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Statistical evidence on the impact of agricultural straw burning on urban air quality in China

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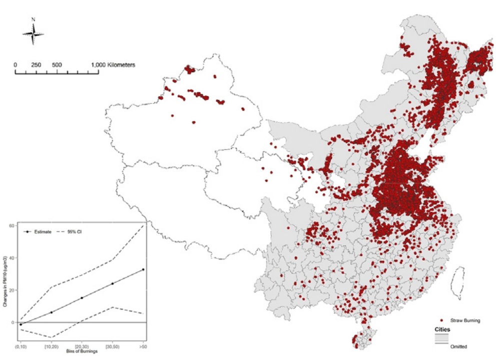
HIGHLIGHTS

- Straw burning deteriorates ambient air quality in prefecture-level cities in China.
- A 10-point increase in straw burning elevates monthly PM_{10} by 5 μg/m^3 on average.
- Straw burning does not impair CO, NO_2, O_3 and SO_2 statistically in Chinese cities.
- The effect is statistically significant for monthly burnings above 20 points.
- Upwind burnings' effect is 2–4 times larger than that of non-upwind burnings.

GRAPHICAL ABSTRACT

Straw burning and its association with PM_{10} in China in 2013–2015.



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ABSTRACT

Agricultural straw burning is prevalent globally with a long history, but evidence on its pollution and health impact is limited in many countries. This study quantifies the effect of agricultural straw burning on urban air quality in China. Fixed-effects (FE) panel regression models are employed to link straw burning points detected by high-resolution satellites to air quality monitored at 1650 ground-level stations from 2013 to 2015. The method can explain over 80% of the monthly variation in urban air quality during straw burning seasons. The results show that straw burning primarily affects particulate matter, and has negligible effects on other pollutants. Specifically, ten additional burning points in a month in the rural farmland of a city can lead to a 5.19 ± 2.54 μg/m^3 (3.67%±1.76%) increase in urban PM_{10} concentration. The effect is statistically significant for monthly burnings over 20 points. Upwind burnings' effect is 2-4 times larger than that of non-upwind burnings. The contribution from straw burning remains significant for daily and annual PM_{10} in urban areas. These estimates imply that straw burning should be properly regulated to improve air quality and protect public health in China, and the method and findings have broad implications for other agrarian regions with similar issues.

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1. Introduction

Agricultural straw burning in the open field is prevalent worldwide as a way to facilitate farming while saving labor (Andreae and Merlet, 2001). However, burning of crop residues can emit harmful substances including particulate matter (PM), volatile organic compounds, greenhouse gases and other toxics (Lemieux et al., 2004; Estrellan and Iino, 2010; Sun et al., 2016), which damage human health (Jacobs et al., 1997). Weather conditions (such as wind, temperature, and humidity) can further interact with emissions from straw burning and generate other secondary pollutants (Keshtkar and Ashbaugh, 2007; Oanh et al., 2011; Sanchis et al., 2014).

As the world's largest producer of both crops and straws, China now faces significant challenges in dealing with straw burning, as the country's crop production has been increasing over the past few decades but the demand for straw as a fuel has been declining in rural areas.[1] Nevertheless, there lacks quantitative evidence on the impact of rural straw burning on urban air quality on a large spatial and temporal scale, which is critical for evidence-based policymaking and for the protection of public health (see Shi et al., 2014; Chen et al., 2017 for recent reviews).

Existing studies usually rely on chamber experiments, field measurement, numerical modeling, and bottom-up calculations to estimate how straw burning emissions affect the environment (e.g., Lee et al., 2005; Dhammapala et al., 2006; Jimenez et al., 2006; Gadde et al., 2009; Wang et al., 2009; Lin et al., 2010; Yamaji et al., 2010; Zhang et al., 2011; Huang et al., 2013; Chen and Xie, 2014; Marlier et al., 2015; Long et al., 2016; Nirmalkar and Deb, 2016; Mehmood et al., 2018). A common caveat of these approaches is that there exist huge uncertainties and high complexities in emission inventories and simulations of complex physiochemical processes. As a result, most of the previous studies focus on small areas within a short period because the simulation models are computationally heavy and expensive for large-scale high-resolution applications. There still lacks large-scale assessment on the contribution of straw burning to ambient pollutant concentrations at urban population centers.

This study provides one of the first statistical evidence on how agricultural straw burning affects urban air quality on a national scale by exploiting both geographical and temporal variations in straw burning and air pollution in China.[2] We compile a novel and comprehensive dataset on straw burning detected by high-resolution satellites and collect air quality readings from 1,650 ground-level stations from 2013 to 2015. We then employ fixed-effects (FE) panel regression models to estimate the effect of straw burning on different air pollutants at the prefectural level.[3] A significant advantage of the FE model is that it can explain a large proportion of the variations in air quality by controlling for unobserved spatial differences and time trends across localities that are difficult to be accounted in numerical modelings, and we can draw credible and robust references on a national scale conveniently (details will be discussed in Section 2.4).

[1] Alternative energy sources (such as coal and natural gas) were gradually introduced in rural areas and replaced the use of straw as domestic fuel in many agricultural households.

[2] Several studies also use statistical models to analyze ther relationship between straw burning and pollution, including those using principle component analysis, positive matrix factorization, and those using time-series analysis (e.g., Wu et al., 2006; Wang et al., 2007; Viana et al., 2008; Zha et al., 2013; Li et al., 2014; Chen et al., 2015). However, like the numerical-modelling studies, they all focus on small geographical areas and some rely on information of different emission sources for estimation.

[3] A prefecture-level city is the subdivision of provinces and it is larger than a county in China. The average area of sampled cities is covered by a radius of 64 km. The minimum radius is 24 km, and the maximum radius is 280 km.

