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ORIGINAL PAPER

Short-term effects of biomass open burning related air pollution on outpatient department visits for cardiovascular and respiratory diseases in Thailand

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Abstract
Numerous epidemiological studies have shown that biomass open-burning (BOB) related air pollution has been associated with adverse health effect, but limited evidence is found in Thailand. We investigated the effects of BOB occurrence on outpatient department (OPD) visits for cardiovascular and respiratory diseases in Thailand and further explored the effects of longer exposure duration and higher exposure intensity to BOB. Fire hotspot data were acquired from the Visible Infrared Imaging Radiometer Suite (VIIRS) on board the Suomi National Polar-orbiting Partnership (Suomi NPP) satellite during January 2016 through December 2020 across Thailand, and OPD visits data were obtained from the National Health Security Office during the same period. A time-stratified case-crossover design with conditional logistic regression was used to examine province-specific estimates of BOB-related air pollution on OPD visits, controlling for many possible confounders, and random-effect meta-analysis was then applied to derive the national estimate. Odds ratio (ORs) of cardiovascular and respiratory OPD visits on the day of BOB occurrence was 1.0105 (95% CI: 0.9971, 1.0240) at lag 5 days and 1.0131 (95% CI: 1.0050, 1.0213) at current day, respectively. ORs of cardiovascular and respiratory OPD visits associated with longer exposure duration to BOB was 1.0272 (95% CI: 1.0104, 1.0442) and 1.0275 (95% CI: 1.0139, 1.0413), respectively. Higher exposure intensity to BOB was not significantly associated with OPD visits for both cardiovascular and respiratory diseases. Findings from this study can be used to establish the warning systems associated with exposure to BOB-related air pollution to reduce adverse health effects in Thailand.

Keywords Biomass open burning · Air pollution · Outpatient department visit · Cardiovascular disease · Respiratory disease · Thailand

1 Introduction

Ambient air pollution (i.e., $PM_{2.5}$, PM_{10}, O_3, CO, SO_2 and NO_2) from various sources is considered one of the significant environmental issues worldwide, contributing to approximately 4.2 million premature deaths per year in 2016 and 91% of them was observed in low- and middle-income countries with the greatest burden in the WHO Western Pacific and South-East Asia regions (WHO 2016). The epidemiological studies conducted in many parts of the world have indicated that exposure to ambient air pollution was significantly associated with increased risk of morbidity and mortality, especially due to cardiovascular and respiratory diseases (Atkinson et al. 2014; Autrup 2010; Klemm et al. 2004; Mueller et al. 2020; Ostro et al. 2006). A prior study conducted in Bangkok, Thailand revealed that every 10 μg/m^3 increase of PM_{10}, O_3, NO_2, SO_2, and 1 mg/m^3 increase of CO was associated with increased risk of hospital admission due to cardiovascular and respiratory diseases (Phosri et al. 2019).

In Thailand, air pollution is considered the major environmental health concerns affecting environment and

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human health problems (Vichit-Vadakan and Vajanapoom 2011). The various sources of air pollution in Thailand have been observed depending upon location, where traffic emission and biomass open burning (BOB) have been found as the major source of air pollution in Bangkok. Specifically, vehicle emission contributed to approximately 33% of PM_{10} and 32% of $PM_{2.5}$ mass, whereas BOB contributed to approximately 33% of PM_{10} and 26% of $PM_{2.5}$ mass at traffic locations (Chuersuwan et al. 2008). In Pathum Thani, an adjacent province of Bangkok, the two major sources of air pollution were vehicle emission and BOB as well. In particular, vehicle emission contributed to approximately 28% and 27% of total $PM_{2.5}$ mass during wet and dry season, respectively whereas 26% and 41% of total $PM_{2.5}$ concentration was contributed from BOB during wet and dry season, respectively (Narita et al. 2019). The vegetation burning was also observed as the largest contributor to PM_{10} concentration in Chiang Mai and Lamphun, the provinces in the northern part of Thailand, contributing to 46–82% of total PM_{10} concentration (Pengchai et al. 2009). Therefore, BOB is considered as a significant source of air pollution emission in Thailand (Yin et al. 2019) that generally increases the concentrations of $PM_{2.5}$, PM_{10}, CH_4, CO, CO_2, N_2O and NO_2 in the ambient air (Boonman et al. 2014). The potential sources of BOB that influence air quality are varied in different regions of Thailand. Specifically, <u>air pollution derived from BOB in the Northern region is originally emitted from the local residue burning activities (</u>Kumar et al. 2020), <u>whereas that in the Southern region is sometime likely to occur from the transboundary air pollution (</u>Phairuang et al. 2020).

A previous epidemiological study conducted in Malaysia has indicated that exposure to PM_{10} emitted from BOB was significantly associated with increased risk of non-accidental and respiratory mortality at various lag structures (Sahani et al. 2014) and the health impact assessment study conducted in Thessaloniki, Greece showed that $PM_{2.5}$ emitted from BOB contributed to an increase of 200 premature deaths or 3,540 years of life lost in 2012–2013 winter compared to the same period of 2011–2012, corresponding to the economic burden up to 1.2 billion euros (Sarigiannis et al. 2015). Furthermore, a previous study conducted in eight Northern provinces of Thailand, the region with the most serious air pollution situation contributed from BOB, revealed that an increase of 10 $\mu g/m^3$ in PM_{10} concentration on the same day (lag 0) was associated with 2.00% (95% CI: 1.20, 2.80) and 2.00% (95% CI: 0.40, 3.50) increased risk of outpatient visits for chronic lower respiratory disease and cerebrovascular disease, respectively (Mueller et al. 2020). Although such studies examined the effect of BOB related air pollution on premature mortality, limited evidence on the effect of exposure to BOB occurrence, as well as exposure duration and intensity to BOB related air pollution on human health is available in Thailand to date. Therefore, this study aimed to investigate the effects of short-term exposure to BOB occurrence on cardiovascular and respiratory outpatient department (OPD) visits in Thailand. The risk of longer exposure duration and higher exposure intensity to BOB related air pollution on OPD visits was also examined.

2 Methods

Thailand consists of 77 administrative provinces. The total area of Thailand is approximately 500 km^2 with roughly 70 million populations in 2020. Thailand is divided into six regions according to the Thai Meteorological Department, including Northern, Northeastern, Central, Eastern, Southern East-Coast and Southern West-Coast (Fig. 1A). This study was conducted in 37 out of 77 provinces because of a limited air pollution and meteorological data (Fig. 1B).

2.1 Fire hotspot data

Fire hotspot data from the Fire Information for Resource Management System (FIRMS) distributes Near Real-Time (NRT) active fire data of satellite observations under the National Aeronautics and Space Administration (NASA) was used as the proxy of BOB in this study. In particular, fire hotspot data was acquired from the Visible Infrared Imaging Radiometer Suite (VIIRS) on board the Suomi National Polar-orbiting Partnership (Suomi NPP) satellite, where the Suomi NPP VIIRS instrument has the overpass local time (LT) at around 1:00–3:00 PM LT with spatial resolution of 375×375 m^2 (https://www.earthdata.nasa.gov/learn/find-data/near-real-time/firms/viirs-i-band-375-m-active-fire-data). Because of the quality of individual fire hotspot pixels is different depending upon the relative temperature anomaly and the potential sun glint contamination, this study considered only the nominal and high confidence fire hotspot pixels with vegetation burning point. The number of fire hotspot was then summed by date and province during January 2016 through December 2020 and BOB occurrence day was defined when fire hotspot was detected in that particular day regardless how many fire hotspot counts was observed. Specifically, a day with active fire hotspot occurrence was assigned as 1, otherwise 0.

