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## Abstract

This study uses satellite data to detect agricultural straw burnings and estimates its impact on air pollution and health in China. We find that straw burning increases particulate matter pollution and causes people to die from cardio-respiratory diseases. Middle-aged and old people in rural areas are particularly sensitive to straw burning pollution. We estimate that a 10μg/m3 increase in PM2.5 will increase mortality by 3.25%. Subsidizing the recycling of straw brings significant health benefits and is estimated to avert 21,400 pre-mature deaths annually.

**Key words:** straw burning, stubble burning, air pollution, mortality, straw recycling

**JEL Classifications:** I18, I31, Q18, Q53, R1

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## 1. Introduction

Farmers often burn agricultural straw residues from crops such as wheat, rice, maize and cotton *in situ* after harvest. Straw burning is particularly prevalent in developing countries that rely heavily on agricultural production and is a major cause of seasonal air pollution (Andreae and Merlet, 2001; Gadde et al., 2009; Rangel and Vogl, forthcoming). However, effective regulations on straw burning are rare and the lack of scientific evidence on how straw burning affects population health can make the government reluctant to design and enforce strict regulations. In this study, we estimate the impacts of straw burning on air pollution and population health using data from China and try to quantify the potential benefits of China's recent efforts in straw recycling.

Our analysis is based on a novel panel dataset that assembles detailed information on straw burning, air pollution and mortality in China. High-resolution satellite image data are used to identify the exact locations of straw burning in China during the years 2013 to 2015. Straw burning data are then linked to local air quality data collected from 1,650 ground-level monitors. Death records from a quarter of Chinese population are obtained from the Disease Surveillance Point system (DSPS) of China's Center for Disease Control and Prevention, which contain information of gender, age group, and cause of death at the county level from 2013 to 2015.

With these data matched at the county level, we then estimate how straw burning affects air pollution and mortality. We argue that, conditional on county, year, and month fixed effects, changes in the number of straw burning points during the burning season (May to July) provide plausibly exogenous variations in air pollution and thus allow us to estimate the causal impact of air pollution on health with an Instrumental Variable (IV) approach. We find that 10 additional straw burns detected by satellite will lead to a 4.79 $\mu g/m^3$ (or 7.62%) increase in monthly fine particulate matter ($PM_{2.5}$, diameter < 2.5μm) and a 1.56% increase in mortality in Chinese counties. Heterogeneity analyses reveal that straw burning primarily affects rural residents and causes deaths from cardiorespiratory diseases. In addition, we find that straw burning only increases particulate matter pollution and estimate that a 10 μg/m$^3$ increase in monthly $PM_{2.5}$ can lead to a 3.25% increase in allcause mortality.

A reasonable concern about our empirical strategy is that the number of straw burnings may be endogenous, i.e. it could be correlated with unobserved local economic activities or policies that also affect population health. To address this concern, we provide four sets of evidence that together strengthens the credibility of our main findings. First, we show that weather conditions, which are typical confounders in estimating the air pollution effect, have negligible impact on our estimates. Second, we show that the number of straw burnings is uncorrelated with previous day's air quality, suggesting that farmers do not consider the air pollution impact when they make decisions. Third, straw burning only elevates particulate matter (PM) concentrations, which primarily cause cardiorespiratory diseases. We indeed find that only cardiorespiratory mortality is affected, confirming that straw burning affects human health through the air pollution channel, rather than economic or behavioral channels. Finally, we construct "improved" instruments based on non-local straw burnings and leverage wind directions to strengthen the identification strategy. These alternative instruments are conceptually more appealing than the simple instrument based on local straw burnings because they exploit arguably "more exogenous" variations in air quality (i.e. air pollution caused by non-local straw burnings and the difference between upwind and downwind straw burnings). However, our analyses show that all of the improved instruments generate quantitatively similar estimates to the baseline model.

Based on our estimates, we then evaluate China's recent straw recycling policy launched in 2016. We find that subsidizing straw recycling effectively improved air quality and the estimated health benefits could outweigh the costs by several orders of magnitude. Specifically, using a Difference-in-Differences approach, we show that the number of straw burnings in subsidized provinces has dramatically declined after the policy (by 233 burns a year), relative to the non-subsidized provinces, and this change brought down the annual average $PM_{2.5}$ concentration by 4.92 μg/m$^3$. These estimates imply that the straw recycling policy could have averted 21,000 pre-mature deaths annually in China.

This paper makes four contributions to the literature. First, to our best knowledge, this is first empirical evidence about how straw burning affects population health (i.e. focus on different diseases, different genders, and different age cohorts). Our analyses show that straw burning imposes significant health risks on middle-aged and old people, and controlling straw burning will bring about significant health benefits.

Second, because straw burning primarily emits PM, we are able to isolate the PM effect from the effects of other air pollutants such as $SO_2$ and $NO_2$. Few studies are able to do so because the commonly-used instruments, such as environmental regulations and thermal inversions, affect multiple air pollutants simultaneously.

Third, we find significant rural-urban heterogeneity in the air pollution effect. Due to data limitations, rural residents have largely been ignored in existing air pollution studies. China's scaling up of its air pollution monitoring and disease surveillance networks in 2013 made it possible for researchers to include both rural and urban areas in empirical analysis. We find that straw burning and air pollution significantly increase the mortality of rural residents, but not that of urban residents. These results may suggest that better socioeconomic conditions can mitigate the health damage of air pollution, as urban people are richer, better informed about air pollution, and have greater access to medical treatment.

Finally, in terms of policy implications, we show China's recent straw-recycling subsidy policy is effective in reducing the number of straw burnings. Historically, the Chinese government relied on command-and-control regulations to reduce straw burning. Due to the high enforcement costs, however, these policies were not successful. In contrast, providing subsidy to farmers and recycling companies immediately lead to fewer burnings points and improvement in air quality. The market-based approach seems outperform the command-and-control approaches in our research context and these findings can be referenced by other agrarian economies with similar agricultural burning issues.

The rest of this paper is structured as follows. Section 2 introduces the practice of straw burning in China and reviews the current literature. Section 3 describes the data on straw burning, deaths, pollution and weather, followed by an introduction on data compilation, summary of key variables and descriptive analyses. Section 4 discusses our empirical strategy. Section 5 reports the main findings with discussions on caveats and robustness checks. Section 6 explores a variety of heterogeneities in the health effects of straw burning and pollution. Section 7 estimates the impact of the straw recycling policy and conducts an exploratory benefit-cost analysis. Section 8 concludes.

# 2. Background

## 2.1 Agriculture and Straw Treatments in China

China has the largest straw resource in the world. With a sown area of 0.11 billion *ha*, China produced 0.62 billion tons of grain in 2015,[1] accounting for 24% of the total grain output worldwide.[2] The major crops in China are maize, rice and wheat. Rice is mainly planted in the south, while wheat is common in northern and central regions. Maize is widely planted and the main production area is northeastern China. Two-season planting is common in central, eastern and southern China but is rare in northern China. This is because northern regions are colder and have longer winter season and thus do not have good weather conditions for the two-season crops. As a result, straw production also varies over time and space.

China produces the largest amount of agricultural straw residues in the world. In 2012, nearly one billion tons of straws were produced, contributing to 18.5% of the global straw production. Straws consist of crop stubbles and stalks. Crop stubbles are usually left in the farmland after harvest and burnt directly. Stalks can be collected after being cut off because they are longer; but a large portion of them remained unrecycled (Shi et al., 2014). According to China's Ministry of Agriculture, 0.32 billion tons of straws were not utilized in 2015, accounting for about 31% of the total straws produced nationwide.[3] The straw burning seasons in China are from late May to late July and from late September to late November each year.[4] Farmers burn straw for several reasons. First, they need to clear out

[1] National Bureau of Statistics: http://www.stats.gov.cn/tjsj/zxfb/201512/t20151208_1286449.html.

[2] Food and Agricultural Organization, United Nations: http://www.fao.org/worldfoodsituation/csdb.

[3] http://www.moa.gov.cn/zwllm/zwdt/201605/t20160526_5151375.htm.

[4] Note that there is no straw burning in the growing seasons by nature.

their fields for the next round of cultivation, but straw cannot be quickly decomposed by nature. Second, the fires kill pests, weeds, fungi and bacteria, which can be harmful for new crops. Third, the ashes can fertilize the farmland. Finally, alternative measures (such as straw recycling) are costly.

There are two primary ways of straw utilization: straw returning and straw recycling, both of which are time-consuming and labor-intensive. Straw returning, or soil incorporation, means to cut straw into smaller pieces and put them back to the farmland as fertilizer. However, the small pieces can make plowing inconvenient. As the decomposition process takes time, straw returning often hinders crop growing in the short run. Straw recycling means to re-use straws for other purposes, such as industrial materials, fuel and animal feed. Because each household only owns a small piece of farmland in China, the cost of straw gathering and recycling is high. Burning straw after harvest thus becomes a common practice in China.

## 2.2 Straw Burning and Air Pollution

Pollution from straw burning is a typical example of a negative externality. It originates from rural farms but travels to distant regions. The impact of straw burning on air pollution has been discussed extensively in the science community, with a focus on measuring pollutant emissions, modeling numerically the transmission of emissions, and analyzing the physicochemical reactions of air pollutants (see Chen et al., 2017 for a recent review).

The substances emitted from straw burning often include PM, volatile organic compounds, carbon dioxide and other compounds known to be toxic (Andreae and Merlet, 2001). Among them, straw burning emits a large amount of PM, which is dominated by submicron and fine particles. For instance, annual $PM_{2.5}$ emissions from open straw burning were about 1.036 million tons, accounting for 7.8% of total anthropogenic emissions in China (Zhang et al., 2016). The share of straw burning emissions could reach 56% in June in East China.

Straw burning emits very little $SO_2$ and $NO_x$, which are common pollutants from other sources such as fossil fuels (Streets and Waldhoff, 2000). Straw burning also creates small amounts of CO and secondary $O_3$, but they are generally less stable and persistent than particulates in the air. Existing evidence shows that amount of CO generated by incomplete combustion during open straw burning is low (Zhang et al., 2013) and association between biomass burning and $O_3$ is also weak (Jaffe et al., 2013; Rangel and Vogl, forthcoming).[5] Weather conditions, such as temperature and humidity, can also affect the smoke's composition and the generation of other secondary pollutants.

PM emissions from straw burning can travel long distances, and critics often blame straw burning for the large-scale and widespread haze episodes.[6] However, there lacks research that credibly quantifies the impacts of straw burning on air quality over longer periods and for larger geographic areas. Most of the scientific studies using numerical modelling approach can only be applied to specific areas within a short period of time, due to the huge uncertainties in the emission inventories and complex interactions between straw burning emissions and meteorological factors (Chen et al., 2017).

## 2.3 Related Literature

This paper contributes to several strands of literature. In terms of research focus and identification, our paper is closely related to studies on the consequences of forest wildfires. Jayachandran (2009) examined the effect of smoke (measured by aerosol from satellites) on early-life mortality during a big forest fire in Indonesia in 1997 and found that the fire significantly worsened infant health in poor areas. Sheldon and Sankaran (2017) showed that Indonesia's wildfire affected Singapore's air pollution and increased hospital admissions. Miller et al. (2017) used smoke plumes to identify pollution from wildfires in US and showed that wildfires could affect PM concentrations and that they could impair the health of the elderly in regions where background levels of air pollution are low. Other studies have shown that wildfires also have impacts on labor supply, housing prices,

[5] $O_3$ in the troposphere is mainly contributed by vehicle and industrial processes, and the formation of $O_3$ is complex depending on nonlinear interactions with temperature, solar radiation and other precursors.

[6] For example, Xinhua News: http://news.xinhuanet.com/politics/2015-10/20/c_1116884784.htm.

hospitalization and defensive expenditures (e.g. De Mendonça et al., 2004; Donovan et al., 2007; Moeltner et al., 2013; Richardson et al., 2012).