2. Material and methods

2.1. Straw burning

Straw burning data were collected from the Ministry of Environmental Protection (MEP) in China. The data are based on MODIS (Moderate Resolution Imaging Spectroradiometer) from two satellites named TERRA and AQUA. The two satellites overpass China twice a day around 10:30 am and 13:30 pm, and twice at night around 10:30 pm and 1:30 am. Flaming or smoldering fires are detected according to thermal anomalies within a 1-km pixel (Giglio et al., 2009; Kaufman et al., 1998; Justice et al., 2002). MEP identifies straw burning based on land use information, and the burnt area detected can be as small as 50 square meters.[4]

Satellite straw burning data offer a good measure of burning intensity for several reasons. First, the satellite data have a good performance in terms of accuracy, resolution and visiting frequency for a spot, which ensures the representativeness of straw burning points. Second, straw burnings are concentrated in granary regions and the farmland sizes are generally large enough to be detected by satellite (Yi et al., 2017).[5] Third, farmers are not aware of the overpassing times of satellites so they will not try to avoid the surveillance.[6]

2.2. Pollution and weather

The hourly average data on air quality were collected from 1,650 local air quality monitoring stations in China. Air quality is measured by PM_{10}, $PM_{2.5}$, CO, SO_2, NO_2, and O_3, which are monitored nationwide (HJ 633–2012).[7] Daily weather data were collected from 403 local meteorological stations in China, which include wind speed, wind direction, relative humidity, precipitation, and temperature.[8]

2.3. Panel construction and summary statistics

Straw burning data during the burning seasons in China from 2013 to 2015 were collected. The satellite surveillance period includes May 20th – July 20th and September 20th – November 20th in each year. Four provinces, namely Tibet, Xinjiang, Qinghai, Gansu, were dropped due to scarcity in burnings and severe sandstorms in many of these places. Each pollution monitoring station was matched with the closest weather station and the data were aggregated by prefecture-city and by month. We focus on monthly data because daily data do not have large enough variation in burning intensity (there are a large number of zeros in a specific day in a city), while annual data cannot capture the seasonality of straw burning.

For air pollution, because there is evidence that the official data are not reliable before 2013 (Ghanem and Zhang, 2014), we focus on data after 2013, when the Chinese government automated the air pollution reporting and upgraded the monitoring system to improve data quality.[9] To deal with missing values in the air quality

[4] The raw fire data can be retrieved from https://earthdata.nasa.gov/earth-observation-data/near-real-time/firms.

[5] Burnings that are too small to be detected will be overlooked by satellite, but their impacts on air quality can be negligible. Fires that are larger than one satellite pixel will be are recorded as multiple fire spots, which partially takes into account the effect of the burnt area. Adding a control of burnt area in the statistical model does not affect our estimates significantly.

[6] A related concern is that straw bunings cannot be detected when it is very cloudy. Nevertheless, as the variation in cloud coverage is likely to be random, this measurement error will not systematically bias our results (as will be shown later).

[7] The air quality data can be retrieved from http://106.37.208.233:20035/.

[8] The meteorological data can be retrieved from ftp://ftp.ncdc.noaa.gov/pub/data/noaa/isd-lite/.

[9] http://106.37.208.233:20035/.

Table 1
Summary Statistics of Key Variables.

VARIABLES		Observations	Mean	S.D.	Max
Panel A. Straw Burning					
	North/Central/East	3365 (56%)	3.1	8.1	101
	Northeast	2005 (33%)	6.6	21.1	158
	Others	625 (11%)	0.4	1.6	25
	Monthly Burnings	5995	2.1	8.9	158
Panel B. Pollution and Weather (monthly)					
	PM_{10} ($\mu g/m^3$)	2513	91.9	44.4	355.4
	Wind Speed (m/s)	2802	2.6	1.0	8.8
	Temperature (C°)	2767	20.7	6.7	32.1
	Relative Humidity (%)	2767	68.7	12.3	96.2
	Precipitation (mm)	2820	4.9	7.8	139.2

Note: This table contains summary statistics of data in the panel. Panel A reports the location of burnings as well as monthly burnings. The north, central and east provinces include Inner Mongolia, Hebei, Henan, Shandong, Anhui, Jiangsu and Hubei. Panel B summarizes PM_{10} and weather conditions. The burning season includes May 20th–July.20th and Sept.20th–Nov.20th in 2013–2015.

data, we exclude cities that have missing values for more than a year from 2013 to 2015.

Summary statistics of the key variables are listed in Table 1. There were 5,995 total straw burnings in 157 cities detected by the satellite in the final city-by-month panel. 56% (3365) of burnings were located in 60 cities in 7 granary provinces in the north, central and east plains, while 33% (2005) of burnings were concentrated in 16 cities of 3 northeast provinces. The rest 11% (6 2 5) of burnings were scattered among 60 cities in 17 provinces mainly in the south. The top 10 provinces with the most straw burnings are Shandong (21.7%), Heilongjiang (14.8%), Hebei (12.2%), Liaoning (10.3%), Henan (8.9%), Jilin (8.3%), Jiangsu (5.8%), Inner Mongolia (3.2%), Shanxi (2.7%), and Anhui (2.4%). They account for 90.4% of all straw burnings during the focal period. The top 10 cities are Qiqihar (7.2%), Shenyang (5.9%), Harbin (5.3%), Baicheng (4.0%), Changchun (3.8%), Jining (3.3%), Handan (3.3%), Linyi (3.1%), Jinzhou (2.8%), Xinxiang (2.7%). There are 49 cities with a record of over 10 straw burnings in a month. 21 cities have zero observation of straw burning in the panel, among which 20 cities are in the south. Straw is burnt intensively within a few clusters of cities, and the distribution is positively skewed with a long tail. The number of monthly burnings in a city is around 2 per month, with a maximum of 158. In terms of temporal variation, there are 2096 burning points in 2013, 1861 in 2014, 2038 in 2015. Straw burning mostly occurs in October (37.6%) and June (31.6%), followed by November (15.9%), May (6.5%), July (5.2%) and September (3.1%). In general, straw burning is most severe in autumn in the northeast provinces, and in summer in the north, central and east plains. This is in line with the cropping and harvesting pattern in China.

Panel B of Table 1 summarizes PM_{10} and key weather variables. The monthly PM_{10} in a city during burning seasons is around 92 $\mu g/m^3$, which is significantly higher than the air quality standards in China (GB 3095–2012).

Fig. 1 shows the spatial distribution of straw burnings and PM_{10} during China's burning seasons in 2013–2015. Straw burning points in different cities are plotted in the upper panel, and the average PM_{10} is shown in the lower panel. It is obvious that cities with more severe straw burning have higher PM_{10} than cities with fewer burnings.

Fig. 2 further depicts the correlation between straw burning and PM_{10} at the city-month level. The scattered dots plot monthly PM_{10} and the number of monthly straw burnings for each observation, and the solid line denotes the simple linear fitting of the two variables. Overall, PM_{10} would increase as the number of straw burnings increases. Fig. 2 serves as suggestive evidence that PM_{10} and straw burning are positively correlated, but more factors need to be considered to capture the contribution of straw burning to PM_{10} (as explored later).

2.4. Methods

2.4.1. Straw burning and air pollution

This study adopts a statistical approach to estimate the relationship between straw burning and air quality. Previous statistical analyses on this issue often rely on principle component analysis or time-series models and focus on a small area. As this study uses panel data consisting of repeated observations in many cities, fixed-effects (FE) models are used to estimate the straw burning-pollution relationship. FE models can reduce omitted variable biases by controlling for unobserved confounders through a rich set of fixed-effects indicators in the regression (Allison, 2009). Unobservables that do not change over time or space can be ruled out through differencing between observations and their corresponding mean values for a location or a period. Having partialled out the time-invariant and location-invariant unobservables, the FE estimates can capture the effects of the independent variable on the outcome variable.

