for each zip code based on the 2010 U.S. Census, the average number of individuals per household for each zip code based on the 2010 U.S. Census, the average house value for each zip code based on the American Community Survey five-year estimate, the average household income for each zip code based on the American Community Survey five-year estimate, and the median age among all individuals for each zip code based on the 2010 U.S. Census. Standard errors (reported in parentheses) are clustered at the zip code level. * p-value < 0.1; ** p-value < 0.05; *** p-value < 0.01.

Table 7: Impact of Light Pollution on Sleep Deprivation

	Dependent variable: Crude Prevalance measured in 0–100 percentage points		Dependent variable: Age adjusted prevalence measured in 0–100 percentage points	
	(1)	(2)	(3)	(4)
Panel A: Effect of light pollution on the prevalence of sleeping less than 7 hours among adults aged ≥ 18 years				
Naked Eye Limiting Magnitude	-0.4633**	-0.4633**	-0.4696**	-0.4696**
(NELM)	[0.2112]	(0.2194)	[0.2152]	(0.2217)
	mean of the prevalence = 35.53 percentage points		mean of the prevalence = 35.52 percentage points	
Panel B: No effect of light pollution on the current asthma prevalence among adults aged ≥ 18 Years				
Naked Eye Limiting Magnitude	-0.0569	-0.0569	-0.0663	-0.0663
(NELM)	[0.0587]	(0.0603)	[0.0575]	(0.0588)
	mean of the prevalence = 9.19 percentage points		mean of the prevalence = 9.15 percentage points	
Control variables used in Panels A and B				
City demographic characteristics	Yes	Yes	Yes	Yes
Number of observations	330	330	330	330

Notes: An increase in NELM means a darker sky. Each observation in the estimation sample is measured at the city level. The outcome variables are obtained from the 500 Cities Project, which provides the prevalence (measured in percentage points from 0 to 100) of each outcome variable for the year 2014, with two versions: the crude prevalence and the age adjusted prevalence (using the year 2000 standard U.S. population, more details provided at https://www.cdc.gov/500cities/measure-definitions.htm). The NELM variable is obtained from the Loss of the Night citizen science project for the year 2014. The city-level NELM value is the average value of the NELMs measured at locations that are within 10 miles of the city centroid. Control variables for city demographic characteristics are average values of zip code level demographic variables, with the zip code centroid located within 10 miles of the city centroid. These control variables include city population size (directly provided in the 500 Cities Project), population size by race and ethnicity (White, Black, and Hispanic) for each zip code based on the 2010 U.S. Census, the number of households for each zip code based on the 2010 U.S. Census, the average number of individuals per household for each zip code based on the 2010 U.S. Census, the average house value for each zip code based on the American Community Survey five-year estimate, the average household income for each zip code based on the American Community Survey five-year estimate, and the median age among all individuals for each zip code based on the 2010 U.S. Census. Standard errors reported in [brackets] are robust to city-level heteroskedasticity. Standard errors reported in (parenthesis) are clustered at the county level. * p -value < 0.1; ** p -value < 0.05; *** p -value < 0.01.

Table 8: Effects of Light Pollution on Gestational Length and Preterm Birth by Race, IV Estimates

	(1) Full sample	(2) Mothers being white	(3) Mothers being black
Panel A: preterm (1/0, equal to 1 if gestational length < 37 weeks)			
Naked Eye Limiting Magnitude (NELM)	-0.0147***	-0.0096*	-0.0349***
	(0.0041)	(0.0052)	(0.0096)
Panel B: gestational length (measured in weeks)			
Naked Eye Limiting Magnitude (NELM)	0.1101***	0.1001***	0.3064***
	(0.0292)	(0.0284)	(0.0831)
First-stage partial *F* statistics	22.37	26.69	16.77
Control variables used in Panels A and B			
Individual level demographic variables	Yes	Yes	Yes
Zip code level control variables	Yes	Yes	Yes
Birth year fixed effects	Yes	Yes	Yes
Number of observations	61,316	29,107	21,498

Notes: An increase in NELM means a darker sky. The estimation sample includes live and singleton births from 2011 to 2015. Individual level demographic variables controlled for are infant being female (1/0), mother's age, mother's race and ethnicity (1/0 dummy variables for White except column 2, Black except column 3, and Hispanic), mother having completed a four-year college education or higher (1/0), mother being married (1/0), the number of prenatal visits, and maternal smoking (1/0). Zip code level control variables include the population size for each zip code based on the 2010 U.S. Census and the associated White, Black and Hispanic subpopulation sizes for that zip code, the number of households for each zip code based on the 2010 U.S. Census, the average number of individuals per household for each zip code based on the 2010 U.S. Census, the average house value for each zip code based on the American Community Survey five-year estimate, the average household income for each zip code based on the American Community Survey five-year estimate, and the median age among all individuals for each zip code based on the 2010 U.S. Census. Standard errors (reported in parentheses) are clustered at the zip code level. * p-value < 0.1; ** p-value < 0.05; *** p-value < 0.01.