Unlike natural wildfires, straw burning is purely anthropogenic. It is often spread across wide geographic regions and occurs frequently and repeatedly during certain seasons. A sizable proportion of China's population lives or works close to the agricultural regions, implying high population exposure to straw burning pollution. That makes straw burning's impacts of great policy relevance. One recent paper has explicitly examined the burning of agricultural straw using panel data. Rangel and Vogl (forthcoming) used satellite data to investigate how smoke from sugarcane burning before harvest affects infant health in Brazil. They found a large adverse effect of sugarcane burning on downwind air quality, length of gestation, in utero survival and birth weight.[7]

Our paper also speaks to the large literature on detrimental health impacts of air pollution (e.g. Arceo et al., 2016; Chay and Greenstone, 2003; Currie and Neidell, 2005; Currie et al., 2014; Schlenker and Walker, 2015). In recent years, a growing strand of literature tries to estimate the causal impacts of air pollution on health in developing countries. Notably, Chen et al. (2013), He et al. (2016), and Ebenstein et al. (2017) have explored different quasi-experimental settings in China and shown that (general) air pollution has significant negative impacts on Chinese people's health in both the short and long run. We add new evidence to this literature by exploiting a different source of variation in air pollution (i.e. straw burning). In addition, we estimate the health impacts separately for both urban and rural residents, as air pollution may affect those two subpopulations differently because of their substantially different socio-economic status and exposure intensity.

Lastly, this study sheds light on the design of effective straw burning regulations. Literally, China has banned straw burning with a zero-burning target since the 1990s. Command-and-control regulations were widely adopted to reduce straw burning. For example, some places required village leaders to patrol and do surveillance; some places

[7] Several associational studies in the public health literature also investigated the relationship between straw burning and health (e.g. Jacobs et al.,1997). Due to lack of clear identification, estimates from these associational studies can be biased (see Dominici et al. 2014).

educated the farmers through propaganda; some places even applied administrative sanctions, such as dismissal or suspension, to local village leaders if people were found burning straw in their villages. However, most of these regulations were ineffective because they were difficult and too costly to implement. Rural households continued to burn the straw regardless various bans. Starting from 2016, the central government oriented to a market-based regulation which provides subsidies to farmers, enterprises and machineries for straw recycling. We show that the straw recycling subsidy is effective and has significantly reduced straw burnings. The estimated benefits of this policy significantly outweigh the costs.

## 3. Data

### 3.1 Straw Burning Data

Straw burning can be detected by remote sensing from satellites. In China, the Satellite Environment Center of the Ministry of Environmental Protection (MEP) collects daily straw burning data from the moderate resolution imaging spectroradiometers (MODIS) of NASA's Satellites TERRA and AQUA. These satellites overpass China twice a day in the daytime (around 10:30 and 13:30 local time) and twice each night (around 22:30 and 1:30 local time) and report all fire pixels detected with 250, 500 or 1000m resolution (Kaufman et al., 1998). A fire point is defined when an abnormality in temperature is detected within a pixel using a contextual algorithm which exploits the mid-infrared radiation from fires (Justice et al., 2002). Therefore, the burnt area can be much smaller than the satellite resolution. MODIS routinely detects both flaming and smoldering fires 1000 square meters in size, and the minimum area reported is about 50 square meters under good conditions. A large fire can be recorded as multiple fire points or pixels. The estimation of the burnt area is not recommended due to large uncertainties in modelling.[8]

[8] For details, see https://earthdata.nasa.gov/firms-faq.

The MEP checks the MODIS fire data and distinguishes straw burning from other types of fires (such as wildfires, which are rare in the granary regions during straw burning seasons in China) based on geographical information and land use. The measure of straw burning is consistent and comparable across time and space. All straw burnings occur during burning seasons in summer and autumn, and there is no straw burning during growing or harvesting seasons.

For the purposes of this study, we aggregated the daily straw burning data to the monthly level for two reasons. First, the daily data contain many zeros because not all counties burn straw every day, even during the burning seasons. Aggregating the data by month creates more variation in the number of straw burning points for each county.[9] Second, we try to avoid estimating the very short-term health effect of air pollution: temporal escalation of air pollution may affect most severely those whose health is already so compromised that they would have died in the short term anyway (known as mortality displacement or the "harvesting" effect). Daily or weekly data may be unduly influenced by such "harvesting" effect. Using monthly data to some extent alleviate this concern.

One limitation of the satellite data is that it does not distinguish large-area burns from smaller ones. However, because each household is only allowed to lease a small piece of land in China, we believe the size of each straw fire is similar within the regions.[10]

Another limitation is that satellites only capture burnings when they pass over the continent. Since straw burning may occur during non-overpassing periods and die out without temperature abnormality when satellites pass, the number of actually burning points can be under-estimated. Thus, the precise interpretation of our regressions is that they estimate the effects of straw burning *detected by satellite* on air pollution and mortality.

[9] Counties are in the third level of administrative hierarchy in China, which are below provinces and prefecture-cities and are above townships and villages. There were 2,854 Chinese counties by 2015. See http://xzqh.mca.gov.cn/statistics/2015.html.

[10] For example, the average area of farmland per agricultural household leased is 5 *mu* or 0.0033 $km^2$ in China in 2015, which is smaller than the size of a fire pixel but is larger than the fire area that can be detected. Source: http://opinion.people.com.cn/n1/2017/0605/c1003-29316482.html.

### 3.2 Death Data

Death data were collected from the Disease Surveillance Point system (DSPS) of China's Center for Disease Control and Prevention (CDC). The county-level DSPS collects the most comprehensive information on deaths in China at daily level with remarkably high quality.[11] Deaths in hospitals or at home are reported by hospital or community doctors and are registered in DSPS strictly following a standard protocol administered by the CDC. A death certificate will be filled in and reported with detailed information, allowing location-specific, gender, age-group specific and cause-of-death mortality rates to be calculated.

The DSPS was launched in the 1990s and its coverage has gradually expanded over the years. From 1991 to 2000, data were collected at 145 locations nationwide chosen as representative. From 2003 the system was expanded to cover 161 urban districts and rural counties. The DSPS was up-scaled again in 2013 to cover 605 counties (283 rural counties and 322 urban districts) with a population of 0.34 billion, encompassing roughly a quarter of China's total population, making it a highly representative data for the whole country. There are over 5 million death records in DSPS during 2013 to 2015.

In this study, we use the logarithm of the number of deaths as the main dependent variables. Age-adjusted mortality rate (number of deaths per 100 thousand people) is also used as a robustness check. Since the population change is small during our sample period, the two measures yield similar estimates. The reported causes of death were categorized as either cardiorespiratory or non-cardiorespiratory. The cardiorespiratory diseases included cardiac complaints and conventional respiratory diseases, but also cerebrovascular dysfunction (mostly stroke), tracheal and bronchial infections and lung cancers. The other reported causes of death were categorized as non-cardiorespiratory. We expect that straw burning and air pollution have larger impacts on cardiorespiratory mortality than on other causes of death.

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[11] More details about the DSPS can be found in He et al. (2016) and Ebenstein et al. (2017).

### 3.3 Pollution and Weather Data

Daily air quality data were collected from the records of 1,650 local monitoring stations, and were averaged by month. Concentrations of fine particulate matter ($PM_{2.5}$) were the key variable of interest, but data on $PM_{10}$, $SO_2$ and $NO_2$ were also collected.

We are aware of concerns on the quality of China's environmental data. In particular, Ghanem and Zhang (2014) show that China's API (Air Pollution Index) data can be manipulated across a threshold (API=100). However, we believe that this is not a big concern in our analysis for several reasons. First, if the manipulation of pollution reporting was only at the threshold, the sample size of the affected days is very small (less than 5% of all days), which does not change the general air pollution patterns across regions and over time. In fact, dropping the potentially problematic observations does not affect our results. Second, we focus on summer burning seasons, during which the PM concentrations are relatively low, ruling out any political incentives for data manipulation.[12] Finally, the quality of air pollution data has significantly improved since 2013 as China automated air quality reporting. Since then, it became more difficult to manipulate the environmental data and we fail to detect data manipulation across the threshold using our monitoring-station level data.

Daily weather conditions were collected from 403 meteorological stations, and were averaged by month too. Daily wind direction was calculated according to wind roses combining wind speed with frequencies in eight directions (fixed octants). Weather conditions may affect both air quality and straw burning and are thus obvious control variables. Wind speed, wind direction, relative humidity, precipitation and temperature were all included in the study's regressions. Wind can carry pollutants to other areas but also disperse them. Strong wind helps fires to spread. Higher humidity might discourage fires and result in less complete combustion. Farmers may hurry to burn straw in advance of rainfall based on their experience and professional forecasts to avoid possible delays to their farming. Rainfall can also of course clean the air to some extent. Temperature can

[12] The air pollution levels are higher during the winter seasons because China's winter heating system burns large amounts of coal.

affect straw burning as well. Straw burning usually happens during warm periods for the crops to grow, and cold environments makes fire grow and spread more slowly.

## 3.4 Summary Statistics

The aforementioned data were merged into one panel at the county-month-year level from May 20th to July 20th each year during 2013 to 2015, during which straw burning data are monitored and verified by the MEP. The DSPS counties were first matched with the locations where air quality data were collected. If a county had no monitoring station within 50 km of its center, that county was dropped from the analysis. If a county had multiple monitoring stations within that range, the average concentrations across all of the stations were used. Counties for which no monthly $PM_{2.5}$ data were reported for more than a year were also dropped. The weather data were matched similarly. The total number of straw burning points observed within 50 km from the center of each county was then tabulated by month. The average area of a Chinese county is 3,363 $km^2$, covered by a radius of around 33 km. We choose 50 km as the main specification and explore other distances from 35 km to 100 km as robustness checks. The final balanced panel covered 107 urban districts and 102 rural counties, with at least one pollution monitoring site within 50 km from each county's center. In total, 390 out of the 605 DSPS counties were dropped due to lack of data on $PM_{2.5}$.

Table 1 reports descriptive statistics summarizing the key variables including the number of straw burning points, air pollution concentrations, and the number of deaths. There were 2,540 burning points detected by the satellites during the period studied, an average of 2 burning points within 50 km of each county's center. Straw burnings were equally distributed along different wind directions, suggesting that wind patterns are largely random during the burning seasons. Both urban districts and rural counties had straw burning detected. The number of burning points was lower in the urban districts. This is because although many urban districts in China have farmland near the borders, the sown area is smaller than that of rural counties. Panel B of Table 1 contains the statistics of air pollution and visibility. The average $PM_{2.5}$ concentration during summer burning seasons was around 49 μg/m³, which is low compared with other seasons. Rural counties have higher $PM_{2.5}$ concentrations than urban districts in summer burning seasons.