Specifically, the following FE model is employed to estimate how changes in air quality are affected by changes in straw burnings:

$$Y_{it} = \alpha_{it} + \beta burning_{it} + X_{it}\delta + \pi_{it} + \lambda_y + \varepsilon_{it} \quad (1)$$

where Y_{it} is the monthly average concentration of one of the six air pollutants or its logarithm in city i in month t. $burning_{it}$ is the number of straw burnings detected in city i in month t. X_{it} controls for meteorological variables, namely wind speed, wind direction, relative humidity, precipitation, and temperature. δ includes the coefficient of each meteorological variable. π_{it} stands for city-by-month fixed effects, which controls for confounders that are specific to each city month. Straw-burning culture, agricultural pattern, natural endowment, economic structure, income, technology and policies on straw burning that are specific to a locality can be controlled by the fixed effects. λ_y represents year fixed effects, which controls for shocks that are common to all cities in a particular year, such as national regulations, crop prices, grain production, climate change, nationwide technology advance and changes in energy structure. In the FE model, only factors co-varying with straw burning within a city and month will be a concerned source of bias. However, this is highly unlikely, as straw burning is seasonal with frequent spots, which largely controlled led by individual farmers and have a random feature by nature. The pattern and emission profile of straw burnings are also different from other sources of urban pollution (such as industrial or vehicle emissions). Therefore, other pollution sources can be isolated by the city-by-month and year fixed effects. α_{it} is the intersection term, while ε_{it} is the error term clustered at the city-month level to account for

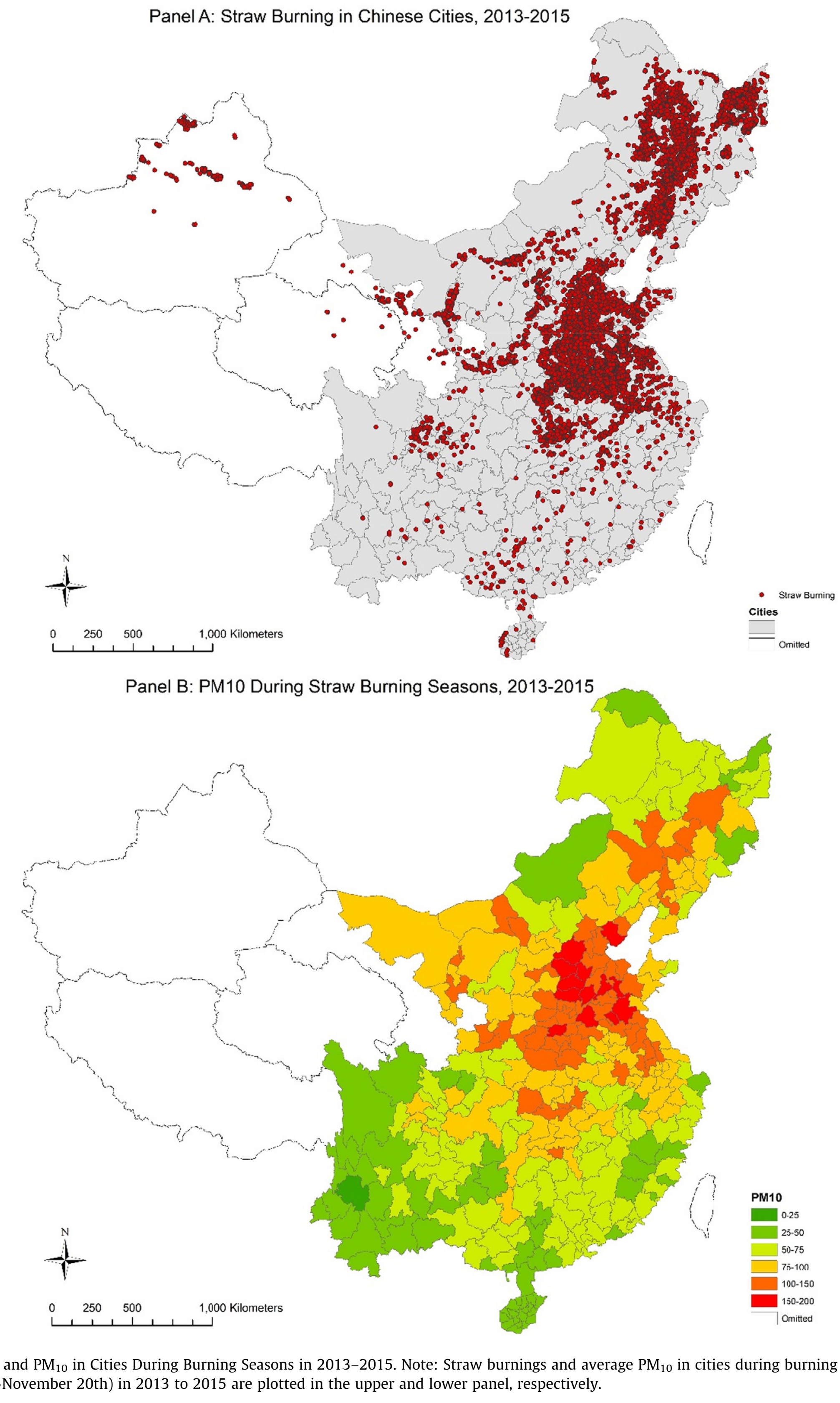

Fig. 1. Straw Burnings and PM_{10} in Cities During Burning Seasons in 2013–2015. Note: Straw burnings and average PM_{10} in cities during burning seasons (May 20th–July 20th, September 20th–November 20th) in 2013 to 2015 are plotted in the upper and lower panel, respectively.

potential autocorrelations in straw burnings and air quality in the same city and in the same month (Cameron and Miller, 2015).