Table 9: Additional Checks on the IV Estimates of the Impact of Light Pollution on Preterm Birth

	(1) Full sample	(2) Male sample	(3) Female sample
Outcome variable: preterm (1/0, equal to 1 if gestational length < 37 weeks)			
Naked Eye Limiting Magnitude (NELM)	-0.0210***	-0.0266***	-0.0154**
	(0.0051)	(0.0071)	(0.0074)
First-stage partial *F* statistics	20.86	20.79	20.86
Control variables			
Individual level demographic variables	Yes	Yes	Yes
Zip code level control variables	Yes	Yes	Yes
Birth year fixed effects	Yes	Yes	Yes
Variables on yearly city-level crimes	Yes	Yes	Yes
Variable on aviation and road noise	Yes	Yes	Yes
Number of observations	61,316	31,065	30,251

Notes: An increase in NELM means a darker sky. The estimation sample includes live and singleton births from 2011 to 2015. Individual level demographic variables controlled for are infant being female (1/0) except columns (2)–(3), mother's age, mother's race and ethnicity (1/0 dummy variables for White, Black, and Hispanic), mother having completed a four-year college education or higher (1/0), mother being married (1/0), the number of prenatal visits, and maternal smoking (1/0). Zip code level control variables include the population size for each zip code based on the 2010 U.S. Census and the associated White, Black and Hispanic subpopulation sizes for that zip code, the number of households for each zip code based on the 2010 U.S. Census, the average number of individuals per household for each zip code based on the 2010 U.S. Census, the average house value for each zip code based on the American Community Survey five-year estimate, the average household income for each zip code based on the American Community Survey five-year estimate, and the median age among all individuals for each zip code based on the 2010 U.S. Census. The variables on yearly city-level crimes are from the New Jersey's Uniform Crime Reports for each year from 2011 to 2015, and they are (1) the yearly number of violent crimes (murder, rape, robbery, and aggravated assault) per 1,000 residents in a city and (2) the yearly number of non-violent crimes (burglary, larceny-theft, and motor vehicle theft) per 1,000 residents in a city. The data on noise are from the U.S. Department of Transportation. The variable on noise (measured in dBA) is for aviation and road noise, for year 2014 and varying by zip code. Standard errors (reported in parentheses) are clustered at the zip code level. * p-value < 0.1; ** p-value < 0.05; *** p-value < 0.01.

Table 10: Effects of LED Streetlight Installation on Birth Outcomes, Camden (NJ) vs. Newark (NJ)

	(1)	(2)	(3)	(4)
Panel A: low birth weight (1/0, equal to 1 if birth weight < 2,500 grams)				
Camden (1/0) × Post (1/0)	0.0146*	0.0146*	0.0146*	0.0217**
	(0.0083)	(0.0083)	(0.0083)	(0.0093)
Camden (1/0)	-0.0238***	-0.0156**		
	(0.0060)	(0.0068)		
Panel B: birth weight (measured in grams)				
Camden (1/0) × Post (1/0)	-33.0927**	-33.3810***	-33.4947***	-44.5678***
	(11.1837)	(11.1461)	(11.1819)	(10.8166)
Camden (1/0)	44.3731***	99.1128**		
	(13.5157)	(40.7137)		
Panel C: preterm (1/0, equal to 1 if gestational length < 37 weeks)				
Camden (1/0) × Post (1/0)	0.0134***	0.0133***	0.0135***	0.0199**
	(0.0040)	(0.0039)	(0.0039)	(0.0077)
Camden (1/0)	-0.0394***	-0.0259		
	(0.0043)	(0.0154)		
Panel D: gestational length (measured in weeks)				
Camden (1/0) × Post (1/0)	-0.2161***	-0.2165***	-0.2167***	-0.2349***
	(0.0425)	(0.0415)	(0.0416)	(0.0609)
Camden (1/0)	0.3780***	0.3898***		
	(0.0279)	(0.0577)		
Control variables used in Panels A through D				
Individual level demographic variables	Yes	Yes	Yes	Yes
Zip code level control variables	No	Yes	No	No
Birth year fixed effects	Yes	Yes	Yes	Yes
Zip code fixed effects	No	No	Yes	Yes
Variables on yearly city-level crimes	No	No	No	Yes
Number of observations	53,741	53,741	53,741	53,741