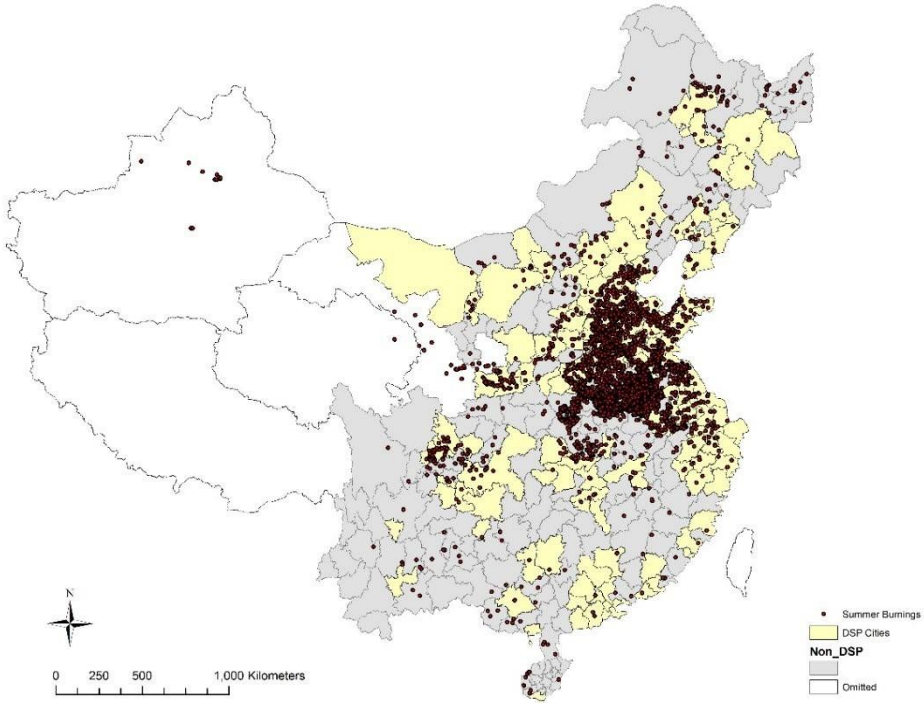
Table 1. Summary Statistics

| VARIABLES | Obs. | Mean | S.D. | Min | Max | Urban | Rural |
|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| *Panel A: Straw Burning* | | | | | | | |
| Straw Burning | 1,935 | 2.0 | 7.8 | 0 | 235 | 1.6 | 2.4 |
| Upwind | 1,935 | 0.5 | 1.7 | 0 | 36 | 0.4 | 0.5 |
| Downwind | 1,935 | 0.5 | 2.2 | 0 | 47 | 0.4 | 0.6 |
| Vertical | 1,935 | 1.0 | 4.6 | 0 | 154 | 0.8 | 1.3 |
| *Panel B: Pollution* | | | | | | | |
| $PM_{2.5}$ (μg/m³) | 1,595 | 49.2 | 24.2 | 5.6 | 133.5 | 47.9 | 50.7 |
| $PM_{10}$ (μg/m³) | 1,601 | 87.6 | 44.6 | 12.8 | 314.1 | 82.6 | 92.9 |
| $SO_2$ (ppb) | 1,641 | 8.7 | 6.7 | 0.6 | 83.9 | 8.0 | 9.5 |
| $NO_2$ (ppb) | 1,635 | 16.1 | 7.5 | 1.6 | 61.7 | 17.2 | 14.9 |
| Visibility(km) | 1,935 | 14.2 | 6.1 | 1.6 | 30.0 | 14.7 | 13.7 |
| *Panel C: Deaths* | | | | | | | |
| *Cause* | | | | | | | |
| All causes | 1,935 | 189 | 141 | 5 | 1,244 | 177 | 201 |
| Cardiorespiratory | 1,935 | 114 | 87 | 1 | 812 | 107 | 120 |
| Non-cardiorespiratory | 1,935 | 54 | 43 | 0 | 338 | 48 | 60 |
| *Age* | | | | | | | |
| 0 | 1,112 | 2 | 2 | 1 | 20 | 2 | 2 |
| 0-40 | 1,884 | 9 | 8 | 1 | 82 | 8 | 10 |
| 40-60 | 1,933 | 31 | 23 | 1 | 189 | 29 | 33 |
| 60+ | 1,935 | 149 | 114 | 5 | 1,003 | 141 | 158 |
| *Gender* | | | | | | | |
| Male | 1,935 | 109 | 81 | 3 | 734 | 102 | 117 |
| Female | 1,935 | 80 | 62 | 2 | 601 | 76 | 84 |

Notes: Summary statistics of monthly straw burning, air pollution and deaths in 209 counties are reported, including mean, standard deviation, minimum and maximum values. Mean statistics in urban and rural counties are listed in the last two columns. The summer burning period includes May.20th–July.20th in 2013–2015.

Panel C of Table 1 shows the number of deaths by cause, age and gender. Around two thirds of the total deaths are caused by cardiorespiratory diseases, and there are more deaths in rural areas compared with urban areas. Nearly 80% of the deaths are among elderly people above 60 years old, and males account for around 58% of the deaths.

Panel A: Straw Burning




Panel B: $PM_{2.5}$ in DSP Cities

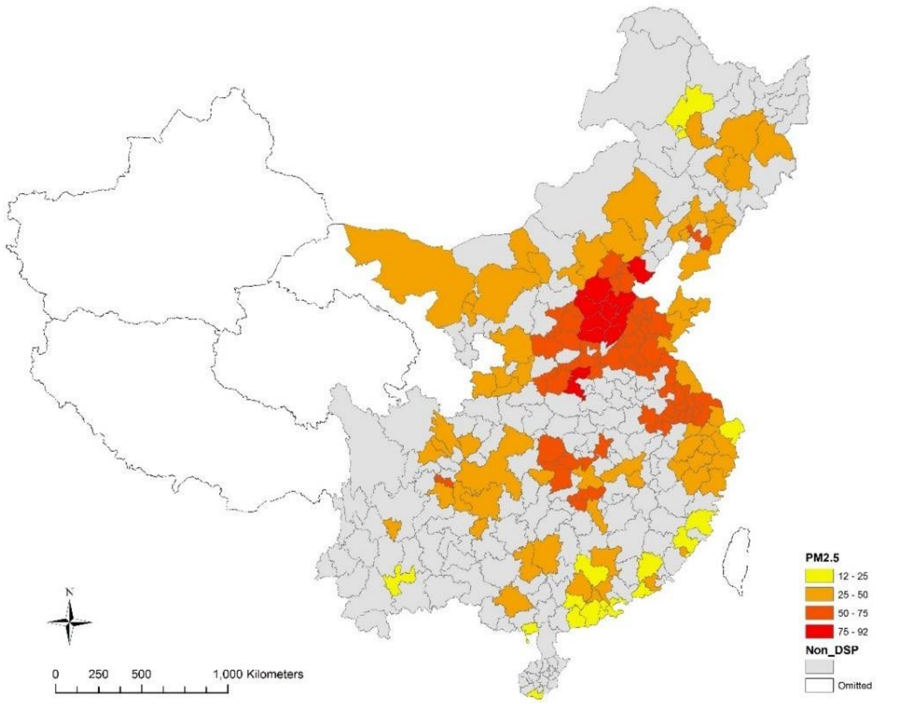



Figure 1. Satellite Detected Straw Burning and $PM_{2.5}$ in Summer During 2013–2015

Notes: Colored polygons represent selected DSP (Disease Surveillance Point) cities with deaths data available. Grey and white areas denote non-DSP cities and dropped regions, respectively. DSP counties are too small for clear visualization and are not plotted.

The spatial distribution of straw burning and air quality is shown in Figure 1. Panel A shows that most of the straw burnings took place in Henan, Hebei, Shandong, Jiangsu and Anhui provinces in central China. Panel B shows the average $PM_{2.5}$ concentrations during the summer burning seasons in 2013–2015. A strong positive correlation between the number of straw burning points and air pollution is evident. In counties with more straw burnings, $PM_{2.5}$ concentrations were higher.

## 4. Empirical Strategy

### 4.1 Main Specifications

We first estimate the impact of straw burning on air quality using the following equation:

$$PPPP_{iiii} = \beta\beta_0 + \beta\beta_1 bbbbbbbbbbbbbb_{iiii} + XX_{iiii}\theta\theta + \tau\tau_{ii} + \pi\pi_{ii} + \xi\xi_{iiii} \quad (1)$$

where $PPPP_{iiii}$ denotes the $PM_{2.5}$ concentration in county *i* in month *t*; $bbbbbbbbbbbbbb_{iiii}$ is the total number of straw burning points detected within 50 km from the center of county *i* in month *t*. $XX_{iiii}$ is a vector of weather variables: wind speed, wind direction, temperature, precipitation and relative humidity.[13] $\tau\tau_{ii}$ are county fixed effects, and $\pi\pi_{ii}$ are year and month fixed effects. $\xi\xi_{iiii}$ are errors. The county fixed effects control for time-invariant confounders specific to a county such as its natural endowments, crop patterns and strawburning cultures. The year and month fixed effects further account for shocks common to all counties in a particular year or month. Standard errors are two-way clustered at county and month level to account for autocorrelations along these two dimensions.

We then estimate the impact of straw burning on health in a similar way:

$$HHHHHHHHHHh_{iiii} = \alpha\alpha_0 + \alpha\alpha_1 bbbbbbbbbbbbbb_{iiii} + XX_{iiii}\vartheta\vartheta + \tau\tau_{ii} + \pi\pi_{ii} + \varepsilon\varepsilon_{iiii} \quad (2)$$

where $HHHHHHHHHHh_{iiii}$ denotes the logarithm of monthly number of deaths in county *i* in month *t*.

[13] Monthly wind directions are calculated based on daily wind directions using vector decomposition.

Equations (1) and (2) also provide the basis for estimating the impact of $PM_{2.5}$ on health. We focus on PM because we find that $SO_2$ and $NO_2$ were not significantly related with straw burning (see Appendix Table A2), which is consistent with the previous scientific evidence. PM can provoke pulmonary inflammatory response, alter cardiac autonomic function, and accelerate chronic obstructive pulmonary disease. We focus on $PM_{2.5}$ rather than $PM_{10}$ because existing epidemiological evidence suggests that smaller particles pose a greater threat to human health than larger ones do (e.g. Zanobetti & Schwartz, 2009). $PM_{2.5}$ can penetrate deeper into the lungs and enter the bloodstream due to its small size, and it can be quickly absorbed and create a direct hurt to the circulatory system (eg. Godleski et al., 2000).

We use the number of straw burning points as the instrumental variable (IV) for $PM_{2.5}$, and Equation (1) served as the first stage. The second stage estimation used the following equation:

$$HHHHHHHHHHh_{iiii} = \gamma\gamma_0 + \gamma\gamma_1 PPPP_{uii} + XX_{iiii}\rho\rho + \tau\tau_{ii} + \pi\pi_{ii} + \mu\mu_{iiii} \quad (3)$$

where $PPPP_{uii}$ is the predicted $PM_{2.5}$ concentrations from Equation (1). County fixed effects, year and month fixed effects, and weather conditions are all included as controls in both stages of IV.

We also compare the IV estimates with conventional OLS estimates, which are obtained by estimating the following equation:

$$HHHHHHHHHHh_{iiii} = \varphi\varphi_0 + \varphi\varphi_1 PPPP_{iiii} + XX_{iiii}\vartheta\vartheta + \tau\tau_{ii} + \pi\pi_{ii} + vv_{iiii} \quad (4)$$

The OLS estimates in Equation (4) may suffer from omitted variable bias and attenuation bias. The omitted variable bias emerges from the fact that we cannot control for all the factors that are correlated with PM and also affect population health. For example, air pollution and meteorological conditions interact with each other in rather complicated ways; as we do not have complete information on these interactions, the direction of the bias caused by unobserved meteorological conditions is unknown. PM can be also correlated with local economic activities that affect human health. The attenuation bias can be caused by the inclusion of many fixed effects in the regression and the existence of measurement errors in air quality levels. For example, our pollutant concentrations are measured at monitoring stations, which are used to proxy the ambient air pollution for the population. This measurement error is inevitable in air pollution studies, raising concerns on whether fixed effects models should be applied at all.

### 4.2 Endogeneity Concern

In applying the IV approach, we implicitly assume that the number of straw burning points can be treated as an exogenous variable, conditional on county, year and month fixed effects and weather controls. Is this a reasonable assumption? Below we try to address the endogeneity concerns in several ways.

The first concern is that farmers' burning decision may depend on air pollution levels. For example, is it possible that they reduce/increase burnings if they observe high pollution? This is highly unlikely because, during our field trips, farmers repeatedly mentioned that they had the rights to burn straws and denied straw burning as the major source of air pollution.[14] In Appendix Table A1, we test if pollution on the previous day affects current-day's straw burnings (=1 if there is at least one straw burning point) and find no statistically significant associations. Thus, we conclude that farmers do not consider pollution when they burn straw.

The second concern is that straw burning can be affected by local regulations that may also influence pollution and health. To test this, we use non-local burnings as the instrument, and estimate how burnings fall outside a county's boundary affect the air pollution and health. The idea is that, because regulatory cooperation in reducing straw burnings across different administrative regions (i.e. counties) are difficult and rare, straw burnings taken place in other counties created more exogenous variations in local air quality. As will be elaborated in the subsequent section, using non-local burning as the instrument produces almost identical results.