β is the key parameter of interest, which measures the marginal contribution of straw burning to air pollution in Chinese cities on average. Conditional on county-by-month fixed effects, year fixed effects and weather, straw burning can bring exogenous variations in urban air quality within a city. In other words, the variation in straw burning within a locality is likely random over time. This

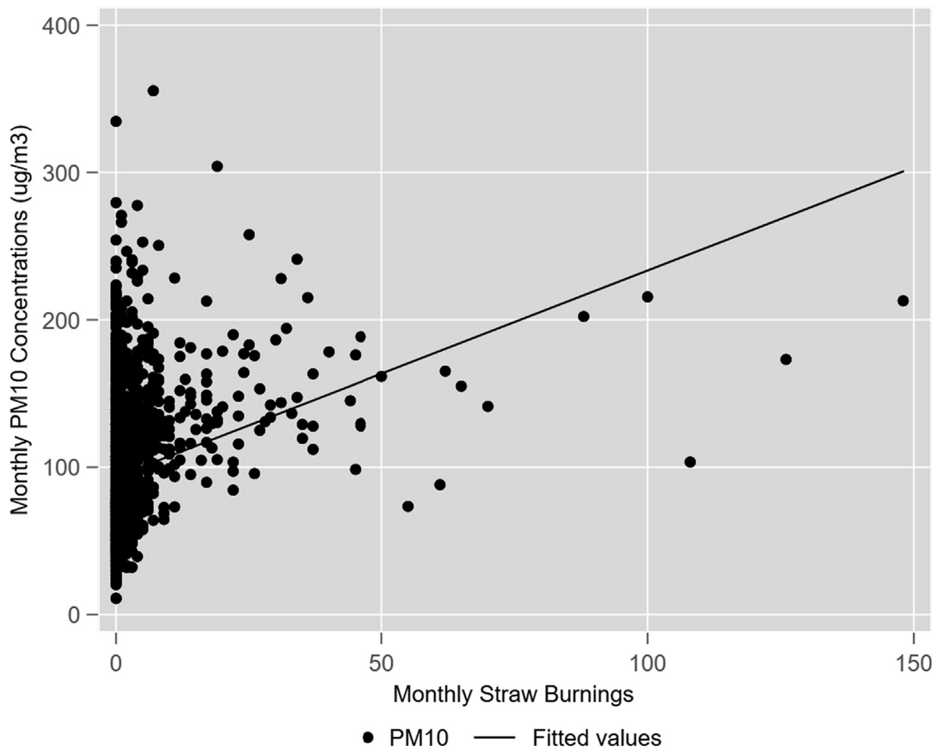

Fig. 2. Correlation of Straw Burnings and PM_{10} at City-Month Level in 2013–2015. Note: Scattered dots represent monthly straw burnings (X Axis) and PM_{10} (Y Axis) in each city in 2013–2015. Linear fit of the data is shown in a solid line.

is also supported by the fact that farmers usually do not consider the emissions when burning straws. The exogeneity of straw burning can further be validated by including different controls one by one into the regression. If β estimates are stable with different controls, the possibility of leaving out important confounders will be low, thus omitted variable bias, if any, would be small and negligible.

The FE approach will benefit current research in multiple ways. First and most importantly, the location and time fixed effects isolate many unobserved factors that could confound the relation between straw burning and air pollution. Second, the panel analysis simplifies the estimation of pollution impacts of straw burning with larger flexibility and broader application. The FE model has a strong statistical power, allowing credible estimation of the average effect of straw burning based on nationwide observations. Meanwhile, it is more convenient to apply and much less computationally expensive than scientific models. The method can supplement previous scientific research with new evidence to facilitate interdisciplinary discussions on straw burning. Lastly, the statistical analyses can provide important policy implications on straw burning in China. Despite official ban, agricultural fires have been frequently spotted over the past two decades. Credible and generalized estimates of straw burning's overall impact is crucial for policy design. The method and findings of this paper can also provide reference for other countries with similar burning issues.

2.4.2. Nonlinear effects of straw burning

To explore the potential nonlinear relationship between straw burning and air pollution, we can divide the sample into different bins according to the number of burning points and estimate the impacts of burnings within each bin using the following equation:

$$Y_{it} = \alpha_{it} + \sum_{j} \beta_{itj} burning_{itj} + X_{it}\delta + \pi_{it} + \lambda_y + \varepsilon_{it} \quad (2)$$

where $burning_{itj}$ is a dummy variable indicating whether the monthly straw burning in city i and month t is in the jth bin. We group the number of straw burnings in to fire bins: (0,10), [10,20), [20,30), [30,50), [50,) so that each bin includes similar number of observations. Zero burning bin serves as the reference group and each β_{itj} measures the effect of monthly straw burnings in bin j on urban PM_{10}, relative to the effect of zero burnings. The other variables are defined the same as Eq. (1). Compared with Eq. (1) which assumes constant linear effects of straw burning on air pollution, Eq. (2) offers a more flexible setting allowing for varying impacts of straw burning at different levels.

2.4.3. Effects of upwind burning

Emission dispersion depends on wind directions. Straw burnings occurred in upwind regions can have larger impacts on air quality downwind. To examine this heterogeneous effect, we define upwind burnings as those located within a certain range (angle) from the dominant wind direction in a city on a day. The direction of a straw burning point to a city is based on coordinates of the burning point and city center located downtown. Burnings located within smaller ranges from the dominant wind direction shall have a larger impact on urban air quality, as pollutants are more likely to be blown to the city center. We check the effects of upwind burnings within different angles, namely 30, 60 and 90°, based on the prevailing wind direction. The downwind burnings are located in the opposite direction. Daily upwind and non-upwind burnings in a city were then aggregated to the monthly level. The following model is estimated:

$$PM_{it} = \alpha_{it} + \beta^{u}_{it} upwind_{it} + \beta^{n}_{it} nonupwind_{it} + X_{it}\delta + \pi_{it} + \lambda_y + \varepsilon_{it} \quad (3)$$

where $upwind_{it}$ denotes the number of straw burnings located in the upwind direction of city i in month t, and $nonupwind_{it}$ represents straw burnings located in other directions. β^{u}_{it} and β^{n}_{it} estimate the effects of upwind and non-upwind burnings on urban PM_{10} in cities. The rest settings are the same as Eq. (1).