2.2 Air pollution and meteorological data

Hourly air pollution (particulate matter with aerodynamic diameter less than or equal to 10 µm: PM_{10} ($\mu g/m^3$), nitrogen dioxide; NO_2 (ppb), and ozone; O_3 (ppb)) and meteorological data (temperature (°C) and relative humidity (%))

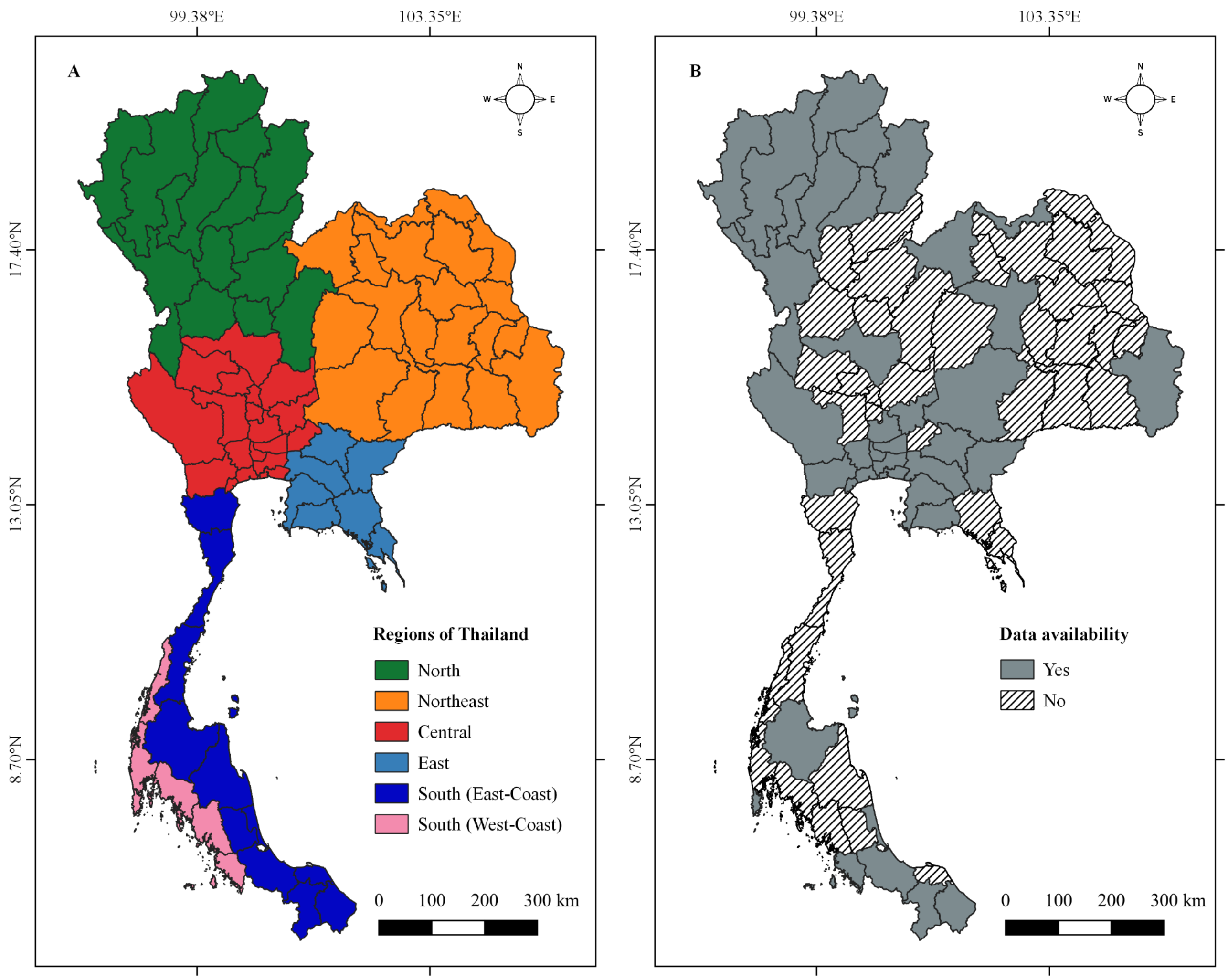

Fig. 1 Regions of Thailand (A) and provinces that are included for analysis in this study (B)

was obtained from air quality monitoring stations operated by Thailand Pollution Control Department (PCD) under the Ministry of Natural Resources and Environment during January 2016 through December 2020. Daily average concentration of individual air pollutants, temperature, and relative humidity was calculated by taking the average of hourly data within the same day, but the day that had missing data more than 6 h was considered as missing. The missing of individual air pollutants, temperature and relative humidity was then imputed using the expectation – maximization (EM) algorithm under the assumptions of a multivariate normal distribution (Junger and Ponce de Leon 2015). In case there are many monitoring stations situated in the same province, daily concentration of air pollutants, ambient temperature, and relative humidity from all available monitoring stations located in the same province were then averaged and utilized as a proxy for daily exposure.

2.3 Outpatient department (OPD) visits data

Daily number of OPD visits for cardiovascular and respiratory disease was obtained from the National Health Security Office (NHSO) during the same period as of fire hotspot, air pollution, and weather variables. The OPD visits data under the Universal Health Coverage (UHC) scheme was considered in this study with anonymously recorded by age, sex, date of OPD visits, and primary diagnostic code according to the International Classification of Diseases 10th revision (ICD-10), where I00-I99 has been coded for total cardiovascular disease and J00-J99 for total respiratory disease. This study was approved by the Ethics Review Board of the Mahidol University Faculty of Public Health as research with exemption category (Protocol No. 145/2564).