The third concern is that straw burning may be associated with temporary income shocks that can affect human health. For example, straw burning takes place after harvesting and

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[14] This finding is also supported by various news reports. For example, Xinhua News report that farmers believe straw burning is not a major contribution to regional air quality compared with industrial and vehicle emissions, and they think it is unfair to prohibit straw burning to improve urban air quality. For example: http://www.xinhuanet.com/energy/2015-10/22/c_1116898554.htm.

harvesting can create positive income shocks to farmers. Were such temporary income increases important for health, we may under-estimate the air pollution effect.

We try to address this concern in two ways. First, income shocks should not affect different diseases in a way that coincides with the air pollution effect. Exiting literature documents that air pollution primarily affects cardiorespiratory diseases and does not affect non-cardiorespiratory diseases, while income can have much more heterogeneous impacts on different diseases. We analyze different causes of death and find that that straw burning indeed only increases cardiorespiratory mortality, implying the air pollution effect is the channel.

Second, we leverage wind directions and construct “improved” instruments that can directly shut down the income channel, if there is any. Specifically, we define an upwind burning point as being located within 45 degrees of the daily prevailing wind (fixed octants calculated from wind rose in Figure 2. Burnings in the opposite direction are defined as downwind points. Presumably, both upwind burnings and downwind burnings may contribute to the temporary income shocks (or any other economic shocks related to straw burning), but upwind straw burnings would create a larger air pollution impact than downwind burnings. Given the randomness of daily wind direction, we construct the following improved instruments: (1) we use the total number of daily upwind fires within 50 km from a county in a month to predict $PM_{2.5}$, as used in Equation (5); (2) we separately estimate how unwind and downwind fires affect air pollution in the first stage, as used in Equation (6); (3) we further combine wind directions with non-local straw burning and use upwind-non-local fires or both upwind-non-local and downwind-non-local fires as the instrument; and finally (4) assuming that each fire contributes equally to the local economic activities, the difference in the coefficients between $\beta\beta_1$ and $\beta\beta_2$ in Equation (6) can shut down the economic channels and captures the pure effect of pollution.

$$PPPP_{iiii} = \beta\beta_0 + \beta\beta_1 UUUUUUbbbbUU_{iiii} + XX_{iiii}\theta\theta + \tau\tau_{ii} + \pi\pi_{ii} + \xi\xi_{iiii} \quad (5)$$

$$PPPP_{iiii} = \beta\beta_0 + \beta\beta_1 UUUUUUbbbbUU_{iiii} + \beta\beta_2 DDDDUUbbUUbbbbUU_{iiii} + XX_{iiii}\theta\theta + \tau\tau_{ii} + \pi\pi_{ii} + \xi\xi_{iiii} \quad (6)$$

The estimates

of using these alternative instruments, which will be elaborated in the next section, remain quantitatively similar.

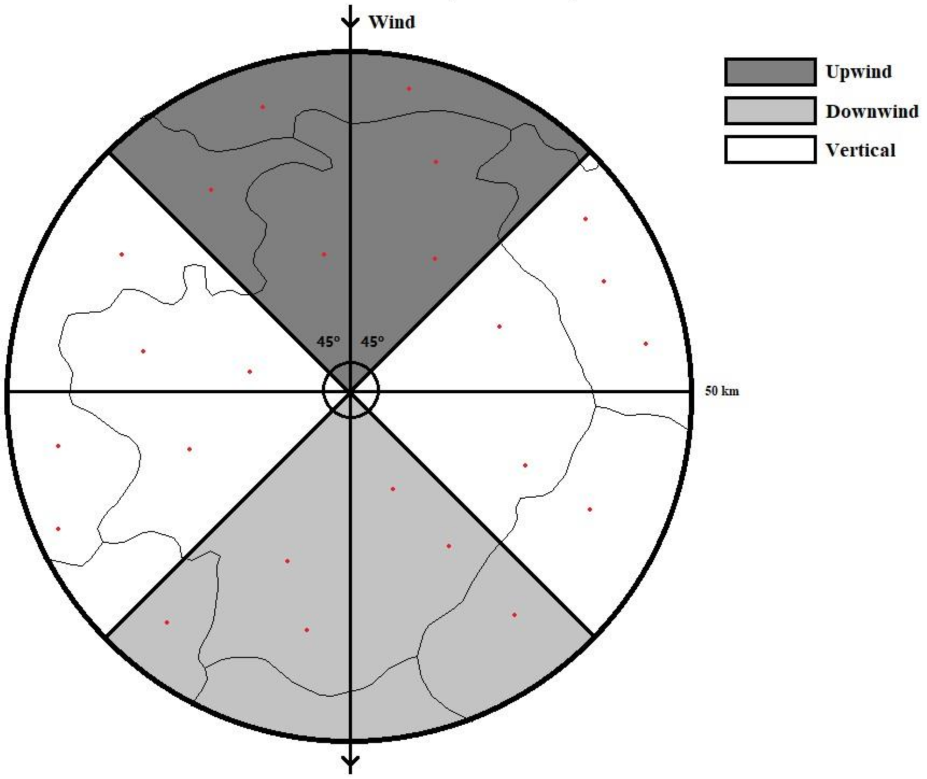


Figure 2. Illustration of Straw Burnings and Wind Direction

Notes: Red dots represents straw burnings within 50 km from a county. The dark gray area includes upwind fires, the light gray area includes downwind fires, and the white area includes other (vertical) fires.

## 5. Main Results

### 5.1 Straw Burning and Air Pollution

Table 2 summarizes the regression results from Equation (1). In Columns (1)–(4), we use $PM_{2.5}$ concentrations as the outcome variable (the results using the logarithm of $PM_{2.5}$ as the outcome variable are listed in Appendix Table A2). In Column (1), only the county fixed effects are included. Column (2) further controls for year fixed effects. Column (3) includes county, year and month fixed effects, and Column (4) includes all the fixed effects as well as a set of weather controls. Since the error term can be auto-correlated within a county or within a month across localities, we two-way cluster the standard errors at the county and month level. Alternative ways of computing the standard errors, such as clustering at the county level only, do not affect the significance level.

Columns (1)–(4) show that 10 additional straw burning points detected by satellite predicts a 4.4 to 5.0 μg/m$^3$ increase in monthly $PM_{2.5}$ concentrations. The pollution effects of straw burning can be heterogeneous by location and time. Columns (5)–(6) compare the effects of straw burning on $PM_{2.5}$ in urban districts and rural counties. The impacts are similar in size. Column (7) further includes both straw burnings in the same month and straw burnings in the previous month in one regression. The results show that the pollution effects of straw burning are contemporaneous within a month, which rules out any lagged effects of straw burning on pollution. Column (8) shows the effects of upwind straw burnings and downwind straw burnings on $PM_{2.5}$ from the same regression in Equation (6). As expected, upwind burnings have larger pollution impacts than downwind burnings.

The F-statistics from Cragg-Donald (1993) tests for weak instruments show that straw burning is a strong instrument for $PM_{2.5}$. Note that adding year fixed effects, month fixed effects and weather controls has negligible impact on the point estimates of the straw burning effect, while having them substantially increases the explanatory power of the model (R-squared). This is encouraging, as it indicates that changes in straw burning over time can indeed be treated as exogenous.

Table 2. Effects of Straw Burning on $PM_{2.5}$ Concentrations

| | $PM_{2.5}$(μg/m³) | | | | Urban | Rural | $PM_{2.5}$ | | $PM_{2.5}$ |
|---|---|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | | (8) |
| Straw Burning | 4.43*** | 4.41** | 5.03*** | 4.79*** | 5.84*** | 3.76*** | 5.22*** | Upwind | 11.70*** |
| *(per 10 burnings)* | (1.48) | (1.75) | (0.93) | (0.82) | (0.56) | (1.21) | (0.37) | | (2.53) |
| | [0.80] | [0.76] | [0.72] | [0.68] | [1.06] | [0.89] | [0.93] | | [4.18] |
| L1. Burning | | | | | | | 0.87 | Downwind | 4.24*** |
| | | | | | | | (0.68) | | (1.18) |
| | | | | | | | [1.41] | | [2.01] |
| Observations | 1,595 | 1,595 | 1,595 | 1,538 | 806 | 732 | 1,029 | | 1,538 |
| F-statistics | 6.0 | 58.2 | 417.6 | 16.2 | 28.0 | 11.2 | 18.8 | | 28.2 |
| R-squared | 0.69 | 0.71 | 0.76 | 0.77 | 0.76 | 0.78 | 0.81 | | 0.77 |
| Number of counties | 215 | 215 | 215 | 209 | 107 | 102 | 209 | | 209 |
| County FE | Y | Y | Y | Y | Y | Y | Y | | Y |
| Year FE | | Y | Y | Y | Y | Y | Y | | Y |
| Month FE | | | Y | Y | Y | Y | Y | | Y |
| Weather | | | | Y | Y | Y | Y | | Y |

Notes: Each column lists results from a separate regression. Columns (1)–(4) report the effects of straw burning on monthly $PM_{2.5}$ concentrations in counties. Columns (5)–(6) compare the effects of straw burning in urban districts and rural counties. Column (7) shows the dynamic effects of straw burnings in the same month and in the previous month. Column (8) shows the effects of upwind and downwind straw burnings on $PM_{2.5}$. Weather includes wind speed, wind direction, precipitation, temperature and relative humidity. Cragg-Donald F-statistics are reported. Standard errors in parentheses are two-way clustered at county and month level. Standard errors in brackets are clustered at county level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

### 5.2 Straw Burning and Deaths

The relationships between straw burning and deaths are reported in Table 3. The first two columns report the relationship between straw burning and the logarithm of monthly number of deaths from all causes. After controlling for county, month and year fixed effects and weather conditions, a 10-point increase in the number of straw burning points predicts a 1.56 % increase in monthly deaths from all causes.

Columns (3) and (4) and Columns (5) and (6) distinguish cardiorespiratory deaths from deaths assigned other causes. Only cardiorespiratory mortality shows a significant relationship with straw burning. This is consistent with previously-published findings (e.g. Ebenstein et al. 2017, and He et al. 2016). If straw burning increases by 10 points, we estimate that cardiorespiratory mortality will increase by 1.82%. In contrast, straw burning has no significant relationship with deaths from other causes. This suggests that straw burning affects mortality only through air pollution.

Table 3. Effects of Straw Burning on Deaths (%)

| | All-Cause | | Cardiorespiratory | | Non-Cardiorespiratory | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Straw Burning | 1.79** | 1.56** | 2.11** | 1.82** | -0.72 | -0.58 |
| *(per 10 burnings)* | (0.92) | (0.80) | (0.98) | (0.81) | (0.86) | (0.96) |
| Observations | 1,595 | 1,538 | 1,595 | 1,538 | 1,595 | 1,538 |
| R-squared | 0.890 | 0.893 | 0.842 | 0.844 | 0.781 | 0.784 |
| N. of counties | 215 | 209 | 215 | 209 | 215 | 209 |
| Fixed Effects | Y | Y | Y | Y | Y | Y |
| Weather | | Y | | Y | | Y |

Notes: Each column lists results from a separate regression. Columns (1)–(2) list effects of 10 additional straw burning points on percentage change in monthly all-cause deaths within a county. Columns (3)–(4) and Columns (5)–(6) examine the effects of straw burning on cardiorespiratory and non-cardiorespiratory deaths, respectively. Weather includes wind speed, wind direction, precipitation, temperature and relative humidity. Standard errors in parentheses are two-way clustered at county and month level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

## 5.3 $PM_{2.5}$ on Deaths

We estimate the impact of fine particulate matter on monthly deaths by using straw burning as the instrumental variable for air pollution. Columns (1) to (4) of Table 4 report the IV results for all-cause deaths, cardiorespiratory deaths and non-cardiorespiratory deaths. A 10 $\mu g/m^3$ increase in $PM_{2.5}$ concentrations will lead to a 3.25% increase in allcause deaths. Again, the size of the coefficient is robust to the inclusion of weather conditions, suggesting that the IV is not correlated with weather conditions. The mortality effect is driven primarily by cardiovascular and respiratory diseases, suggesting that air pollution is likely to be a causal factor.