Table 2
Impacts of Fixed Effects and Weather on Estimating Straw Burning and PM_{10} in Cities.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
VARIABLES	PM_{10}	PM_{10}	PM_{10}	PM_{10}	PM_{10}	PM_{10}	PM_{10}	PM_{10}	PM_{10}
(per 10 points)									
Burning	11.4***	7.48***	5.66***	5.46***	5.55***	5.75***	5.64***	5.61***	5.19***
	(2.63)	(1.01)	(0.94)	(1.41)	(1.34)	(1.31)	(1.31)	(1.31)	(1.29)
Wind Speed						−5.63***	−5.57***	−5.78***	−6.88***
						(2.08)	(2.10)	(2.10)	(2.10)
Precipitation							−0.38***	−0.35***	−0.12
							(0.11)	(0.11)	(0.10)
Temperature								1.05	0.32
								(0.84)	(0.81)
Relative Humidity									−0.64***
									(0.11)
Observations	2,460	2,460	2,460	2,460	2,460	2,460	2,460	2,460	2,460
R-squared: within	–	0.043	0.326	0.536	0.611	0.616	0.619	0.620	0.632
R-squared: overall	0.052	0.593	0.714	0.803	0.834	0.837	0.838	0.838	0.844
RMSE	43.25	29.27	24.59	24.99	22.90	22.79	22.71	22.69	22.32
Number of cities	154	154	154	154	154	154	154	154	154
City FE		Y	Y						
Month FE			Y						
City-by-Month FE				Y	Y	Y	Y	Y	Y
Year FE					Y	Y	Y	Y	Y
Wind Direction						Y	Y	Y	Y

Note: Each column represents a separate regression. Different fixed effects (city, month, city-by-month, year) and weather conditions (wind speed, wind direction, precipitation, temperature, relative humidity) are explored. Standard errors in parentheses are clustered at city-month level. *** $p < 0.01$

3. Results

This section presents the estimates of straw burning's effect on urban air quality. First, we examine the impacts of adding different controls in the FE model, followed by a detailed investigation on straw burning's effects on various pollutants. Then, we explore the nonlinearity in the association between straw burning and urban PM_{10}. Next, we differentiate the effects of upwind burnings from the effects of non-upwind burnings in cities. Lastly, we explore the impact heterogeneity and check the robustness of the findings.

3.1. Impacts of controlling fixed effects and weather

Fixed effects and weather factors can be added one by one in the regression to check their impacts on the estimation of straw burning's effect on pollution. We select PM_{10} as an example and report the results in Table 2. If one simply regresses PM_{10} concentration on straw burning without any controls, the estimate will be largely biased with very low goodness-of-fit (R-squared), as shown by Column (1). The estimate corresponds to the slope of the fitted line in Fig. 2. The linear regression fits the data poorly and overestimates the effects due to omitted variable bias.

Column (2) shows that adding city fixed effects significantly lowers the estimate while improving the goodness-of-fit substantially from 0.05 to 0.59. The root mean square errors (RMSE) are improved as well. This suggests that air pollution and straw burning are city-specific to a large extent. Some cities have higher pollution levels from other fixed sources or have more straw burnings due to larger areas of farmland, and these cross-city differences need to be controlled by the city fixed effects. Adding month fixed effects further reduces the magnitude of estimates while improving the model fitting, as shown by Column (3). If we include county-by-month fixed effects instead, the estimates further shrink slightly, as reported in Column (4). The estimates are rather stable by adding year fixed effects, and the FE model can explain more than 80% of PM_{10} variations. One may worry that the large improvement in the overall R-squared is mainly driven by the unobserved fixed effects. We also report within-group R-squared, which measures the contribution of straw burning in a city in a month to PM_{10} in the same city and month. The within-group variation of straw burning explains over 60% of the variations in PM_{10}, which contributes most to the overall R-squared in the FE model.

Columns (6)–(9) of Table 2 further report the effects of adding different weather controls. First, stronger wind and more precipitation will decrease PM_{10}. However, the effect of precipitation disappears once relative humidity is controlled. Temperature does not significantly affect urban PM_{10} at the city-month level. Second, the effect of straw burning is consistent over different settings, suggesting that omitted variable bias is trivial. On average, 10 additional burning points will increase monthly PM_{10} in cities by around 5.19 $\mu g/m^3$ and is statistically significant at 1% level. Third, in our preferred specification, when all the fixed effects and weather conditions are controls, the model can explain over 84% of the variations in urban PM_{10}, as reported in Column (9). The results indicate that, conditional on weather conditions and fixed effects, straw burning can be treated as exogenous and is responsible for most of the variation in urban PM_{10} during burning seasons. The findings are consistent with projections from scientific models (Zhang et al., 2016).

3.2. Effects of straw burning on air quality

Table 3 reports the contribution of straw burning on all the six pollutants estimated by Eq. (1). The first row lists the monthly mean of each pollutant as reference. The following two panels list the concentration changes and percentage changes in pollution in response to changes in monthly straw burnings in cities, respectively. The 95% Confidence Interval (CI) of each estimate is reported.

Conditional on weather conditions and fixed effects, an increase of 10 straw burning points would elevate monthly PM_{10} concentrations in cities by 5.19 ± 2.54 $\mu g/m^3$ or 3.67 ± 1.76%. The impact is significant and considerably large. Monthly $PM_{2.5}$ in cities would also increase by 3.16 ± 1.74 $\mu g/m^3$ or 3.93 ± 1.90%, which is consistent with the PM_{10} estimates. In contrast, there is no significant impact of straw burning on CO, SO_2, NO_2 or O_3, as shown by Columns (3)–(6) in Table 3. The results support previous scientific findings on straw burning emissions, as will be discussed in Section 4 in detail.

Table 3
Effects of Straw Burning on Pollutants at City-Month Level.

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	PM_{10}	$PM_{2.5}$	CO	SO_2	NO_2	O_3
(per 10 points)	($\mu g/m^3$)	($\mu g/m^3$)	(ppm)	(ppb)	(ppb)	(ppb)
Monthly Mean	91.9	53.0	0.92	9.92	17.8	32.6
Concentration	5.19***	3.16***	−0.004	−0.08	0.01	−0.40
	(1.29)	(0.88)	(0.02)	(0.13)	(0.16)	(0.27)
95% CI	[2.65,7.72]	[1.42,4.89]	[-0.03,0.03]	[-0.33, 0.17]	[-0.18,0.46]	[-0.94,0.13]
Percentage (%)	3.67***	3.93***	−0.04	0.28	0.64	−0.91
	(0.90)	(0.97)	(1.36)	(0.96)	(0.71)	(0.89)
95% CI	[1.91,5.44]	[2.03,5.83]	[-2.71,2.62]	[-1.60,2.17]	[-0.75,2.04]	[-2.65,0.83]
Observations	2,460	2,373	2,369	2,476	2,476	2,369
R-squared	0.872	0.878	0.824	0.878	0.878	0.867
Number of cities	154	154	154	154	154	154
City-by-Month FE	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y
Weather	Y	Y	Y	Y	Y	Y

Note: Each column represents a separate regression. City-by-month fixed effects and year fixed effects are controlled. Weather includes wind speed, wind direction, precipitation, temperature, relative humidity. Standard errors in parentheses are clustered at city-month level. The 95% Confidence Interval (CI) of each estimate is reported. *** $p < 0.01$

Notablly, the goodness of fit of the FE models for the percentage change in pollution are generally higher than 0.8. The FE models can explain most of the variations in pollution, and the estimates of straw burning's impacts on air pollution are plausibly causal.