2.4 Statistical analysis

The time-stratified case-crossover design with conditional logistic regression was used to examine the province-specific association between BOB related air pollution and OPD visits for cardiovascular and respiratory diseases. In particular, this design generally takes into account comparison between case and control periods, where each case serves as his/her own control but in different periods of time (Maclure 1991). In this study, exposure to BOB related air pollution at the date of OPD visits (case day) was compared with that in the same day of the week within the same calendar month of the same year (control days). This design is therefore automatically controlled for day of the week, long-term trend and seasonality by design that assumed to be constant within the same stratum. To explore province-specific effect of BOB occurrence on OPD visits, the indicator variable for of fire hotspot occurrence was fitted in the conditional logistic regression model adjusting for temperature and relative humidity using the natural cubic spline function with three degrees of freedom at moving average lag 0–3 days for both temperature and relative humidity because previous studies purported that adjusting for temperature and relative humidity at lag 0–3 days did not confound the estimates of the association between air pollution and health outcome (Lin et al. 2013; Thongphunchung et al. 2021). The maximum adequate model was selected based on minimizing Bayesian Information Criterion (BIC) value, in which three degrees of freedom of the natural cubic splines function for both temperature and relative humidity provided the lowest BIC value that was then used as the best model fit in this study (Table S1). The following equation was used to investigate the association between BOB related air pollution and OPD visits for cardiovascular and respiratory diseases in this study.

$$logit\left(P_{y=1i}\right) = \alpha + \beta_i * BOB_{t,i} + ns\left(tmean_{t,i}, df = 3\right) + ns\left(humid_{t,i}, df = 3\right) + stratum_{t,i} \quad (1)$$

Where logit($P_{y=1i}$) is the natural logarithm of odds ratio comparing case and control days within the same stratum at province *i*; α is the model intercept; $BOB_{t,i}$ is the indicator variable of fire hotspot occurrence at day *t* and province *i* ; β_i is the coefficient of BOB occurrence associated with OPD visits at province *i*; *ns(●)* is the natural cubic splines function with three degrees of freedom; $tmean_{t,i}$ and $humid_{t,i}$ define daily mean temperature and relative humidity at day *t* and province *i*, respectively; $stratum_{t,i}$ defines the case and control day within the same stratum *t* at province *i*. The effect of BOB occurrence on OPD visits was examined until lag 7 days using unconstrained distributed lag model because the preliminary analysis indicated that the estimated effect was relatively constant after 7 days lag.

Moreover, to examine the province-specific effect of longer exposure duration to BOB on OPD visits, a dummy variable of two or more consecutive day of fire hotspot occurrence was fitted in the conditional logistic regression model controlling for temperature and relative humidity as shown in the following equation;

$$logit\left(P_{y=1i}\right) = \alpha + \beta_i * DUR_{t,i} + ns\left(tmean_{t,i}, df = 3\right) + ns\left(humid_{t,i}, df = 3\right) + stratum_{t,i} \quad (2)$$

Where $DUR_{t,i}$ indicates the dummy variable for the longer duration of exposure to BOB at day *t* and province *i*, defined by two or more consecutive days of fire hotspot occurrence. Specifically, a day with two or more consecutive days of active fire hotspot occurrence at particular province was assigned as 1, otherwise 0. This method was used to inspect whether or not exposure to BOB related air pollutant for more than one day is associated with higher estimated effect on OPD visits for cardiovascular and respiratory diseases than that up to one day.

The province-specific effect of higher exposure intensity to BOB on OPD visits for cardiovascular and respiratory disease was also investigated by fitting an indicator variable for higher exposure intensity to BOB, defined by daily average of province-specific PM_{10} concentration higher than the 1st quartile (a priori) on the day of fire hotspot occurrence, in the conditional logistic regression model controlling for temperature and relative humidity as shown in the following equation;

$$logit\left(P_{y=1i}\right) = \alpha + \beta_i * INT_{t,i} + ns\left(tmean_{t,i}, df = 3\right) + ns\left(humid_{t,i}, df = 3\right) + stratum_{t,i} \quad (3)$$

Where $INT_{t,i}$ represents an indicator variable of BOB intensity at day *t* and province *i*. In particular, a day of fire hotspot occurrence coincided with daily concentration of PM_{10} higher than 1st quartile was assigned as 1, otherwise 0.

The province-specific estimates of BOB on cardiovascular and respiratory OPD visits obtained from Eqs. (1), (2), and (3) were then pooled to derive the national estimate using the random-effect meta-analysis with restricted maximum likelihood (REML) estimation.

$$\beta'_i = \beta + \delta_i + \varepsilon_i \quad (4)$$

$$\beta'_i \sim N\left(\beta,\ \upsilon_i + \tau^2\right) \quad (5)$$

Where β'_i is the estimated risk of OPD visits for cardiovascular and respiratory disease associated with exposure to BOB related air pollution for province *i*; β is the pooled estimates of OPD visits associated with exposure to BOB that we would like to obtain; δ_i and ε_i indicate the within-province and between-province random errors, respectively. The δ_i and ε_i is assumed to be normally distributed, where υ_i

Table 1 Summary statistics for number of fire hotspot occurrence, daily concentration of air pollutants and meteorological variables across 37 provinces of Thailand from January 2016 to December 2020

Variables	Mean	SD	Min	P25	P50	P75	Max
Fire hotspot occurrence (days)	563	297	10	327	686	766	1119
PM_{10} (μg/m^3)	35.7	22.4	3.9	21.1	30.0	45.4	170.0
O_3 (ppb)	36.8	18.7	4.1	24.1	33.9	47.6	96.1
NO_2 (ppb)	9.8	6.2	0.4	6.0	8.8	12.5	50.8
Temperature (^{o}C)	27.0	7.7	18.0	26.6	27.9	29.2	34.2
Relative humidity (%)	71.6	22.7	39.8	65.1	72.1	78.7	96.5

Note: SD = Standard Deviation; Min = Minimum; P25 = 25th Percentile; P50 = 50th Percentile (Median); P75 = 75th Percentile; Max = Maximum.

is within-province variance and τ^2 indicates between-province variance.

The sensitivity analysis was also performed by changing degree of freedom of the natural cubic spline function for temperature and relative humidity that were used as confounding factors on the association between BOB and OPD visits. The quartile cut-off point for defining higher exposure intensity to BOB occurrence was also varied to explore the robustness of the effect estimates. The estimates of BOB occurrence and those of longer exposure duration and higher exposure intensity to BOB-related air pollution were also adjusted for other air pollutants by incorporating other air pollutants into the model one at a time. All analyses were performed using R packages for statistical computing (Version 4.1.0), where *"survival"* and *"splines"* packages were used to analyse province-specific effect of BOB on OPD visits, whereas the *"metafor"* package was used to perform the random-effect meta-analysis. The result was presented as odds ratio (ORs) with its 95% confidence interval (CI).

3 Results

The average number of fire hotspot occurrence over 37 provinces during the study period was 563 out of 1,827 days (Table 1), ranged from 10 days in Samut Songkhram to 1,119 days in Nakhon Sawan (Table S2). Daily average concentration ± standard deviation (SD) of PM_{10}, O_3, and NO_2 during the study period was 35.7 ± 22.4 μg/m^3, 36.8 ± 18.7 ppb, and 9.8 ± 6.2 ppb, respectively. Meanwhile, daily average temperature and relative humidity was 27.0 ± 7.7 ^{o}C and 71.6 ± 22.7%, respectively (Table 1). The spatial variations for fire hotspot and PM_{10} concentration during the study period are indicated in Fig. S1. The daily average PM_{10} concentration was significantly different between the day with and without burning occurrence (p-value < 0.001), where higher concentration was observed in the days with fire hotspot occurrence. Similarly, PM_{10} concentration was significantly different between 1-day exposure and longer exposure duration (p-value < 0.001). Moreover, PM_{10} concentration was higher in the days with high exposure intensity compared to that in the days with low intensity (p-value < 0.001) (Table S3). The total number of OPD visits for cardiovascular disease over 37 provinces during the study period was 50,302,593 cases (Table 2), ranged from 266,955 cases in Mae Hong Son to 4,683,507 cases in Bangkok, whereas that for respiratory disease was 46,845,417 cases with the minimum number of cases observed in Samut Songkhram (316,931 cases) and maximum number in Nakhon Ratchasima (4,092,245 cases). The prevalence rate of OPD visits for cardiovascular disease per 1000 populations during the study period was 1,324, ranged from 825 in Bangkok to 2,772 in Phrae, whereas those for respiratory disease was 1,233, ranged from 412 in Bangkok to 1,836 in Yala (Table S4). There was an average of 399 days that were assigned as longer exposure duration (a day with two or more consecutive days of active fire hotspot occurrence) during the study period. The daily average PM_{10} concentration for the days with longer exposure duration was 64.02 μg/m^3 and daily mean number of OPD visits for cardiovascular and respiratory diseases was 883 and 769 cases, respectively (Table S5). During the study period, 435 days were assigned as higher exposure intensity with daily average PM_{10} concentration of 60.87 μg/ m^3 and daily mean number of OPD visits for cardiovascular and respiratory diseases of 889 and 739 cases, respectively (Table S6).