Notes: The estimation sample includes live and singleton births. The "Camden (1/0)" variable is equal to 1 for the city of Camden and 0 for the city of Newark. The "Post (1/0)" variable is equal to 1 for the post-period including birth years 2011 through 2015, and it is equal to 0 for the pre-period including birth years 2004 through 2008. Individual level demographic variables controlled for are infant being female (1/0), mother's age, mother's race and ethnicity (1/0 dummy variables for White, Black, and Hispanic), mother having completed a four-year college education or higher (1/0), mother being married (1/0), the number of prenatal visits, and maternal smoking (1/0). Zip code level control variables include the population size for each zip code based on the 2010 U.S. Census and the associated White, Black and Hispanic subpopulation sizes for that zip code, the number of households for each zip code based on the 2010 U.S. Census, the average number of individuals per household for each zip code based on the 2010 U.S. Census, the average house value for each zip code based on the American Community Survey five-year estimate, the average household income for each zip code based on the American Community Survey five-year estimate, and the median age among all individuals for each zip code based on the 2010 U.S. Census. The variables on yearly city-level crimes are from the New Jersey's Uniform Crime Reports for each year from 2004 to 2015, and they are (1) the yearly number of violent crimes (murder, rape, robbery, and aggravated assault) per 1,000 residents in a city and (2) the yearly number of non-violent crimes (burglary, larceny-theft, and motor vehicle theft) per 1,000 residents in a city. Standard errors (reported in parentheses) are clustered at the zip code level. * p-value < 0.1; ** p-value < 0.05; *** p-value < 0.01.

Appendix Table A1: Effects of Light Pollution on Low Birth Weight and Preterm Births, IV Estimates

Outcome variable in columns (1): low birth weight (1/0, equal to 1 if birth weight < 2,500 grams)		
Outcome variable in columns (2): preterm birth (1/0, equal to 1 if gestational length < 37 weeks)		
	(1)	(2)
Naked Eye Limiting Magnitude (NELM)	-0.0039	-0.0147***
	(0.0027)	(0.0041)
Individual level demographic variables		
Female infant (1/0)	0.0119***	-0.0100***
	(0.0019)	(0.0029)
Mother's age	0.0010***	0.0023***
	(0.0003)	(0.0003)
Mother's race and ethnicity:		
White (1/0)	-0.0148***	-0.0025
	(0.0045)	(0.0036)
Black (1/0)	0.0036	0.0186***
	(0.0037)	(0.0040)
Hispanic (1/0)	-0.0115***	0.0076*
	(0.0027)	(0.0044)
Mother having completed a four-year college education or higher (1/0)	-0.0074***	-0.0154***
	(0.0025)	(0.0037)
Mother being married (1/0)	-0.0103***	-0.0210***
	(0.0026)	(0.0030)
Number of prenatal visits	-0.0079***	-0.0120***
	(0.0006)	(0.0006)
Maternal smoking (1/0)	0.0451***	0.0218***
	(0.0061)	(0.0058)
Zip code level control variables		
Population size for each zip code (based on the 2010 U.S. Census)	0.0000	0.0000
	(0.0000)	(0.0000)
Associated White subpopulation sizes for that zip code	-0.0000**	-0.0000
	(0.0000)	(0.0000)
Associated Black subpopulation sizes for that zip code	-0.0000	0.0000
	(0.0000)	(0.0000)
Associated Hispanic subpopulation sizes for that zip code	-0.0000	0.0000
	(0.0000)	(0.0000)
Number of households for each zip code (based on the 2010 U.S. Census)	0.0000	0.0000
	(0.0000)	(0.0000)
Average number of individuals per household for each zip code (based on the 2010 U.S. Census)	0.0009	-0.0063
	(0.0058)	(0.0114)
Average house value ($) for each zip code (based on the American Community Survey five-year estimate)	0.0000	0.0000
	(0.0000)	(0.0000)
Average household income ($) for each zip code (based on the American Community Survey five-year estimate)	-0.0000	-0.0000*
	(0.0000)	(0.0000)
Median age among all individuals for each zip code (based on the 2010 U.S. Census)	-0.0002	0.0006
	(0.0005)	(0.0007)
First-stage partial F statistics	22.37	22.37
Birth year fixed effects	Yes	Yes
Number of observations	61,316	61,316

Notes: An increase in NELM means a darker sky. The estimation sample includes live and singleton births from 2011 to 2015. Standard errors (reported in parentheses) are clustered at the zip code level. * p-value < 0.1; ** p-value < 0.05; *** p-value < 0.01.