In the following sections, we will focus primarily on the impact of straw burning on PM_{10} concentrations instead of $PM_{2.5}$ concentrations, since not all the cities monitor $PM_{2.5}$ at the beginning of our sample period, and $PM_{2.5}$ is part of PM_{10} and coarse particulate matters between 2.5 μm and 10 μm can also harm human health. However, all the findings remain the same if we use the available $PM_{2.5}$ data as the outcome variable (as reported in the robustness checks and appendix).

3.3. Nonlinearity in straw Burning's effects

We explore the nonlinear effects of straw burning on pollution by estimating Equation (2) and report the results in Table 4. Columns (1)–(2) summarize the effects of straw burning on PM_{10} concentrations for all 5 bins. Columns (3)–(4) list the corresponding percentage changes in PM_{10}.

Table 4
Nonlinear Effects of Straw Burning on PM_{10} at City-Month Level.

	Change in PM_{10} ($\mu g/m^3$)		Percentage change in PM_{10} (%)	
Variables	(1)	(2)	(3)	(4)
bins of burnings				
(0,10)	0.54	−1.30	1.16	−0.47
	(1.87)	(1.63)	(1.56)	(1.30)
[10,20)	10.24	6.25	11.8*	8.67
	(8.62)	(7.98)	(6.44)	(6.07)
[20,30)	20.5***	15.1**	19.1***	14.8***
	(7.88)	(7.25)	(5.08)	(4.85)
[30,50)	25.0***	24.1***	20.9***	19.4***
	(7.46)	(7.51)	(5.90)	(6.37)
[50,)	36.7**	32.7**	25.8**	21.7**
	(16.37)	(13.91)	(12.40)	(11.10)
Observations	2,513	2,459	2,513	2,459
R-squared	0.607	0.631	0.649	0.681
Number of cities	157	154	157	154
City-by-Month FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
Weather		Y		Y

Note: Each column represents a separate regression. Each row contains the effects of straw burning on PM_{10} within a certain range of numbers. Zero burning is used as reference. Weather includes wind speed, wind direction, precipitation, temperature, relative humidity. Standard errors in parentheses are clustered at city-month level. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

The effect of the first bin of straw burning is close to zero and statistically insignificant. The effect of the second bin grows larger but remains insignificant. This indicates that if there are only a few burning points (<20 points per month), the air pollution effect would not be very large. When the number of burning points increase to 20 or above, air pollution becomes significantly worse. Cities with monthly burnings over 20 points would significantly lower the monthly PM_{10} by 15.1–32.7 $\mu g/m^3$ (14.8%–21.7%) if all the burnings disappear. This threshold effect is purely empirical, suggesting that smaller and fewer fires may not elevate ambient concentrations significantly. Lastly, weather conditions hardly alter the estimates on straw burning's effects. By controlling for weather in Columns (2) and (4) of Table 4, the size of impact becomes slightly smaller but remain statistically significant.

We also plot the estimated coefficients in Fig. 3. The connected dots represent the estimates, and the dashed lines denote the 95% CI. Fig. 3 shows a close-to-linear line with no sign of concavity nor convexity. However, the 95% CI shows that only the estimates for groups with straw burning points more than 20 are statistically significant. This nonlinear threshold effect reveals that a small number of fire incidents in rural farmland is unlikely to deteriorate ambient air quality in urban areas significantly. They could still impact the air quality in areas nearby, but the smoke may not spread far enough to have a significant and substantial impact on air quality in urban areas where the majority of the population resides.

3.4. Effects of upwind burning

Table 5 compares upwind burnings with non-upwind burnings. Columns (1)–(3) list the changes in PM_{10} concentration in response to straw burnings within 30, 60 and 90°from the upwind direction, respectively. Columns (4)–(6) list the corresponding percentage changes in PM_{10}.

A larger effect of upwind fires is observed compared with burnings in other directions. An increase of 10 straw burning points within 60 degrees of upwind direction is associated with a 13.2 $\mu g/m^3$ increase in monthly PM_{10}. The effect will shrink if the angle gets larger or smaller. A larger range would include more burnings, and the pollution effect becomes less direct for burnings away from the upwind direction. A smaller range would cover fewer burnings, thus leading to smaller estimates. In comparison, the effects of non-upwind burnings are 2–4 times smaller than the effects of upwind fires, but the effects remain statistically sig-

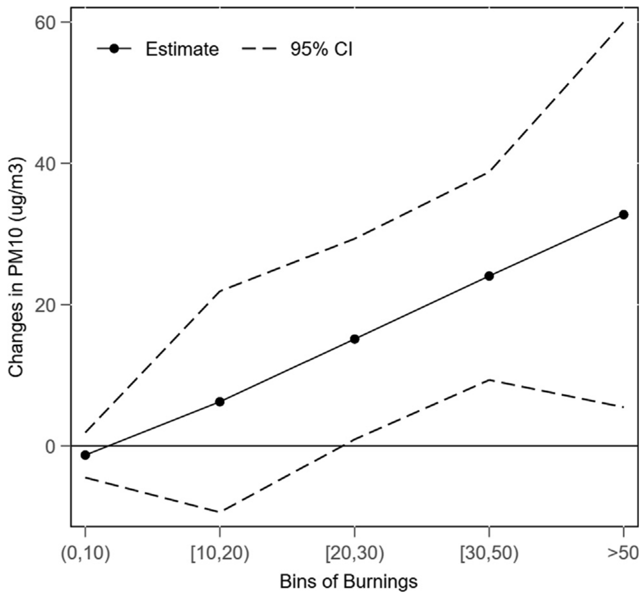

Fig. 3. Nonlinear Effects of Straw Burning on PM_{10} at City-Month Level. Note: Effects of straw burnings in each bin on PM_{10} at city-month level are plotted with 95% CI. The connected dots represent the estimates, and dashed lines denote the 95% CI. Weather conditions (wind speed, wind direction, precipitation, temperature, relative humidity), city-by-month FE and year FE are controlled.

nificant. As a result, policymakers shall pay more attention to upwind straw burnings than non-upwind burnings.

3.5. Heterogeneity by season and region

In this section, we explore the spatial and seasonal heterogeneities of the straw burning effect. First, we compare summer straw burnings with fall straw burnings. We define May, June, and July as the summer season, and interact the summer dummy with the straw burning variable. The findings are summarized in Column (1) and Column (3) of Table 6. We do not find significant seasonal heterogeneity, i.e. the effects of straw burning on PM_{10} seem to be the same over different seasons.