One reasonable concern about the satellite-detected straw burning data is that thick clouds may cover small burns, which will result in measurement errors in the number of straw burnings. We thus directly include cloud coverage in the regression and check whether the estimates are affected. In Column (3), we find that controlling for cloud coverage yields to similar IV estimates of pollution impacts of straw burning. This finding implies that cloud coverage does not have a significant impact on our IV estimation. We believe this is because the number of days with thick clouds are rare and cloud variation is largely random.[15]

Column (4) further controls for $SO_2$ and $NO_2$ and the $PM_{2.5}$ estimates remain robust. This finding suggests that changes in $PM_{2.5}$ concentrations, induced by straw burning, are not correlated with changes in $SO_2$ and $NO_2$.

Columns (5) to (8) summarize the OLS estimates of $PM_{2.5}$'s effect on deaths. We see that all the coefficients are not statistically significant at the conventional level. The OLS estimates are also substantially smaller than the IV estimates, suggesting that OLS estimates are downward biased.

[15] Note that if it was raining, there will be no measurement errors in straw burning because there will be no burning on rainy days.

Table 4. Effects of $PM_{2.5}$ on Deaths (%)

| | IV | | | | OLS | | | |
|---|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| *Panel A. All-Cause* | | | | | | | | |
| $PM_{2.5}$ | 3.56*** | 3.25** | 3.16** | 3.17*** | 0.13 | 0.32 | 0.33 | 0.25 |
| *(per 10 μg/m³)* | (1.38) | (1.43) | (1.44) | (1.20) | (0.26) | (0.23) | (0.23) | (0.29) |
| *Panel B. Cardiorespiratory* | | | | | | | | |
| $PM_{2.5}$ | 4.19*** | 3.80*** | 3.69** | 3.87*** | 0.29 | 0.47 | 0.52 | 0.39 |
| *(per 10 μg/m³)* | (1.45) | (1.48) | (1.48) | (1.21) | (0.43) | (0.38) | (0.38) | (0.43) |
| *Panel C. Non-Cardiorespiratory* | | | | | | | | |
| $PM_{2.5}$ | -1.43 | -1.21 | -1.27 | -1.11 | -0.46 | -0.25 | -0.24 | -0.24 |
| *(per 10 μg/m³)* | (1.78) | (2.10) | (2.13) | (2.03) | (0.35) | (0.47) | (0.48) | (0.41) |
| Number of counties | 215 | 209 | 208 | 203 | 215 | 209 | 208 | 203 |
| Fixed Effects | Y | Y | Y | Y | Y | Y | Y | Y |
| Weather | | Y | Y | Y | | Y | Y | Y |
| Cloud | | | Y | Y | | | Y | Y |
| $SO_2$, $NO_2$ | | | | Y | | | | Y |

Notes: Each cell represents a separate regression. Columns (1)–(4) report IV estimates of effects of $PM_{2.5}$ on mortality, and Columns (5)–(8) report the OLS estimates. County, month and year fixed effects, weather conditions (wind speed, wind direction, temperature, precipitation, relative humidity), cloud coverage, $SO_2$ and $NO_2$ are controlled one by one. Standard errors in parentheses are two-way clustered at county and month level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

In Table 5, we use alternative instruments to estimate the air pollution effect. Column (1) replicates the IV estimate using all straw burnings within 50 km from a county as an instrument. Column (2) reports the IV estimate using non-local straw burning within 50 km from a county as an instrument. A non-local burning point defined as being located outside the county boundary but is within 50 km from the county center. The two estimates are quantitatively similar. In Column (3), we leverage variations in wind direction and straw burning and use upwind burning as an instrument. We find that a 10 $\mu g/m^3$ increase in $PM_{2.5}$ will increase all-cause deaths by 4.21%. These estimates are slightly larger than estimates in Columns (1) and (2), but the differences are insignificant. Column (4) further lists the estimates using upwind and downwind fires as an instrument. Again, the estimates are quantitatively indifferent from those in Columns (1)–(3). Furthermore, we combine wind direction with non-local burnings and use upwind-non-local burnings or both upwind-non-local and downwind-non-local burnings as an instrument for $PM_{2.5}$, and find similar estimates in size in Columns (5) and (6). Finally, in Column (5) we provide the close-to Wald estimate using variations in differences between upwind and downwind straw burnings. The estimate is slightly larger but remains similar in magnitude. Our interpretation of this result is that, although the income effect can potentially cause downward bias in our air pollution effect estimates, this bias in reality is almost negligible. These additional checks together suggest that monthly variation in the number of straw burnings during the harvesting season within a county is as good as random and can thus be used as a valid instrument of $PM_{2.5}$. Given its simplicity and easy interpretation, in subsequent analyses, we just use the number of straw burning points as the preferred instrument.

Table 5. Multiple IV Estimates of the Effects of $PM_{2.5}$ on Deaths (%)

| | All | Non-local | Upwind | Upwind+ Downwind | Upwind* Non-local | (Upwind+Downwind) *Non-local | Upwind- Downwind |
|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| $PM_{2.5}$ | 3.25** | 3.21** | 4.21*** | 4.18*** | 4.11** | 4.02*** | 4.47 |
| *(per 10 μg/m³)* | (1.43) | (1.43) | (1.60) | (1.57) | (1.72) | (1.53) | |
| Observations | 1,538 | 1,538 | 1,538 | 1,538 | 1,538 | 1,538 | 1,538 |
| R-squared | 0.884 | 0.885 | 0.878 | 0.879 | 0.879 | 0.880 | |
| Number of counties | 209 | 209 | 209 | 209 | 209 | 209 | 209 |
| Fixed Effects | Y | Y | Y | Y | Y | Y | Y |
| Weather | Y | Y | Y | Y | Y | Y | Y |

Notes: Each column represents a separate regression. Column (1) reports the IV estimate using all straw burnings within 50km from a county. Column (2) reports the IV estimate using non-local straw burnings beyond the county boundary within 50km from a county. Column (3) reports the IV estimates using upwind straw burnings. Column (4) lists the estimate using upwind and downwind straw burnings as an instrument. Columns (5) and (6) reports the IV estimates using upwind-non-local straw burnings or both upwind and downwind non-local straw burnings. Column (7) lists the akin-to Wald estimator using differences between upwind and downwind straw burnings. County, month, year fixed effects, weather conditions (wind speed, wind direction, temperature, precipitation, relative humidity) are controlled. Standard errors in parentheses are two-way clustered at county and month level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

## 5.4 Avoidance Behavior

Avoidance or defensive behaviors can complicate the interpretations of the estimated impacts of air pollution. If people take measures to reduce exposure, such as reducing outdoor activities or using air filters, the true physiological impact of pollution will be underestimated (e.g. Moretti and Neidell, 2011).

There are three reasons why we think avoidance behavior does not play an important role in our setting. First, we use data in the summer seasons, during which there are better meteorological conditions for pollutant dispersion and the average $PM_{2.5}$ concentrations during summer months are relatively low. Pollution alerts are rarely triggered during summer seasons so we expect people take little avoidance.

Second, our analyses on visibility show that straw burning does not significantly degrade visibility and including visibility as a control in the regression has no impact on the air pollution effect (See Appendix Table A2 and Table A3).

Third, we examine whether straw burning affects people's online searches for defensive equipment using Baidu Search Index. Baidu Search Index is analogous to Google Trends and tells us how many people search for certain keywords within certain period of time in cities. We focus on people's searches for "anti-$PM_{2.5}$ mask", "haze", "$PM_{2.5}$" and "Air Quality Index" (AQI) as previous studies show that these keywords are good measures of avoidance behaviors and are strongly correlated with online sales of defensive equipment (eg. Liu et al., 2018). As reported in Appendix Table A4, there is no impact of straw burning on these outcomes during the summer seasons. In contrast, in autumn and winter seasons when air quality is poor, people search more for these items when straw burning increases. These results suggest that the public is not quite aware of pollution and straw burning in the summer seasons, so our estimates approximate the true physiological impacts of air pollution. We also use data for "bottled water" as a placebo, and find that it is not related to short-run variations of pollution and straw burning for both summer and winter seasons.

## 5.5 Robustness Checks

The results of a variety of robustness checks are reported in the Appendix. First, we use the logarithm of the number of straw burning points as the explanatory variable to estimate the effect of a percentage change in straw burning on mortality. The results are reported in Appendix Table A5. We find that a 10% increase in monthly straw burning in a county will increase all-cause deaths by 0.09%. The effect is driven primarily by extra deaths from cardiorespiratory diseases, consistently with the main findings.

Second, we include polynomial terms of straw burning to explore if there is any nonlinear effect of straw burning. Appendix Table A6 represents the estimates with the quadratic term of straw burning. Straw burning's effect on deaths is slightly concave with a turning point of around 40. Given that the mean of the number of straw burning is two (with a standard deviation of 8) in our data, we conclude that the health effect of straw burning is close to linear.

Third, in Appendix Table A7, we summarize the results using different matching distances between monitoring stations and counties. We find the IV estimates of the effects of straw burning are similar using different matching methods.

In Appendix Table A8, instead of using the number of deaths as the outcome, we use the standardized mortality rate based on death data and census data as the alternative outcome. The standardized mortality rate is defined as age-adjusted number of deaths per 100 thousand people. We find consistent results using the alternative health measure. If monthly straw burning increases by 10 points, all-cause and cardiorespiratory mortality rate will increase by 1.71% and 1.91%, respectively. The IV estimates show that a 10 $\mu g/m^3$ increase in monthly $PM_{2.5}$ will lead to a 3.57% and a 4.00% increase in all-cause and cardiorespiratory mortality rate, respectively.

Our main specification merges all data using the geometric county centers. Alternatively, we can match all data sets using the administrative centers. The results are reported in Appendix Table A9. We find a consistent impact of straw burning on all-cause deaths through cardiorespiratory diseases. The IV estimates are also similar in size with our main findings.

Lastly, we estimate the effects of straw burning using prefecture-level data. The prefecture-level death data were aggregated based on the same county-level data included in the main setting. Straw burning, pollution and weather data were averaged within 50 km from the city center. With such data a 10-point increase in monthly straw burning elevates $PM_{2.5}$ by 3.40 $\mu g/m^3$ (or 5.45%) on average, and predicts an 0.80% increase in all-cause deaths (Appendix Table A10). If monthly $PM_{2.5}$ increases by 10 $\mu g/m^3$, all-cause deaths and cardiorespiratory deaths will increase by 2.60% and 3.55%, respectively. These results remain similar.

## 6. Heterogeneity

The health effects of burning straw can differ among subpopulations, as different groups may have distinct exposures or physical responses to air pollution. We explore the health effects of straw burning by location, gender, and age in Table 6.

Panel A compares the relative health risk between urban districts and rural counties. The data show that straw burning has a large and statistically significant impact on rural mortality but not on urban mortality. Specifically, if the number of monthly straw burning points increases by 10, all-cause mortality will increase by 2.52% in a rural county, but there is no significant relationship for the urban areas. The IV estimates of $PM_{2.5}$ are consistent with the reduced-form estimates using straw burning. Column (2) shows that a 6.69% increase in mortality is associated with a 10$\mu g/m^3$ increase in $PM_{2.5}$ in rural areas, while there is no impact of pollution caused by straw burning on mortality in the urban areas. Column (3) in Panel A shows that naïvely regressing mortality on $PM_{2.5}$ leads to attenuated estimates indifferent from zero.

Although straw burning degrades both urban and rural air quality, only residents in rural counties die from it. The sharp contrast between urban and rural areas indicates that previous studies of urban mortality may be biased by not taking into account the large health costs in rural counties.