Table 2 Total number of OPD visits for cardiovascular and respiratory diseases throughout 37 provinces of Thailand from January 2016 to December 2020

OPD visits	Total	Min	Max
Cardiovascular disease (I00-I99)	50,302,593	266,955	4,683,507
Respiratory disease (J00-J99)	46,845,417	316,931	4,092,245

The association between BOB occurrence and OPD visits for cardiovascular and respiratory disease at different lag structures is shown in Fig. 2. The effect of BOB occurrence on cardiovascular OPD visits at national level was the highest at lag 5 days. In particular, the ORs of cardiovascular OPD visits associated with BOB occurrence day was 1.0105 (95% CI: 0.9971, 1.0240), compared to non-BOB occurrence day. The significant heterogeneity of the effect estimate among provinces was found with I^2 of 99.3% and

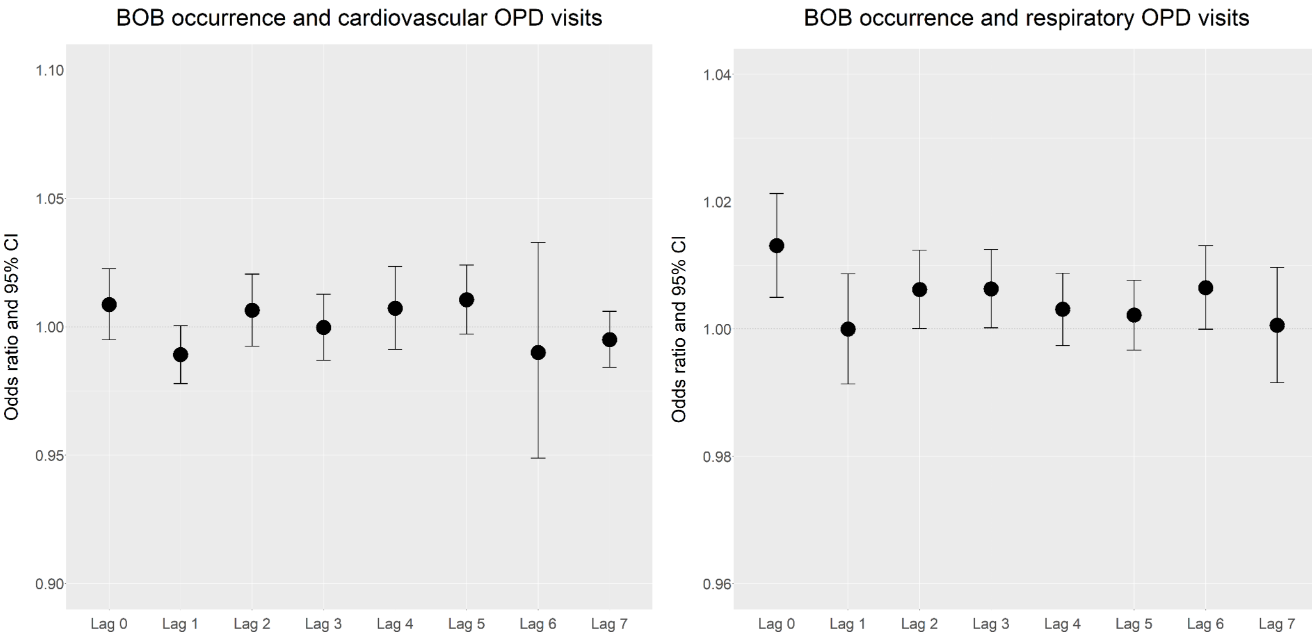

Fig. 2 ORs (95% CI) of OPD visits for cardiovascular and respiratory disease associated with BOB occurrence at different lag structures

Table 3 The pooled estimate of longer exposure duration and higher exposure intensity to BOB on OPD visits for cardiovascular and respiratory disease over 37 provinces in Thailand

Exposure to BOB	Odds Ratio and 95% CI	
	Cardiovascular OPD visits	Respiratory OPD visits
Longer duration	1.0272 (95% CI: 1.0104, 1.0442)	1.0275 (95% CI: 1.0139, 1.0413)
Higher intensity	0.9828 (95% CI: 0.9641, 1.0018)	0.9936 (95% CI: 0.9831, 1.0049)

Note: Longer duration is defined as a day with two or more consecutive days of active fire hotspot occurrence, and higher intensity is a day of fire hotspot occurrence coincided with daily concentration of PM_{10} higher than 1st quartile.

p-value from Cochran's Q test < 0.001. Moreover, the highest estimate of BOB occurrence on respiratory OPD visits was observed at current day lag (lag 0), where ORs of respiratory OPD visits associated with BOB occurrence was 1.0131 (95% CI: 1.0050, 1.0213). The significant difference on the effect estimates among provinces was also observed with I^2 of 97.6% and p-value from Cochran's Q test < 0.001. The province-specific ORs of OPD visits for cardiovascular and respiratory disease associated with BOB occurrence at different lag structures is shown in Table S7.

Table 3 presents the pooled estimate of exposure duration and intensity to BOB on OPD visits for cardiovascular and respiratory disease in Thailand. Specifically, exposure to longer duration of BOB (two or more consecutive day of BOB occurrence) was significantly associated with increased risk of OPD visits for cardiovascular disease with ORs of 1.0272 (95% CI: 1.0104, 1.0442) ($I^2 = 99.4\%$ and p-value from Cochran's Q test < 0.001) and respiratory diseases with ORs of 1.0275 (95% CI: 1.0139, 1.0413) ($I^2 = 99.0\%$ and p-value from Cochran's Q test < 0.001). Nevertheless, we did not observe the significant effect of higher exposure intensity to BOB (daily average PM_{10} concentration higher than 1st quartile on fire hotspot occurrence day) on OPD visits, where ORs of OPD visits for cardiovascular and respiratory diseases associated with exposure to higher intensity of BOB was 0.9828 (95% CI: 0.9641, 1.0018) ($I^2 = 99.4\%$ and p-value from Cochran's Q test < 0.001) and 0.9936 (95% CI: 0.9831, 1.0049) ($I^2 = 97.8\%$ and p-value from Cochran's Q test < 0.001), respectively. The province-specific effects of longer exposure duration and higher exposure intensity to BOB related air pollution on OPD visits for cardiovascular and respiratory diseases are shown in Tables S8 and S9, respectively.