Second, we investigate whether the effect differs between northern and southern Chinese cities. We group the cities based on a natural line dividing the north and south: Qinling Mountain and Huai River. We generate a dummy variable for cities in the north, and interact it with burnings. The results are presented in Column (2) and Column (4) of Table 6, which show that straw burning has a smaller effect on urban air quality in northern China than that in southern China. This result highlights the effective management and control of straw burnings are especially important in southern China.

Table 6
Heterogeneous Effects of Straw Burning by Season and Location.

Variables	Change in PM_{10} ($\mu g/m^3$) (1)	(2)	Percentage change in PM_{10} (%) (3)	(4)
(per 10 points)				
burning	5.56***	9.60**	3.61***	10.9***
	(0.86)	(4.64)	(0.93)	(3.72)
summer*burning	−1.46		0.26	
	(1.59)		(1.59)	
north*burning		−4.49		−7.38**
		(4.07)		(3.00)
Observations	2,460	2,460	2,460	2,460
R-squared	0.844	0.844	0.872	0.872
Number of cities	154	154	154	154

Note: Each column represents a separate regression. City-by-month fixed effects and year fixed effects are controlled. Weather includes wind speed, wind direction, precipitation, temperature, relative humidity. Standard errors in parentheses are clustered at city-month level. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

3.6. Effects of straw burning on daily and annual PM_{10}

The impacts of straw burning on urban air quality may vary by timescale. It is of research and policy interest to know whether the impact of straw burning would be significant for daily and annual PM_{10}. This section estimates the daily and annual impacts of straw burning (during burning seasons) on urban PM_{10} following a similar specification with Equation (1) by replacing the month fixed effects with day or year fixed effects. Table 7 summarizes the effects of straw burning on urban PM_{10} on daily and annual level, respectively. Columns (1)–(2) contain the daily effects of straw burning on PM_{10}. An increase of straw burnings by 10 points in a day would elevate the PM_{10} concentration by 31.2 $\mu g/m^3$ and 25.1%. The pollution effect is substantially significant and may induce high health costs. The daily straw burnings in a city can be as high as 67 points. This implies that intensive straw burnings within a short period can have acute impacts on local and regional air quality. A further dynamic analysis reveals that the effects of straw burning on urban air quality can last for around 7 to 8 days, as shown in Appendix Table A.1. The previous one day would have the largest effect as it takes time for straw burning emissions to travel from rural farmland to urban sites.

Columns (3)–(4) of Table 7 report the annual changes in urban PM_{10} caused by straw burning. The annual PM_{10} (including burning

Table 5
Effect of Upwind Straw Burning on PM_{10} at City-Month Level.

Variables	Change in PM_{10} ($\mu g/m^3$) (1)	(2)	(3)	Percentage change in PM_{10}(%) (4)	(5)	(6)
Angle	30°	60°	90°	30°	60°	90°
Upwind	7.50**	13.15***	8.60**	7.65***	10.0***	6.62**
(per 10 burnings)	(2.59)	(4.91)	(3.51)	(2.13)	(3.47)	(2.85)
Non-Upwind	4.90***	3.77***	4.07***	3.45***	2.54***	2.71***
(per 10 burnings)	(0.66)	(0.81)	(1.01)	(0.69)	(0.75)	(0.79)
Observations	2,459	2,459	2,459	2,459	2,459	2,459
R-squared	0.632	0.633	0.632	0.681	0.681	0.681
Number of cities	154	154	154	154	154	154
City-by-Month FE	Y	Y	Y	Y	Y	Y
Weather	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y

Note: Each column represents a separate regression. Upwind burnings are defined as straw burning points located within 30, 60, or 90°from the daily dominant wind direction. Weather includes wind speed, wind direction, precipitation, temperature, relative humidity. Standard errors in parentheses are clustered at city-month level. *** $p < 0.01$, ** $p < 0.05$

Table 7
Effects of Straw Burning on Daily and Annual PM_{10} in Cities.

	Day		Year	
	(1)	(2)	(3)	(4)
VARIABLES	PM_{10}(μg/m^3)	PM_{10}(%)	PM_{10}(μg/m^3)	PM_{10}(%)
Straw Burning	31.2***	25.1***	2.24***	1.67***
(per 10 burnings)	(7.73)	(5.25)	(0.49)	(0.46)
	[7.87]	[6.70]	[0.74]	[0.50]
Observations	49,202	49,202	446	446
R-squared	0.299	0.365	0.310	0.354
Number of cities	154	154	154	154
City FE	Y	Y	Y	Y
Weather	Y	Y	Y	Y
Day FE	Y	Y		
Year FE			Y	Y

Note: Each column represents a separate regression. Only straw burning seasons are included. Weather includes wind speed, wind direction, precipitation, temperature, relative humidity. Standard errors in parentheses are clustered at city-day level and city-year level, respectively. Standard errors in square brackets are clustered at province-day level and province-year level, respectively. *** $p < 0.01$.

seasons only) in cities would increase by 2.24 μg/m^3 (or 1.67%) if 10 more straw burning points are detected. The average straw burnings in a city over a year is around 13 points, and the maximum reaches 248 points.

In conclusion, straw burning's effect on urban PM_{10} can be both acute in short term (within a day or month) and chronic in the long term (during burning seasons in a year). Due to seasonality, the pollution contribution of straw burning is substantial in the short run at daily or monthly level during burning seasons, but is small on a yearly basis. The results support the previous estimates from scientific models. For instance, Zhang et al. (2016) found that the annual PM_{10} emissions from straw burning contribute to 7.8% of total anthropogenic emissions, and monthly contributions can reach 26% in China (and even much higher in granary regions).

3.7. Robustness checks

We conduct a rich set of robustness checks in this section, which lend additional credibility of the main results.

First, we examine the details of the effects of straw burning on $PM_{2.5}$ in addition to PM_{10}. The results are listed in Table A.2. We find that the estimates are consistent with those for PM_{10}, suggesting that straw burning primarily affects PM on average.

Second, we check the sensitive of our results using alternative matching methods between straw burning and air quality. In our main analyses, we match straw burnings and air quality by city boundaries. An alternative is to match the data based on the distance from a city center. In Table A.3, we examine how air quality is affected by the number of straw burnings within the radii of 25 km, 50 km, 75 km, 100 km, and 200 km. First, the estimated coefficient of straw burning will shrink as we use wider radius. This is reasonable because wider radius will include more straw burnings that are far away, making the marginal effect of straw burning decrease. Therefore, close and local fires contribute more to urban air pollution. Second, the impact of straw burning within 50 km is similar in size with the estimates adopting municipal divisions, as 50 km is close to the average radius of a Chinese city.