Table 6. Heterogeneous Effects of Straw Burning and $PM_{2.5}$ on Deaths (%)

| | Reduced | IV | OLS |
|---|---|---|---|
| | (1) | (2) | (3) |
| | *(per 10 burnings)* | *(per 10 μg/m³)* | |
| *Panel A: Urban vs Rural* | | | |
| Urban | 0.12 | 0.20 | 0.23 |
| | (0.39) | (0.69) | (0.24) |
| Rural | 2.52** | 6.69*** | 0.34 |
| | (1.17) | (1.83) | (0.43) |
| *Panel B: Male vs Female* | | | |
| Female | 1.40 | 2.92 | 0.27 |
| | (1.02) | (1.79) | (0.20) |
| Male | 1.74** | 3.64** | 0.34 |
| | (0.76) | (1.55) | (0.34) |
| *Panel C: By Age* | | | |
| 60+ | 1.53** | 3.20*** | 0.57** |
| | (0.70) | (1.20) | (0.27) |
| 40-60 | 3.03** | 6.32** | 0.19 |
| | (1.36) | (2.58) | (0.38) |
| 40- | 0.40 | 0.89 | -0.70** |
| | (2.03) | (4.60) | (0.34) |
| 0 | 2.62 | 6.17 | 0.90 |
| | (2.08) | (5.33) | (0.76) |
| Fixed Effects | Y | Y | Y |
| Weather | Y | Y | Y |

Notes: Each cell represents a separate regression. Column (1) lists the reduced-form estimates of effects of straw burning on deaths in percentage. Columns (2) and (3) report the IV and OLS estimates of the effects of $PM_{2.5}$ on deaths in percentage, respectively. Panel A compares the effects between urban districts and rural counties. Panel B compares the effects between males and females. Panel C compares the effects on different age groups. County, month and year fixed effects and weather conditions (wind speed, wind direction, temperature, precipitation, relative humidity) are the controls. Standard errors in parentheses are two-way clustered at county and month level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

There are a few possible explanations. First, rural residents may be less aware of the potential harms of air pollution and do not take avoidance measures due to lack of information or other constraints. Second, urban residents have better medical care and access to hospitals. When air pollution triggers a heart attack or acute respiratory disease, they can get immediate treatment while rural residents often cannot. Urban incomes are typically higher than rural incomes, which could help mitigate more of the pollution damage for urban residents than for rural residents. Third, rural residents may have higher dose of pollution exposure. Rural counties have more straw burnings than urban districts. Rural residents may also live closer to the burning fields. However, we are unable to pin down the exact channels, and further research is warranted to identify these relationships.

Panel B of Table 6 reports that the mortality risk associated with straw burning is more significant for males than for females. One explanation is that males do more farm work and thus breath more the concentrated smoke.[16] Another explanation favored by the public health literature is that males are more vulnerable to air pollution because there are more male smokers who have damaged cardiorespiratory systems. However, both explanations are highly conjectural and future research is warranted to investigate this gender difference.

Susceptible groups such as infants and the elderly can be particularly sensitive to air pollution. Previous studies have typically found that infants and the elderly are the most vulnerable groups. In this study, the sample was divided into four age-groups: infants, those younger than 40, those between 40 and 60, and the elderly above 60 years old. The results are reported in Panel C of Table 6. Straw burning was a significant predictor of mortality for people over 60 years old. A 10-point increase in the monthly number of straw burnings was associated with a 1.53% increase in mortality risk for that group. But somewhat surprisingly, straw burning also has a larger effect on middle-aged people between 40 and 60. If monthly straw burning increases by 10 points, the mortality risk for that middle-aged group will increase by 3.03%. Rural middle-aged people are susceptible to air pollution, while their counterparts in urban districts are less affected. Straw burning does not significantly predict mortality among those below 40 years old, including infants. The IV regressions show similar patterns. The effects of $PM_{2.5}$ are large and statistically significant

[16] Note that we cannot statistically significantly reject the null hypothesis that the air pollution impact on male is greater than that on female.

for people over 40 years old. People below 40 are not likely to die from air pollution caused by straw burning. In comparison, the OLS estimates in Column (3) are small and unstable. For example, the OLS approach suggests a positive correlation between $PM_{2.5}$ and deaths among the elderly, but deaths among young people below 40 would decline when $PM_{2.5}$ increases. This again illustrates that associational estimates can be highly sensitive to the choice of model and setting.

The estimated coefficients using the IV approach were larger than associational estimates provided by public health and epidemiological studies in both developed and developing countries (e.g. Dockery et al., 1993; Samoli et al., 2008; Shang et al., 2013; Yin et al., 2017; Zanobetti & Schwartz, 2009; Zhou et al., 2015). For example, Shang et al. (2013) reviewed 33 studies in China and found that a 10 $\mu g/m^3$ increase in $PM_{2.5}$ will increase total, respiratory, and cardiovascular mortality by 0.38%, 0.51%, and 0.44%, respectively. In terms of rural impacts of outdoor air pollution, Zhou et al. (2015) provided the only rural estimates showing that each 10 $\mu g/m^3$ increase in $PM_{2.5}$ was associated with a 1.2% and a 0.55% increase in mortality risk in two Chinese counties. Our IV estimates are, however, quantitatively close to those of several recent studies using quasiexperimental approaches to estimate the health impacts of air pollution (e.g. Chen et al., 2013; Ebenstein et al., 2017; He et al., 2016). These results confirm that associational estimates can significantly under-estimate the air pollution effect.

## 7. Straw Recycling

China has been regulating straw burning since the 1990s. In the early years, straw burning was regulated mostly by command-and-control policies. However, most of the early regulation efforts were ineffective, as the number of straw burning points in many places, particularly in Northern provinces, increased significantly from 2012 to 2015.[17]

[17] For example, the annual total number of straw burning points detected by the MEP in Heilongjiang rose from 99 in 2012 to 1,815 in 2015.

Starting from 2016, the central government enforced a market-based policy that subsidizes individuals and enterprises that recycled straw from the field.[18] The 10 provinces with the most straw burning each received 100 million RMB in 2016 to recycle straw. The total amount of central subsidy was 1 billion RMB nationwide. These provinces are Henan, Anhui, Heilongjiang, Shandong, Jilin, Hebei, Jiangsu, Liaoning, Shanxi and Inner Mongolia.

We examine how this subsidy program affects straw burning using a Difference-in-Differences (DiD) approach:

$$YY_{iiii} = \alpha\alpha + \beta\beta * ssbbbbssbbUUss_{iiii} + \gamma\gamma * XX_{iiii} + \mu\mu_{ii} + \pi\pi_{ii} + \varepsilon\varepsilon_{iiii} \qquad (7)$$

where $YY_{iiii}$ is the number of burning points or the PM concentrations in province *i* in year *t*. Each "year" is defined by the two straw burning seasons from May 20th to July 20th and from September 20th to November 20th, a total of 124 days. $ssbbbbssbbUUss_{iiii}$ is a dummy variable set equal to 1 if province *i* received a subsidy in year *t*. $XX_{iiii}$ is a vector of meteorological conditions including wind speed, wind direction, temperature, relative humidity and precipitation. $\mu\mu_{ii}$ and $\pi\pi_{ii}$ control for province and year fixed effects. $\beta\beta$ is the key parameter of interest. It estimates the effect of central subsidy on straw burning or air quality. In addition to straw burning and air pollution during burning seasons as the outcomes, we also check the effects of straw-recycling subsidy on air quality during nonburning seasons as a placebo test.

We test the parallel trends assumption using an event-study approach and plot the estimates in the lower Panel B of Figure 3. We see that straw burning trends in the subsidized provinces and the control group are plotted in the upper figure in Panel A. Before the subsidy policy, the number of burning points in the treatment and control locations were statistically indistinguishable. After the program was introduced, i.e. for the year 2016, there was a dramatic decline in the number of straw burning points in the treated

[18] http://nys.mof.gov.cn/zhengfuxinxi/czpjZhengCeFaBu_2_2/201606/t20160603_2311988.html.

(subsidized) provinces.[19] The regression results of the parallel trend tests are reported in Appendix Table A11.

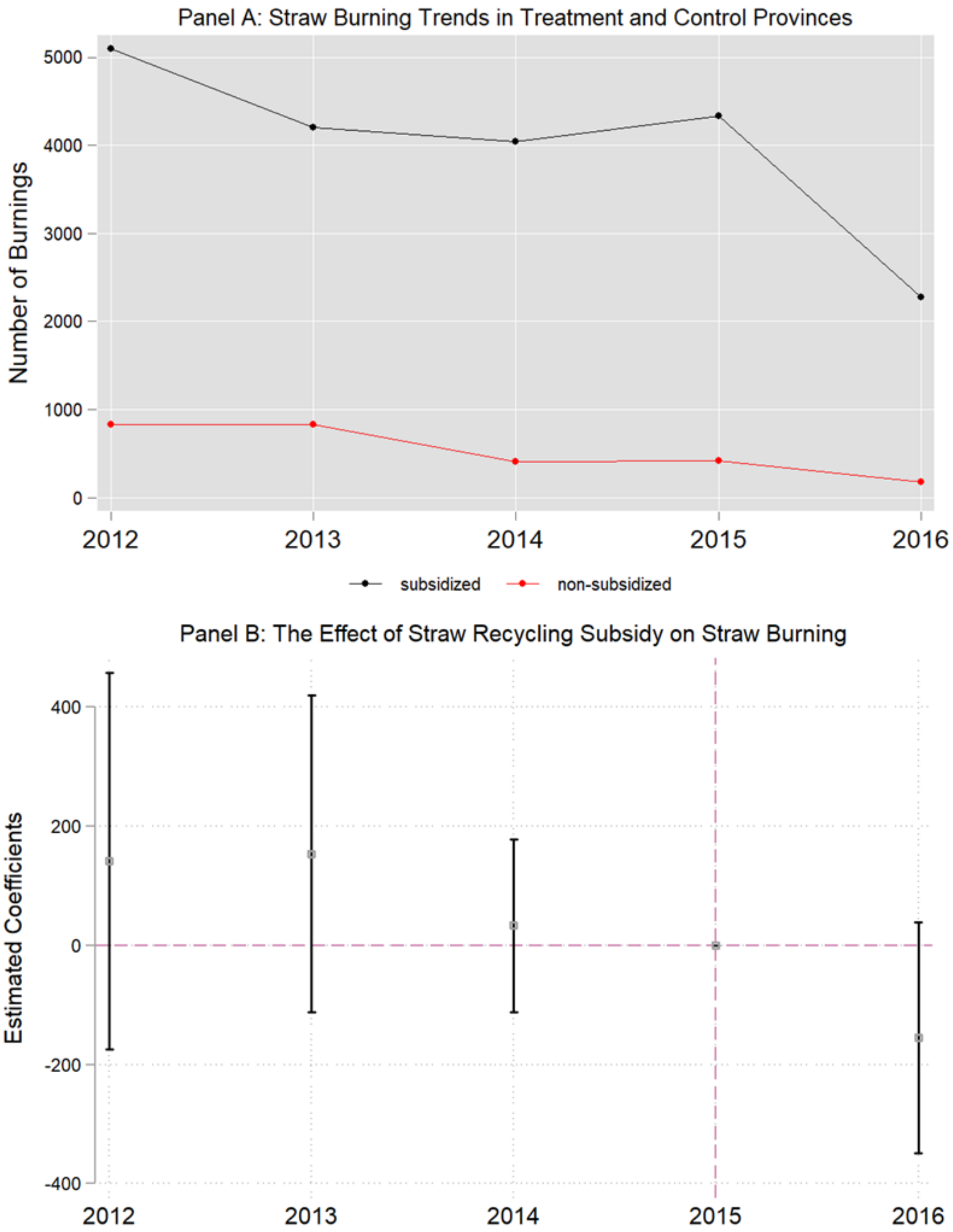


Figure 3. Test for Parallel Pre-Trends in Straw Burning at the Provincial Level

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[19] Due to restrictions in data availability after 2016, we only have one-year sample during the treatment period. The findings should be interpreted with some caution because of the short time window.

Notes: The upper figure in Panel A plots the straw burning trends in pilot provinces (black) and non-pilot provinces (red). The lower figure in Panel B plots estimated coefficients and their 95% confidence intervals from event study regressions. 2015 before the straw recycling subsidy program is the base year.

Table 7 summarizes the DiD results. Column (1) shows that the total number of straw burning points in the subsidized provinces dropped by 233 (about 58%) during the year compared with provinces without subsidies. Column (2) shows that the average $PM_{2.5}$ level in the treated provinces decreased by 4.92 μg/$m^3$ (8.6%) in 2016 compared with the unsubsidized areas. Column (3) further shows that the average $PM_{10}$ during the burning seasons dropped by 9.42 μg/$m^3$ (9.6%) due to the subsidy. There was, however, no significant change in other pollutants including $SO_2$ and $NO_2$, as shown by Columns (4) and (5).