The results of sensitivity analysis revealed that the effects of exposure to BOB, as well as its longer duration and higher intensity, on OPD visits for cardiovascular and respiratory diseases were not different even when degrees of freedom of the natural cubic splines function for daily temperature and relative humidity was varied (Fig. 3 and Table S10). Furthermore, when we changed the definition of higher exposure intensity, the effect estimate of higher exposure intensity to BOB on cardiovascular and respiratory OPD visits was relatively robust (Table 4). The estimate of BOB occurrence, longer exposure duration, and higher exposure intensity on OPD visits for cardiovascular and respiratory

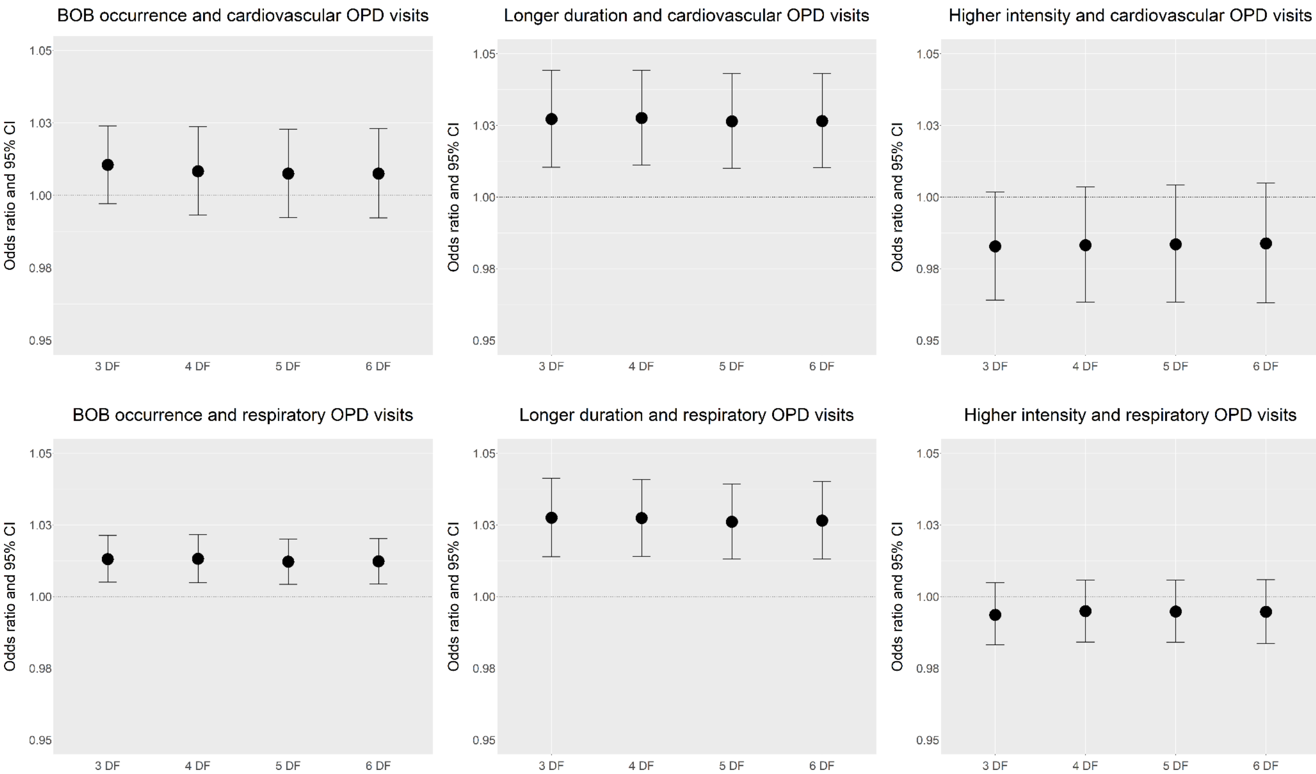

Fig. 3 ORs (95% CI) of OPD visits for cardiovascular and respiratory diseases associated with BOB occurrence, longer exposure duration, and higher exposure intensity to BOB adjusted for temperature and relative humidity using various degrees of freedom of the natural cubic splines function

Table 4 ORs (95% CI) of OPD visits for cardiovascular and respiratory diseases associated with higher exposure intensity to BOB using different definitions of higher exposure intensity throughout 37 provinces in Thailand

Definitions	Cardiovascular OPD visits	Respiratory OPD visits
> 1st quartile of PM_{10}	0.9828 (95% CI: 0.9641, 1.0018)	0.9936 (95% CI: 0.9831, 1.0049)
> 2nd quartile of PM_{10}	0.9984 (95% CI: 0.9733, 1.0242)	0.9986 (95% CI: 0.9854, 1.0120)
> 3rd quartile of PM_{10}	0.9844 (95% CI: 0.9523, 1.0176)	0.9982 (95% CI: 0.9804, 1.0164)

Note: > 1st quartile of PM_{10}, > 2nd quartile of PM_{10}, and > 3rd quartile of PM_{10} define a day of fire hotspot occurrence with daily concentration of PM_{10} higher than 1st, 2nd, and 3rd quartile, respectively.

disease was robust even after adjusting for other air pollutants (Table S11).

4 Discussion

In this study, we investigated the effect of short-term exposure to BOB occurrence using fire hotspot as indicator, as well as that of longer exposure duration and higher exposure intensity to BOB on OPD visits for cardiovascular and respiratory diseases in Thailand during the period spanning from January 2016 to December 2020. The results indicate that BOB occurrence day was associated with higher risk of cardiovascular and respiratory OPD visits compared to non-BOB occurrence day. The negative effect of exposure to BOB on cardiovascular OPD visits was found at lag 1 (Fig. 2). This finding may be due in part to the harvesting effect, where the susceptible persons may visit the OPD due to cardiovascular disease at earlier time after exposure, leading to a fewer number of OPD visits at later lag (Schwartz 2001; Zanobetti et al. 2002). Longer exposure duration to BOB was also associated with increased risk of cardiovascular and respiratory OPD visits. Higher exposure intensity was not significantly associated with OPD visits for both cardiovascular and respiratory diseases. The effect estimates were robust even when changing degrees of freedom of the natural cubic spline function for adjusting temperature and relative humidity and varying the definition of higher exposure intensity, as well as after adjusting for other air pollutants.