Third, the cloud can introduce measurement error in straw burning. Therefore, we include cloud coverage in regression to check if the main results hold. The results are shown in Appendix Table A.4. The effects of straw burning on PM_{10} grow slighter larger and remain significant when we control for cloud coverage. This implies that variations in cloud coverage can be stochastic, which will not significantly bias our estimation.

Fourth, as aforementioned in Section 2.3, we dropped four provinces that have very few straw burnings in our main analysis. In this section, we include all 338 Chinese cities in the FE model. As shown by Appendix Table A.5, the magnitudes of impacts do not change much, and the effects of straw burning on air quality remain statistically significant.

Finally, the distribution of straw burning has a fat tail (as shown in Fig. 3). To address the concern that previous main findings of straw burning's effect on air pollution may be driven by the extremely large values of straw burning points, we drop observations with monthly straw burning more than 50 points and report the estimates in Appendix Table A.6. The estimated coefficients remain quantitatively similar when these outliers are dropped.

4. Discussions

Our main findings are largely consistent with the previous scientific literature on straw burning emissions. However, it is difficult to compare our statistical estimates with numerical modeling outputs directly. First, emissions can be different from pollution concentrations. Second, most of the studies are in a particular small area for a short time, whereas our estimates hold statistically on average over the whole China and are immune to localized random fluctuations. Therefore, our estimates are supplementary to previous studies with a novel perspective from regressional analysis. Notably, the baseline results are remarkably robust to alternative specifications, suggesting that they are not driven by specific ways to construct the data. Specifically, we obtain quantitatively similar results when using daily or yearly data, adopting alternative matching methods, dropping outliers, and applying different sampling criteria.

In general, we show that straw burning has significant impacts on PM, but not on SO_2, NO_2, CO or O_3, which is in line with the fact that straw burning primarily emits PM, characterized by levoglucosan, potassium (K), chlorine (Cl), a high ratio of organic carbon over elemental carbon (OC/EC), and a lower ratio of SO_2, NOx and CO (Streets and Waldhoff, 2000; Li et al., 2007; Calvo et al., 2011; Zhang et al., 2013; Zhang et al., 2016; Zhang et al., 2017a, b). Secondary O_3 is very complex depending on nonlinear interactions with temperature, solar radiation and other pollutants, and the biomass burning effects on O_3 can be weak (Jaffe et al., 2013). Note that some studies that use localized experiments indeed find that burning straws can generate various pollutants. The minor inconsistency is mainly because this paper tries to capture how rural straw burning affects urban air pollution by traveling relatively long distances from farmland to urban areas, while the local experiments try to test what can be emitted at the site of burning. The null impact on SO_2, NO_2, CO and O_3 in this study indicates these pollutants are local to the burning points and have dispersed before they reach the urban areas.

In addition, we document that the burning-pollution relationship is not linear. There are various reasons for the burning-pollution relationship being nonlinear. For example, the impact of emissions on air quality may enhance as the level of emissions increase, since emissions can elevate ambient pollution by changing conditions such as planetary boundary layer (Petäjä et al., 2016). In addition, pollutants emitted from straw burning in rural areas can be dispersed while traveling to urban areas, and the effect of straw burning on air quality may attenuate over distance. We find that when the number of straw burning is below 20 in a month, air quality in urban areas will not be significantly affected. However, as there are more and more straw burnings, air quality will deteriorate. These results suggest that the socially optimal level of straw burning should be above zero (Hanley and Lingard, 1987) and policies aiming at zero straw burning may be too stringent and will incur too high administrative costs. Nevertheless, this policy implication shall be noted with caution, as straw burning's effect on rural air quality remains unclear due to no observation.

We also find that the pollution effect of straw burning is heterogeneous across regions and the effect is larger for southern cities. In China, northern cities are generally more polluted than southern cities because they burn massive amounts of coals for the heating system and rely more on large heavy industries in production. The baseline PM_{10} concentration is 113.3 $\mu g/m^3$ in northern China, which is 42.5 $\mu g/m^3$ higher than that the south (70.8 $\mu g/m^3$). Northern Chinese also differ from southern Chinese in terms of the food they eat and the crops they grow: more wheat and corn are grown in the north, while more rice is grown in the south. This regional heterogeneity indicates crop type also matters for the straw burning effect.

These findings can have important policy implications on straw burnings management and control. China has been relying on command-and-control regulations banning straw burning since the late 1990 s, including sanctions and fines on local farmers and cadres. However, the number of straw burning has been increasing over the years despite these regulations. A great controversy in policy discussion is that there lacks credible evidence showing agricultural straw burning has led to worse air quality, particularly at a larger scale. The government is thus reluctant to enforce tighter regulations on farmers. Compared with previous studies that typically focus on small geographical areas, this study uses data from entire China; our findings are thus more general and can be used for national regulations.

In recent years, more incentive-based instruments were introduced to encourage the collection and recycling of straws from the farmland. These incentives include subsiding farmers and enterprises to collect straws instead of burning them and are reported to be effective in reducing straw burning and increasing the straw recycling rate.[10] Due to data limitation, we cannot further examine whether these incentive-based instruments can indeed help reduce straw burning. That being said, this study shows that the straw-burning effect can be nonlinear, depends on local wind directions, and varies among different regions. These results can help local governments to design more flexible incentives to control straw burning. For example, regions with large number straw burnings should be prioritized because the effect is nonlinear; and upwind regions relative to city centers should be more stringently regulated as they contribute more to local air quality than downwind straw burnings.

5. Conclusions

Agricultural straw burning can impose negative externalities on the environment by emitting hazardous particulates and gases. This study employs a statistical approach to investigate the effects of agricultural straw burning on urban air quality in China. We use straw burning points detected by satellites as a proxy for the intensity of burning activities in a city, and explore the variations of air pollutants in cities that can be attributed to rural burning using fixed-effects regression models. The results show that straw burning in rural farmland significantly deteriorates particulate matter in cities in both short and long run (from day to month to year), while the effects on SO_2, NO_2, CO, and O_3 may be only a local issue in rural areas. The impact becomes significant as the number of straw burnings increases, indicating a nonlinear threshold effect of straw burnings on air quality.

Since the Chinese government declared "the war against pollution" in 2014, a series of radical regulations have been adopted to improve air quality in major cities. Most of the new regulations have been focused on coal consumption and industrial emissions. This paper, by showing that straw burning is an important source of seasonal air pollution in urban areas, calls the government to tighten the regulation on agricultural emissions. Related to this topic, little is known about the health and social costs of straw burning, and future research on these issues is warranted in China and other regions with similar challenges.

[10] http://www.gov.cn/xinwen/2017-07/05/content_5208176.htm.

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Appendix A. Supplementary analyses and data

Supplementary analyses and data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.134633.

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