In Columns (6) and (7), we check whether straw recycling subsidy affects agricultural production. We find that the policy does not affects agricultural yield or total grain output. These results suggest that the program does not lead to meaningful changes in agricultural production. We can thus consider the total amount of subsidy as the major cost component in the exploratory benefit-cost analysis.

Lastly, we find no difference in air quality in non-burning seasons (or growing seasons) between the subsidized provinces and the non-subsidized provinces, as shown by Columns (8)–(11). This alleviates the concern that other agricultural or pollution policies targeted at the subsidized provinces may confound the estimates, or the two groups of provinces are systematically different in other ways. In fact, we are not aware of any other policy in company with the straw-recycling subsidy that was applied to the same set of provinces in 2016.

Table 7. Effects of Straw Recycling Policy on Straw Burning, Air Quality and Agricultural Production

| | Burning Season | | | | | | | Non-Burning Season | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) |
| VARIABLES | Burning | $PM_{2.5}$ | $PM_{10}$ | $SO_2$ | $NO_2$ | Yield | Grain Output | $PM_{2.5}$ | $PM_{10}$ | $SO_2$ | $NO_2$ |
| | (points) | (μg/m$^3$) | (μg/m$^3$) | (ppb) | (ppb) | (kg/ha) | (10k tons) | (μg/m$^3$) | (μg/m$^3$) | (ppb) | (ppb) |
| Subsidy | -233.0*** | -4.92** | -9.42** | -0.35 | 1.41 | -55.61 | 36.57 | -1.54 | -3.37 | -0.43 | 1.36 |
| | (89.57) | (2.38) | (4.68) | (1.02) | (1.06) | (58.32) | (25.72) | (2.28) | (4.24) | (1.52) | (1.15) |
| Observations | 155 | 128 | 155 | 155 | 155 | 155 | 155 | 128 | 155 | 155 | 155 |
| R-squared | 0.33 | 0.75 | 0.59 | 0.58 | 0.42 | 0.22 | 0.30 | 0.69 | 0.62 | 0.53 | 0.41 |
| Province FE | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |
| Year FE | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |
| Weather | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |

Notes: Each column represents a separate DiD regression. Column (1) lists the effect of straw recycling subsidy on number of straw burning points in a province during straw burning seasons in a year. Columns (2)–(5) report the effects of subsidy on air pollutants including $PM_{2.5}$, $PM_{10}$, $SO_2$ and $NO_2$. Columns (6)–(7) present the effects of subsidy on agricultural yield and total grain output. Columns (8)–(11) show the pollution effects during non-burning seasons. Province and year fixed effects and weather conditions (wind speed, wind direction, temperature, precipitation, relative humidity) are controlled. Standard errors in parentheses are clustered by province. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

The significant drops in both straw burning and PM have important implications for public health in China. A back-of-the-envelope calculation can roughly compare the benefits of the policy with its costs. The mortality rate of the 10 treated provinces was 6.41 per thousand in 2015, and the total population of the 10 provinces was 614.2 million. To simplify the discussion, assume that the deaths are equally distributed throughout the year, so the total number of deaths during the straw burning seasons would have been around 1.34 million in 2015. According to the IV estimate in Section 5.2, a 10 $\mu g/m^3$ change in $PM_{2.5}$ predicts a 3.25% change in mortality. That implies that a 4.92 $\mu g/m^3$ reduction in mean $PM_{2.5}$ concentration during the burning season would bring down the mortality rate by 1.60%, equivalent to averting roughly 21,400 pre-mature deaths.[20]

We can monetize the health benefit using the value of statistical life (VSL). Since straw burning has a negligible effect on urban residents, the cost of pre-mature death is estimated for rural residents only. Fan et al. (2018) suggested using 2.92 million RMB (about 440,000 USD) as the VSL for a typical Chinese rural resident. That results in an estimate of the health benefits of the straw recycling policy of about 62.5 billion RMB, which seems to outweigh the policy's cost by several orders of magnitude.

These rough estimates should be interpreted with caution for several reasons. On the one hand, some of the administrative and recycling costs that are not fully covered by the subsidy are not taken into account. On the other hand, the benefit calculation ignores savings on defensive expenditures such as air filters and facial masks, reduced hospitalization, and potential gains in labor productivity (Zhang and Mu, 2018; Chang et al., 2019; Graff Zivin and Neidell, 2012; He et al., 2019). In addition, the potential cobenefits from reductions in greenhouse gas emissions are also omitted. The VSL is not adjusted by age groups in our calculations as discounting VSL is controversial in the literature.[21] Lastly, we also ignore the potential benefits of straw burning from labor saving, and pesticide and fertilizer usage. These benefits are expected to be small compared with

[20] The mortality data in 2016 are unavailable for the researchers to use in this project. Hence, the time windows for mortality estimation and policy evaluation are different.

[21] More discussions on it can be found in USEPA (2003) and European Commission (2001).

the health costs. Crop stalks often come along with harvesting and do not need to be collected separately, thus the additional labor benefit of straw burning are unlikely to be substantial. A majority of rural farmers are the elderly, for which the opportunity cost is likely to be small. The effects of straw burning used as indirect fertilizer and pesticide are hard to quantify, but they are expected to be much smaller and less significant than chemical pesticides and fertilizers used during growing seasons.

## 8. Conclusions

This paper investigates the impacts of agricultural straw burning on air pollution and mortality in China. We estimate that a 10-point increase in the number of straw burns detected by satellites in a county in a month will lead to a 7.62% increase in monthly $PM_{2.5}$ concentrations and a 1.56% increase in deaths. Using straw burning as an instrument for $PM_{2.5}$, we further estimate that a 10 $\mu g/m^3$ change in $PM_{2.5}$ will cause a 3.25% change in mortality, which is consistent with previous causal estimates in China. Introducing exogenous variations in wind directions offers quantitatively similar estimates, supporting the causal interpretations of our estimates. The likelihood of public avoidance behaviors against straw burning is low in summer, allowing for the significant physiological health impact of $PM_{2.5}$ at low levels of concentration.

The health impacts of straw burning are highly heterogeneous. Specifically, the effects are greater in rural counties than in urban districts. Straw burning mainly impairs the health of males and people above 40 years old. The findings suggest that those who practice less avoidance and are more exposed to the smoke are more likely to die due to straw burning.

Overall, these findings highlight the large health impacts of straw burning and the need for more effective regulatory efforts. We find that subsidizing straw recycling has reduced air pollution and can bring about tremendous health benefits. Our exploratory analysis suggests that the benefits of subsiding straw recycling are likely to be substantially larger than the costs. Other countries that facing similar problems may consider adopting similar policies.

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## Appendix

Table A1. Daily Straw Burning Decision in Summer in 2013-2015

| | (1) | (2) | (3) |
|---|---|---|---|
| VARIABLES | Burn | Burn | Burn |
| $L1.PM_{2.5}$ | 0.00014* | 0.00012 | 0.00012 |
| | (0.00008) | (0.00008) | (0.00008) |
| $L1.SO_2$ | -0.000004 | -0.00012 | -0.00011 |
| | (0.000304) | (0.00030) | (0.00030) |
| $L1.NO_2$ | 0.00005 | 0.00011 | 0.00007 |
| | (0.00021) | (0.00021) | (0.00022) |
| Wind Speed | 0.00067 | 0.00105 | 0.00020 |
| | (0.00090) | (0.00092) | (0.00094) |
| Precipitation | 0.00003 | 0.00004 | 0.00002 |
| | (0.00004) | (0.00005) | (0.00005) |
| Temperature | 0.00157** | 0.00145* | 0.00184** |
| | (0.00068) | (0.00077) | (0.00076) |
| Relative Humidity | -0.00177*** | -0.00180*** | -0.00162*** |
| | (0.00016) | (0.00016) | (0.00016) |
| Observations | 27,178 | 27,178 | 27,178 |
| R-squared | 0.073 | 0.077 | 0.106 |
| Number of counties | 204 | 204 | 204 |
| Wind Direction | Y | Y | Y |
| County FE | Y | Y | Y |
| Week FE | Y | Y | |
| Week-by-Year FE | | Y | |
| Day FE | | | Y |

Notes: Each Column represents a separate regression of straw burning decision (burn=1 if there is at least one burning point within a county) on air pollution of previous day and weather conditions (wind speed, wind direction, precipitation, temperature and relative humidity). L1 denotes concentrations of air pollutants on previous day. Standard errors in parentheses are clustered by county. *** p<0.01, ** p<0.05, * p<0.1

Table A2. Effects of Straw Burning on Pollution in Summer (%)

| | (1) | (2) | (3) | (4) | (5) |
|---|---|---|---|---|---|

| VARIABLES | $PM_{2.5}$ | $PM_{10}$ | $SO_2$ | $NO_2$ | Visibility |
|---|---|---|---|---|---|
| Straw Burning | 7.62*** | 4.70*** | -1.04 | 1.23 | -0.07 |
| *(per 10 burnings)* | (0.84) | (0.65) | (2.50) | (1.45) | (0.77) |
| Observations | 1,538 | 1,429 | 1,467 | 1,461 | 1,538 |
| R-squared | 0.823 | 0.377 | 0.220 | 0.144 | 0.386 |
| Number of counties | 209 | 203 | 204 | 204 | 209 |
| County FE | Y | Y | Y | Y | Y |
| Year FE | Y | Y | Y | Y | Y |
| Month FE | Y | Y | Y | Y | Y |
| Weather | Y | Y | Y | Y | Y |

Notes: Each Column lists results from a separate regression. Columns (1)–(4) report the effects of 10 additional straw burning points on monthly $PM_{2.5}$, $PM_{10}$, $SO_2$ and $NO_2$ in counties. Column (5) reports the effects on monthly visibility. Weather includes wind speed, wind direction, precipitation, temperature, relative humidity. Standard errors in parentheses are two-way clustered at county and month level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table A3. Multiple IV Estimates of the Effects of $PM_{2.5}$ on Deaths with Visibility (%)

| | All | Non-local | Upwind | Upwind+ Downwind | Upwind* Non-local | (Upwind+Downwind) *Non-local |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| $PM_{2.5}$ | 3.29*** | 3.16** | 3.48** | 3.57** | 3.60** | 3.80*** |
| *(per 10 μg/m³)* | (1.27) | (1.31) | (1.42) | (1.42) | (1.60) | (1.46) |
| Observations | 1,452 | 1,452 | 1,449 | 1,449 | 1,452 | 1,452 |
| R-squared | 0.883 | 0.884 | 0.882 | 0.882 | 0.881 | 0.880 |
| Number of counties | 203 | 203 | 203 | 203 | 203 | 203 |
| Fixed Effects | Y | Y | Y | Y | Y | Y |
| Weather | Y | Y | Y | Y | Y | Y |
| Cloud | Y | Y | Y | Y | Y | Y |
| $SO_2$, $NO_2$ | Y | Y | Y | Y | Y | Y |
| Visibility | Y | Y | Y | Y | Y | Y |

Note: Each column reports the IV estimates of effects of $PM_{2.5}$ on all-cause deaths. Column (1) reports the IV estimate using all straw burnings within 50km from a county. Column (2) reports the IV estimate using non-local straw burnings beyond the county boundary within 50km from a county. Column (3) reports the IV estimate using upwind straw burnings. Column (4) lists the estimate using upwind and downwind burnings as an instrument. Columns (5) and (6) reports the IV estimates using upwind-non-local straw burnings or both upwind and downwind non-local straw burnings. County, month, year fixed effects and weather conditions (wind speed, wind direction, temperature, precipitation, relative humidity), cloud coverage, $SO_2$, $NO_2$ and visibility are controlled. Standard errors in parentheses are two-way clustered at county and month level. *** p<0.01, ** p<0.05, * p<0.1