The estimated risk of cardiovascular and respiratory OPD visits associated with BOB occurrence was 1.0105 (95% CI: 0.9971, 1.0240) and 1.0131 (95% CI: 1.0050, 1.0213) times higher than non-BOB occurrence. This finding is similar to the result observed in previous studies in the upper Northern of Thailand, indicating that every 10 μg/m^3 increase of PM_{10} on biomass burning day was associated with increased risk of OPD visits for respiratory diseases (Mueller et al. 2020; Uttajug et al. 2021). We also observed that the occurrence of BOB was significantly associated with respiratory OPD visits, but was not significantly associated with cardiovascular OPD visits, which is in agreement with previous studies (Johnston et al. 2014; Karanasiou et al. 2021; Martin et al. 2013). This finding might be speculated that there is no truly association between BOB occurrence and cardiovascular OPD visits or it could reflect the heterogeneity of the effect estimates among provinces. Nevertheless, the plausible mechanism underlying the effect of BOB occurrence on cardiovascular diseases has been suggested. In particular, exposure to smoke particles is likely to influence systemic inflammation, blood coagulation, and lipid peroxidation that are the cardiovascular risk factors (Barregard et al. 2006; Chen et al. 2021). Moreover, higher risk of hospital admission for cardiovascular disease has been associated with wildfire events where BOB-related $PM_{2.5}$ is largely generated (Requia et al. 2021). Finding of this study also reveals that BOB occurrence was associated with a sudden increase in OPD visits for respiratory disease and with a lagged increase in OPD visits for cardiovascular disease. Support of this result comes from a prior study suggesting that people with chronic respiratory conditions is susceptible to the exacerbation by exposure to air pollution, leading to an increase of respiratory morbidity (Jiang et al. 2016). However, the onset of cardiovascular disease requires lagged time after exposure (Peters et al. 2001). In order to reduce the effect of BOB related air pollution, specific actions are therefore required to reduce exposure or to reduce the emission of air pollution from BOB.

We observed the significantly high heterogeneity among the province-specific estimates, showing that the association between BOB related air pollutant and OPD visits for cardiovascular and respiratory diseases highly varies among provinces. There is no clear evidence explaining the heterogeneity of the association between BOB related air pollutant and cardiovascular and respiratory diseases that is similarly observed in this study, but this high heterogeneity might be partly explained by the variation in geographical locations, as well as demographical and socioeconomic characteristics (Jones et al. 2020; Karanasiou et al. 2021) that require further investigations.

Longer exposure duration to BOB was significantly associated with increased risk of OPD visits for cardiovascular and respiratory diseases. Specifically, exposure to BOB occurrence for two or more consecutive day was associated with 1.0272 (95% CI: 1.0104, 1.0442) and 1.0275 (95% CI: 1.0139, 1.0413) times higher risk of cardiovascular and respiratory OPD visits than shorter exposure duration, respectively. These findings have been supported by the concept of the continuous exposure to high concentrations of particulate matter reporting that higher exposure to wildfire-related particulate matter was associated with increased burden of all-cause, cardiovascular, and respiratory hospital admission (Requia et al. 2021; Ye et al. 2021). Specifically, exposure to biomass smoke activates the production of many pro-inflammatory mediators such as interleukin-6 (IL-6), interleukin-8 (IL-8), tumor necrosis factor alpha (TNF-α), thereby causing intracellular damage through the production of reactive oxygen species (ROS) and the reduction of antioxidant mechanisms. This would induce chronic obstructive pulmonary disease and increase burden of respiratory morbidity (De Oliveira Alves et al. 2017; Dutta et al. 2013; Silva et al. 2015). Moreover, higher exposure to smoke particles can affect cardiovascular system through inhalation pathway, where inhaled particle may penetrate into the circulatory system via the air-blood barrier (Wu et al. 2018), leading to oxidative stress, activation of autonomic reflex, and systemic inflammation (Chen et al. 2021). Avoiding longer exposure to BOB related air pollution that last for many days might be difficult because of daily activities, but finding of this study can be useful for establishing the warning system of BOB-related air pollution in Thailand taken into account exposure duration to prevent harmful health effect of BOB-related air pollution since there was no official BOB warning system in Thailand to date.

We observed the negative association between higher exposure intensity to BOB and OPD visits for cardiovascular and respiratory disease, although there was statistically insignificant. This might be due in part to the effectiveness of protective practices in which people may spend less time outdoor during high concentration of particulate matter emitted by biomass burning in order to avoid exposure (De Pretto et al. 2015). Moreover, people may wear face masks in outdoor activities or use air purifier indoor when severe haze concentration has been reported upon checking the relevant air quality index (AQI) on daily basis (Majumder et al. 2019; Sereenonchai et al. 2020). However, this negative association may also be observed by chance.

Several limitations of this study are acknowledged. First, we applied fire hotspot data from the Suomi NPP VIIRS instrument as indicator for the occurrence of BOB-related air pollution, which might not accurately represent the emission of air pollution from BOB because satellite observation sometimes cannot detect fire emission even when substantial amount of grounded-levels particles was emitted by BOB (Johnston et al. 2018). In case of few points of fire hotspot included, it may not significantly increase the concentration of air pollutants on that particular day which means that the main contributor may be originated from other sources such as vehicle exhaust, particularly in the urban areas. This can lead to exposure misclassification. In addition, air pollution from BOB might be affected by burning events from surrounding countries (transboundary haze), in which air pollution from BOB might not be captured as no occurrence of fire hotspot in this study area was detected. However, we observed that concentration of PM_{10}, one of the major air pollutants emitted from BOB (Chen et al. 2017; Junpen et al. 2018), in the day with BOB occurrence was significantly higher than that in the day with non-BOB occurrence (p-value < 0.001) (Fig. S2). Hence, using fire hotspot data as a proxy for BOB occurrence in this study is reasonable, to some extent. Second, fire hotspot data was obtained from the satellite database, as well as air pollution and meteorological data was obtained from the air quality monitoring stations that is not well representing personal exposure. This could result in non-differential misclassification that biases the effect estimate towards the null hypothesis (Copeland et al. 1977). Therefore, findings from this study are unlikely due to false positive. Third, we did not quantify the concentration of air pollution that is specifically emitted by BOB. Nevertheless, we characterized higher intensity of BOB according to fire hotspot occurrence and PM_{10} concentration that is well correlated (Fig. S2), indicating that higher PM_{10} concentration may be contributed from BOB occurrence. Moreover, we explored the effects of longer exposure duration to BOB related air pollutant on OPD visits by defining two or more consecutive days of active fire hotspot occurrence as indicator for longer exposure duration. This result is only reflected that the effects of two or more consecutive days of exposure have the same effect on OPD visits. Fourth, we did not take into account the effect of BOB occurrence on OPD visits in different population groups, such as age, sex, or other socioeconomic characteristics. Therefore, findings of this study could not determine which groups of population are more susceptible to the effects of BOB that may need to consider in the future study.

Several strengths of this study are also noted. First, it is the first multi-provinces study across Thailand determined the effect of BOB occurrence and health outcomes taken into account longer exposure duration and higher exposure intensity. Therefore, findings of this study could provide an insight into understanding the possible health effects of BOB occurrence over the whole Thailand. Second, we estimated the association between BOB occurrence and OPD visits using both PM_{10} concentration data from air quality monitoring stations and fire hotspot data from satellite observations that might be more accurate reflecting exposure to BOB-related air pollution compared to previous studies that used only PM_{10} concentration to categorize burning event (Martin et al. 2013; Mueller et al. 2020; Sahani et al. 2014). Third, the study design used in this study inherently controls for day of the week, long-term trend and seasonality, and personal characteristics because each case was served as their own controls. Moreover, we comprehensively controlled for air pollution and meteorological variables that may influence the occurrence of BOB-related air pollution and number of OPD visits for cardiovascular and respiratory disease. Therefore, results of this study are reliable, to some extent.

5 Conclusions

Exposure to BOB occurrence was associated with an immediate effect on respiratory OPD visits and a lagged effect on cardiovascular OPD visits. We also observed that longer exposure duration to BOB was significantly associated with higher risk of OPD visits for cardiovascular and respiratory diseases. However, we found that higher exposure intensity to BOB-related air pollution was associated with lower risk of OPD visits, although it is not statistically significant. Finding from this study can be used to improve or establish the warning systems to reduce cardiovascular and respiratory risk associated with exposure to BOB-related air pollution and longer exposure duration. Further study may also require quantifying the compositions of BOB-related air pollution so as to gain insight into understanding the toxicological effects of BOB occurrence in Thailand.

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Author contributions MR and AP conceived and designed the study. MR analyzed the data along with interpreting the result and drafted the manuscript. AP contributed to data collection and provided feedback on study findings. TS and TN contributed substantially to discussion and approved the final version of manuscript.

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Data Availability The data generated in this study are available in supplementary files and from the corresponding author on reasonable request.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

Ethical approval This study has been approved by the Ethics Review Board of the Mahidol University Faculty of Public Health as research with exemption category (Protocol No. 145/2564).

Consent to participate Not applicable.

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References

Atkinson RW, Kang S, Anderson HR, Mills IC, Walton HA (2014) Epidemiological time series studies of PM2.5 and daily mortality and hospital admissions: a systematic review and meta-analysis. Thorax 69(7):660–665. https://doi.org/10.1136/thoraxjnl-2013-204492

Autrup H (2010) Ambient air pollution and adverse health effects. Procedia Soc Behav Sci 2(5):7333–7338. https://doi.org/10.1016/j.sbspro.2010.05.089

Barregard L, Sällsten G, Gustafson P, Andersson L, Johansson L, Basu S, Stigendal L (2006) Experimental exposure to wood-smoke particles in healthy humans: Effects on markers of inflammation, coagulation, and lipid peroxidation. Inhal Toxicol 18(11):845–853. https://doi.org/10.1080/08958370600685798

Boonman T, Garivait S, Bonnet S, Junpen A (2014) An inventory of air pollutant emissions from biomass open burning in Thailand using MODIS burned area product (MCD45A1).J Sustain Energy Environ5

Chen H, Samet JM, Bromberg PA, Tong H (2021) Cardiovascular health impacts of wildfire smoke exposure. Part Fibre Toxicol 18(1):1–22. https://doi.org/10.1186/s12989-020-00394-8

Chen J, Li C, Ristovski Z, Milic A, Gu Y, Islam MS, Wang S, Hao J, Zhang H, He C, Guo H, Fu H, Miljevic B, Morawska L, Thai P, Fat LAMY, Pereira G, Ding A, Huang X, Dumka UC (2017) A review of biomass burning: emissions and impacts on air quality, health and climate in China. Sci Total Environ 579:1000–1034. https://doi.org/10.1016/j.scitotenv.2016.11.025

Chuersuwan N, Nimrat S, Lekphet S, Kerdkumrai T (2008) Levels and major sources of PM2.5 and PM10 in Bangkok Metropolitan Region. Environ Int 34(5):671–677. https://doi.org/10.1016/j.envint.2007.12.018

Copeland KT, Checkoway H, McMichael AJ, Holbrook RH (1977) Bias due to misclassification in the estimation of relative risk. Am J Epidemiol 105(5):488–495

De Oliveira Alves N, Vessoni AT, Quinet A, Fortunato RS, Kajitani GS, Peixoto MS, de Souza Hacon S, Artaxo P, Saldiva P, Menck CF, de Medeiros SRB (2017) Biomass burning in the Amazon region causes DNA damage and cell death in human lung cells. Sci Rep 7(1):1–13. https://doi.org/10.1038/s41598-017-11024-3

De Pretto L, Acreman S, Ashfold MJ, Mohankumar SK, Campos-Arceiz A (2015) The link between knowledge, attitudes and practices in relation to atmospheric haze pollution in peninsular Malaysia. PLoS ONE 10(12):1–18. https://doi.org/10.1371/journal.pone.0143655

Dutta A, Roychoudhury S, Chowdhury S, Ray MR (2013) Changes in sputum cytology, airway inflammation and oxidative stress due to chronic inhalation of biomass smoke during cooking in premenopausal rural indian women. Int J Hyg Environ Health 216(3):301–308. https://doi.org/10.1016/j.ijheh.2012.05.005

Jiang XQ, Mei XD, Feng D (2016) Air pollution and chronic airway diseases: what should people know and do? J Thorac Dis 8(1):E31–E40. https://doi.org/10.3978/j.issn.2072-1439.2015.11.50

Johnston FH, Purdie S, Jalaludin B, Martin KL, Henderson SB, Morgan GG (2014) Air pollution events from forest fires and emergency department attendances in Sydney, Australia 1996–2007: a case-crossover analysis. Environ Health 13(1):1–9. https://doi.org/10.1186/1476-069X-13-105

Johnston JM, Johnston LM, Wooster MJ, Brookes A, McFayden C, Cantin AS (2018) Satellite detection limitations of sub-canopy smouldering wildfires in the north american boreal forest. Fire 1(2):1–16. https://doi.org/10.3390/fire1020028

Jones CG, Rappold AG, Vargo J, Cascio WE, Kharrazi M, McNally B, Hoshiko S (2020) Out-of-hospital cardiac arrests and wildfire-related particulate matter during 2015–2017 California wildfires. J Am Heart Assoc 9:e014125. https://doi.org/10.1161/JAHA.119.014125

Junger WL, Ponce de Leon A (2015) Imputation of missing data in time series for air pollutants. Atmos Environ 102:96–104. https://doi.org/10.1016/j.atmosenv.2014.11.049

Junpen A, Pansuk J, Kamnoet O, Cheewaphongphan P, Garivait S (2018) Emission of air pollutants from rice residue open burning in Thailand, 2018. Atmosphere 9(11). https://doi.org/10.3390/atmos9110449

Lin H, Zhang Y, Xu Y, Xu X, Liu T, Luo Y, Xiao J, Wu W, Ma W (2013) Temperature changes between neighboring days and mortality in summer: a distributed lag non-linear time series analysis. PLoS ONE 8(6):e66403. https://doi.org/10.1371/journal.pone.0066403

Karanasiou A, Alastuey A, Amato F, Renzi M, Stafoggia M, Tobias A, Reche C, Forastiere F, Gumy S, Mudu P, Querol X (2021) Short-term health effects from outdoor exposure to biomass burning emissions: a review. Sci Total Environ 781:146739. https://doi.org/10.1016/j.scitotenv.2021.146739

Klemm RJ, Lipfert FW, Wyzga RE, Gust C (2004) Daily mortality and air pollution in Atlanta: two years of data from ARIES. Inhal Toxicol 16:131–141. https://doi.org/10.1080/08958370490443213