Table A4. Straw Burning and Baidu Online Search in Summer and Autumn During 2013-2015 (%)

| | (1) | (2) | (3) | (4) | (5) |
|---|---|---|---|---|---|
| VARIABLES | Anti-$PM_{2.5}$ Mask | Haze | $PM_{2.5}$ | AQI | Bottled Water |
| *(per 10 burnings)* | | | | | |
| *Panel A: Summer* | | | | | |
| Straw Burning | -0.26 | -1.48 | 0.14 | -10.70 | 1.57 |
| | (7.24) | (3.09) | (1.35) | (6.52) | (4.59) |
| *Panel B: Autumn* | | | | | |
| Straw Burning | 15.30*** | 6.17** | 5.21*** | 13.40*** | 0.76 |
| | (4.60) | (2.47) | (1.22) | (1.43) | (2.34) |
| Observations | 1,383 | 1,383 | 1,383 | 1,383 | 1,383 |
| R-squared: summer | 0.139 | 0.283 | 0.381 | 0.155 | 0.401 |
| R-squared: autumn | 0.288 | 0.602 | 0.554 | 0.391 | 0.299 |
| Number of cities | 154 | 154 | 154 | 154 | 154 |
| City FE | Y | Y | Y | Y | Y |
| Month FE | Y | Y | Y | Y | Y |
| Year FE | Y | Y | Y | Y | Y |
| Weather | Y | Y | Y | Y | Y |

Notes: Each cell represents a separate regression. Dependent variables include monthly Baidu Search Indices for anti-$PM_{2.5}$ mask, haze, $PM_{2.5}$, AQI and bottled water. Effects of straw burning are reported for summer and autumn in two panels, respectively. City, month and year fixed effects are always controlled. Weather controls include wind speed, wind direction, temperature, precipitation and relative humidity. Standard errors in parentheses are two-way clustered at city and month level. *** p<0.01, ** p<0.05, * p<0.1

Table A5. Effect of Percentage Change in Straw Burning on Deaths (%)

| | All-Cause | | Cardiorespiratory | | Non-Cardiorespiratory | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Straw Burning | 0.11** | 0.09** | 0.11** | 0.09*** | 0.03 | 0.06 |
| *(per 10%)* | (0.05) | (0.04) | (0.05) | (0.03) | (0.11) | (0.12) |
| Observations | 1,595 | 1,538 | 1,595 | 1,538 | 1,595 | 1,538 |
| Number of counties | 215 | 209 | 215 | 209 | 215 | 209 |
| Fixed Effects | Y | Y | Y | Y | Y | Y |
| Weather | | Y | | Y | | Y |

Notes: Each Column lists results from a separate regression. Columns (1)–(2) list effects of a 10% increase in straw burning points on percentage change in monthly all-cause mortality within a county. Columns (3)–(4) and Columns (5)–(6) examine the effects of straw burning on cardiorespiratory and non-cardiorespiratory mortality, respectively. Weather includes wind speed, wind direction, precipitation, temperature, relative humidity. Standard errors in parentheses are two-way clustered at county and month level. *** p<0.01, ** p<0.05, * p<0.1

Table A6. Nonlinearity in Effects of Straw Burning on Deaths (%)

| | All-Cause | | Cardiorespiratory | | Non-Cardiorespiratory | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| *(per 10 burnings)* | | | | | | |
| Straw Burning | 3.71*** | 3.37*** | 4.50*** | 4.00*** | 1.82 | 2.42 |
| | (1.37) | (1.15) | (1.34) | (1.10) | (1.68) | (1.75) |
| Straw Burning^2 | -0.04*** | -0.04*** | -0.05*** | -0.05*** | -0.05*** | -0.06*** |
| | (0.01) | (0.01) | (0.01) | (0.01) | (0.02) | (0.02) |
| Observations | 1,595 | 1,538 | 1,595 | 1,538 | 1,595 | 1,538 |
| R-squared | 0.890 | 0.893 | 0.842 | 0.844 | 0.782 | 0.784 |
| Number of counties | 215 | 209 | 215 | 209 | 215 | 209 |
| Fixed Effects | Y | Y | Y | Y | Y | Y |
| Weather | | Y | | Y | | Y |

Notes: Each Column lists results from a separate quadratic regression. Columns (1)–(2) list effects of 10 additional straw burning points on percentage change in monthly all-cause deaths within a county. Columns (3)–(4) and Columns (5)–(6) examine the effects of straw burning on cardiorespiratory and non-cardiorespiratory deaths, respectively. Weather includes wind speed, wind direction, precipitation, temperature and relative humidity. Standard errors in parentheses are clustered at county and month level. *** p<0.01, ** p<0.05, * p<0.1

Table A7. IV Estimates of Effects of $PM_{2.5}$ on Deaths with Varying Distance (%)

| | (1) | (2) | (3) |
|---|---|---|---|
| | All-Cause | Cardiorespiratory | Non-Cardiorespiratory |
| *(per 10 μg/m³)* | | | |
| *35km* | 2.78 | 4.10** | -3.11 |
| | (2.00) | (1.70) | (3.13) |
| *40km* | 2.76 | 3.92** | -2.83 |
| | (1.92) | (1.69) | (2.84) |
| *45km* | 3.11** | 4.03*** | -2.22 |
| | (1.48) | (1.45) | (2.40) |
| 50km | 3.25** | 3.80** | -1.21 |
| | (1.43) | (1.48) | (2.10) |
| *60km* | 3.22*** | 3.63*** | -0.79 |
| | (1.02) | (1.14) | (1.72) |
| *70km* | 3.32*** | 3.70*** | -0.76 |
| | (0.97) | (1.09) | (1.70) |
| *80km* | 3.23*** | 3.68*** | -0.64 |
| | (1.09) | (1.22) | (1.40) |
| *90km* | 3.25*** | 3.53*** | -0.10 |
| | (1.22) | (1.26) | (1.23) |
| *100km* | 3.26** | 3.47*** | 0.29 |
| | (1.27) | (1.28) | (1.26) |
| Observations | 1,538 | 1,538 | 1,538 |
| Number of counties | 209 | 209 | 209 |

Notes: Note: Each cell represents an IV estimate of the effect of $PM_{2.5}$ on mortality from a separate regression. Straw burning points and $PM_{2.5}$ within 35 km to 100 km from a county are explored in each row, respectively. Columns (1)–(3) report the effects on allcause deaths, cardiorespiratory deaths and non-cardiorespiratory deaths, respectively.

County, month, year fixed effects and weather conditions (wind speed, wind direction, temperature, precipitation, relative humidity) are controlled. Standard errors in parentheses are clustered at county and month level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table A8. Effects of Straw Burning and $PM_{2.5}$ on Mortality Rate (%)

| | (1) | (2) | (3) |
|---|---|---|---|
| | All-Cause | Cardiorespiratory | Non-Cardiorespiratory |
| *Panel A: Reduced Form* | | | |
| Straw Burning | 1.71* | 1.91* | 1.13 |
| *(per 10 burnings)* | (0.95) | (1.09) | (0.82) |
| *Panel B: Second Stage and OLS* | | | |
| IV: $PM_{2.5}$ | 3.57** | 4.00** | 2.37 |
| *(per 10 μg/m³)* | (1.78) | (2.00) | (1.55) |
| OLS: $PM_{2.5}$ | 0.45** | 0.67* | 0.22 |
| *(per 10 μg/m³)* | (0.20) | (0.34) | (0.43) |
| Observations | 1,538 | 1,538 | 1,538 |
| Number of counties | 209 | 209 | 209 |

Notes: Each cell represents a separate regression. Panel A lists the reduced-form estimates of straw burning's effects on mortality rate. Panel B presents the IV and OLS estimates of effects of $PM_{2.5}$ on mortality rate. County, month, year fixed effects and weather conditions (wind speed, temperature, precipitation, relative humidity) are controlled. Standard errors in parentheses are two-way clustered at county and month level. *** p<0.01, ** p<0.05, * p<0.1

Table A9. Effects of Straw Burning and $PM_{2.5}$ on Deaths Using Administrative Center (%)

| | (1) | (2) | (3) |
|---|---|---|---|

| | All-Cause | Cardiorespiratory | Non-Cardiorespiratory |
|---|---|---|---|
| *Panel A: Reduced Form* | | | |
| Straw Burning | 1.14** | 1.37** | -1.00 |
| *(per 10 burnings)* | (0.53) | (0.56) | (0.88) |
| *Panel B: Second Stage and OLS* | | | |
| IV: $PM_{2.5}$ | 2.57*** | 3.09*** | -2.24 |
| *(per 10 μg/m³)* | (0.94) | (1.00) | (2.16) |
| OLS: $PM_{2.5}$ | 0.46** | 0.69** | -0.22 |
| *(per 10 μg/m³)* | (0.19) | (0.32) | (0.42) |
| Observations | 1,868 | 1,868 | 1,868 |
| Number of counties | 255 | 255 | 255 |

Notes: Each cell represents a separate regression. Panel A lists the reduced-form estimates of straw burning's effects on deaths. Panel B presents the IV and OLS estimates of effects of $PM_{2.5}$ on deaths. County, month, year fixed effects and weather conditions (wind speed, wind direction, temperature, precipitation, relative humidity) are controlled. Standard errors in parentheses are two-way clustered at county and month level. *** p<0.01, ** p<0.05, * p<0.1

Table A10. Effects of Straw Burning and $PM_{2.5}$ on Deaths at Prefecture-Month Level (%)

| | (1) | (2) | (3) | (4) | (5) |
|---|---|---|---|---|---|
| | $PM_{2.5}$ | $PM_{2.5}$ (%) | All-Cause | Cardiorespiratory | Non-Cardiorespiratory |
| *Panel A: First Stage* | | | | | |
| Straw Burning | 3.40*** | 5.45*** | | | |
| *(per 10 burnings)* | (0.40) | (0.60) | | | |
| *Panel B: Reduced Form* | | | | | |
| Straw Burning | | | 0.80*** | 1.07*** | 0.12 |
| *(per 10 burnings)* | | | (0.20) | (0.30) | (0.52) |
| *Panel C: Second Stage and OLS* | | | | | |
| IV: $PM_{2.5}$ | | | 2.60*** | 3.55*** | -0.16 |
| *(per 10 $\mu g/m^3$)* | | | (0.81) | (0.88) | (2.17) |
| OLS: $PM_{2.5}$ | | | 0.81*** | 1.18*** | 0.16 |
| *(per 10 $\mu g/m^3$)* | | | (0.27) | (0.23) | (0.71) |
| Observations | 991 | 991 | 991 | 991 | 991 |
| Number of cities | 136 | 136 | 136 | 136 | 136 |

Notes: Each cell represents a separate regression. Panel A reports the first-stage estimates of straw burning's effects on $PM_{2.5}$ concentrations and the percentage change in $PM_{2.5}$. Panel B lists the reduced-form estimates of straw burning's effects on deaths. Panel C presents the IV and OLS estimates of the effects of $PM_{2.5}$ on deaths. City, month and year fixed effects and weather conditions (wind speed, wind direction, temperature, precipitation, relative humidity) are the controls. Standard errors in parentheses are two-way clustered at prefecture and month level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table A11. Tests for Pre-Trends in Straw Burning

| | (1) | (2) | (3) |
|---|---|---|---|
| 2016 | -205.9*** | -194.4*** | -154.8 |
| | (64.81) | (65.04) | (98.85) |
| 2014 | -29.40 | -28.54 | 33.11 |
| | (110.4) | (110.4) | (73.87) |
| 2013 | -13.50 | -33.02 | 153.5 |
| | (193.3) | (193.6) | (135.7) |
| 2012 | 75.80 | 56.56 | 141.7 |
| | (255.5) | (255.6) | (161.4) |
| Observations | 155 | 155 | 155 |
| R-squared | 0.072 | 0.075 | 0.344 |
| Number of provinces | 31 | 31 | 31 |
| Province FE | Y | Y | Y |
| Year FE | | Y | Y |
| Weather | | | Y |

Notes: Each column represents a separate regression predicting the number of burnings using an event-study approach (Jacobson et al., 1993). 2015 before the straw recycling subsidy program is the base year. Standard errors in parentheses are clustered by province. *** p<0.01, ** p<0.05, * p<0.1