Kumar I, Bandaru V, Yampracha S, Sun L, Fungtammasan B (2020) Limiting rice and sugarcane residue burning in Thailand: current status, challenges and strategies. J Environ Manage 276:111228. https://doi.org/10.1016/j.jenvman.2020.111228

Maclure M (1991) The case-crossover design: a method for studying transient effects on the risk of acute events. Am J Epidemiol 133(2):144–153

Majumder S, Sihabut T, Saroar MG (2019) Assessment of knowledge, attitude and practices against inhaled particulate matter among urban residents in Dhaka, Bangladesh. J Health Res 33(6):460–468. https://doi.org/10.1108/JHR-12-2018-0168

Martin KL, Hanigan IC, Morgan GG, Henderson SB, Johnston FH (2013) Air pollution from bushfires and their association with hospital admissions in Sydney, Newcastle and Wollongong, Australia 1994–2007. Aust N Z J Public Health 37(3):238–243. https://doi.org/10.1111/1753-6405.12065

Mueller W, Loh M, Vardoulakis S, Johnston HJ, Steinle S, Precha N, Kliengchuay W, Tantrakarnapa K, Cherrie JW (2020) Ambient particulate matter and biomass burning: an ecological time series study of respiratory and cardiovascular hospital visits in northern Thailand. Environ Health 19(1):1–12. https://doi.org/10.1186/s12940-020-00629-3

Narita D, Kim Oanh NT, Sato K, Huo M, Permadi DA, Chi NNH, Ratanajaratroj T, Pawarmart I (2019) Pollution characteristics and policy actions on fine particulate matter in a growing asian economy: the case of Bangkok Metropolitan Region. Atmosphere 10(5):1–18. https://doi.org/10.3390/atmos10050227

Ostro B, Broadwin R, Green S, Feng WY, Lipsett M (2006) Fine particulate air pollution and mortality in nine California counties: results from CALFINE. Environ Health Perspect 114(1):29–33. https://doi.org/10.1289/ehp.8335

Pengchai P, Chantara S, Sopajaree K, Wangkarn S, Tengcharoenkul U, Rayanakorn M (2009) Seasonal variation, risk assessment and source estimation of PM10 and PM10-bound PAHs in the ambient air of Chiang Mai and Lamphun, Thailand. Environ Monit Assess 154(1–4):197–218. https://doi.org/10.1007/s10661-008-0389-0

Peters A, Dockery DW, Muller JE, Mittleman MA (2001) Increased particulate air pollution and the triggering of myocardial infarction. Circulation 103(23):2810–2815. https://doi.org/10.1161/01.CIR.103.23.2810

Phairuang W, Inerb M, Furuuchi M, Hata M, Tekasakul S, Tekasakul P (2020) Size-fractionated carbonaceous aerosols down to PM0.1 in southern Thailand: local and long-range transport effects. Environ Pollut 260:114031. https://doi.org/10.1016/j.envpol.2020.114031

Phosri A, Ueda K, Phung VLH, Tawatsupa B, Honda A, Takano H (2019) Effects of ambient air pollution on daily hospital admissions for respiratory and cardiovascular diseases in Bangkok, Thailand. Sci Total Environ 651:1144–1153. https://doi.org/10.1016/j.scitotenv.2018.09.183

Requia WJ, Amini H, Mukherjee R, Gold DR, Schwartz JD (2021) Health impacts of wildfire-related air pollution in Brazil: a nationwide study of more than 2 million hospital admissions between 2008 and 2018. Nat Commun 12(1):1–9. https://doi.org/10.1038/s41467-021-26822-7

Sahani M, Zainon NA, Wan Mahiyuddin WR, Latif MT, Hod R, Khan MF, Tahir NM, Chan CC (2014) A case-crossover analysis of forest fire haze events and mortality in Malaysia. Atmos Environ 96:257–265. https://doi.org/10.1016/j.atmosenv.2014.07.043

Sarigiannis DA, Karakitsios SP, Kermenidou MV (2015) Health impact and monetary cost of exposure to particulate matter emitted from biomass burning in large cities. Sci Total Environ 524–525:319–330. https://doi.org/10.1016/j.scitotenv.2015.02.108

Schwartz J (2001) Is there harvesting in the association of airborne particles with daily deaths and hospital admissions? Epidemiol 12(1): 55–61. https://doi.org/10.1097/00001648-200101000-00010

Sereenonchai S, Arunrat N, Kamnoonwatana D (2020) Risk perception on haze pollution and willingness to pay for self-protection and haze management in Chiang Mai Province, Northern Thailand. Atmosphere 11(6). https://doi.org/10.3390/atmos11060600

Silva R, Oyarzún M, Olloquequi J (2015) Pathogenic mechanisms in chronic obstructive pulmonary disease due to biomass smoke exposure. Arch Bronconeumol 51(6):285–292. https://doi.org/10.1016/j.arbr.2015.04.013

Thongphunchung K, Phosri A, Sihabut T, Patthanaissaranukool W (2021) Short–term effects of particulate matter on outpatient department visits for respiratory diseases among children in Bangkok Metropolitan Region: a case–crossover study. Air Qual Atmos Health 14:1785–1795. https://doi.org/10.1007/s11869-021-01053-3

Uttajug A, Ueda K, Oyoshi K, Honda A, Takano H (2021) Association between PM10 from vegetation fire events and hospital visits by children in upper northern Thailand. Sci Total Environ 764:142923. https://doi.org/10.1016/j.scitotenv.2020.142923

Vichit-Vadakan N, Vajanapoom N (2011) Health impact from air pollution in Thailand: current and future challenges. Environmen Health Perspect 119(5):196–198. https://doi.org/10.1289/ehp.1103728

WHO (2016) Ambient air pollution: A global assessment of exposure and burden of disease. Geneva, Switzerland. Retrieved from https://www.who.int/teams/environment-climate-change-and-health/air-quality-and-health/ambient-air-pollution

Wu W, Jin Y, Carlsten C (2018) Inflammatory health effects of indoor and outdoor particulate matter. J Allergy Clin Immunol 141(3):833–844. https://doi.org/10.1016/j.jaci.2017.12.981

Ye T, Guo Y, Chen G, Yue X, Xu R, Coêlho MDSZS, Saldiva PHN, Zhao Q, Li S (2021) Risk and burden of hospital admissions associated with wildfire-related PM2.5 in Brazil, 2000-15: a nationwide time-series study. Lancet Planet Health 5(9):e599–e607. https://doi.org/10.1016/S2542-5196(21)00173-X

Yin S, Wang X, Zhang X, Guo M, Miura M, Xiao Y (2019) Influence of biomass burning on local air pollution in mainland Southeast Asia from 2001 to 2016. Environ Pollut 254:112949. https://doi.org/10.1016/j.envpol.2019.07.117

Zanobetti A, Schwartz J, Samoli E, Gryparis A, Touloumi G, Atkinson R, Le Tertre A, Bobros J, Celko M, Goren A, Forsberg B, Michelozzi P, Rabczenko D, Aranguez Ruiz E, Katsouyanni K (2002) The temporal pattern of mortality responses to air pollution: a multicity assessment of mortality displacement. Epidemiol 13(1):87–93. https://doi.org/10.1097/00001648-200201000-00014