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Risk of acute respiratory infection from crop burning in India: estimating disease burden and economic welfare from satellite and national health survey data for 250 000 persons

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Abstract

Background: Respiratory infections are among the leading causes of death and disability globally. Respirable aerosol particles released by agricultural crop-residue burning (ACRB), practised by farmers in all global regions, are potentially harmful to human health. Our objective was to estimate the health and economic costs of ACRB in northern India.

Methods: The primary outcome was acute respiratory infection (ARI) from India's fourth District Level Health Survey (DLHS-4). DLHS-4 data were merged with Moderate-Resolution Imaging Spectroradiometer satellite data on fire occurrence. Mutually adjusted generalized linear models were used to generate risk ratios for risk factors of ARI. Overall disease burden due to ACRB was estimated in terms of disability-adjusted life years.

Results: Seeking medical treatment for ARI in the previous 2 weeks was reported by 5050 (2%) of 252 539 persons. Living in a district with intense ACRB—the top quintile of fires per day—was associated with a 3-fold higher risk of ARI (mutually adjusted risk ratio 2.99, 95% confidence interval 2.77 to 3.23) after adjustment for socio-demographic and household factors. Children under 5 years of age were particularly susceptible (3.65, 3.06 to 4.34 in this subgroup). Additional ARI risk factors included motor-vehicle congestion (1.96, 1.72 to 2.23), open drainage (1.91, 1.73 to 2.11), cooking with biomass (1.73, 1.58 to 1.90) and living in urban areas (1.35, 1.26 to 1.44). Eliminating ACRB would avert 14.9 million disability-adjusted life years lost per year, valued at US$152.9 billion over 5 years.

Conclusions: Investments to stop crop burning and offer farmers alternative crop-residue disposal solutions are likely to improve population-level respiratory health and yield major economic returns.

Key words: Respiratory health, agriculture, disease burden, India, air pollution

Key Messages

- Burning of agricultural crop residue to clear fields is a major contributor to air pollution. When rice farmers in north-western India burn their fields, fine particulate matter ($PM_{2.5}$) concentrations in Delhi, the highly populated capital city located downwind of burning areas, spike to about 20 times beyond the World Health Organization's threshold for safe air.
- Our results suggest that living in areas where crop burning is intense—measured using daily satellite imaging data over a 5-month period—is associated with a 3-fold higher risk of acute respiratory infection—one of the leading global causes of lost disability-adjusted life years. Children are particularly susceptible to the health effects of crop burning.
- Solutions to eliminate crop burning exist but require further investments. We found that crop-burning abatement would be highly cost-effective and, in northern India, would avert disability-adjusted life years equivalent to US$152.9 billion over a 5-year period.
- Reducing crop burning would benefit human health.

Introduction

Respiratory infections are the most common chronic disease of children globally, are a leading cause of death in developing countries and make a large contribution to the overall burden of disease as measured by disability-adjusted life years (DALYs) lost.[1,2] Air pollution is a recognized contributor to respiratory disease, as airborne fine particulate matter ($PM_{2.5}$) from the burning of solid fuels, vehicle exhaust, windblown soil, construction and other sources can penetrate deep into lung tissue, triggering an inflammatory cascade and oxidative stress.[3] $PM_{2.5}$ exposure has been linked to increased asthma-related emergency-room visits and hospitalizations,[3] progression of carotid intima-medial thickness,[4] greater chronic obstructive pulmonary disease mortality[5] and reduced life expectancy.[4] In India in 2015, exposure to outdoor air pollution was found to be the third leading risk factor (after high blood pressure and high fasting plasma glucose) contributing to mortality among 79 behavioural, environmental and metabolic factors.[6] A recent study found that 12.5% of the total deaths in India in 2017 were attributable to air pollution.[7] Delhi was the state with the highest annual population-weighted mean $PM_{2.5}$, followed by Uttar Pradesh, Bihar and Haryana in north India. Whereas indoor air pollution due to burning of solid fuels in poor states like Uttar Pradesh and Bihar were important factors, the ambient particulate-matter pollution was highest in the north Indian states of Uttar Pradesh, Haryana, Delhi, Punjab and Rajasthan.[7]

Delhi, India's large capital city and home to 25 million residents, is experiencing a public-health emergency due to high levels of air pollution. Delhi was the most polluted large city in the world in 2016, with an average annual $PM_{2.5}$ of 122 μgm^{-3} (micrograms per cubic meter)—12 times the World Health Organization (WHO)'s recommended target of 10 μgm^{-3}.[8] Air pollution in Delhi is particularly extreme during the winter months—a period when farmers in the neighbouring upwind states of Haryana and Punjab—where the burden of outdoor air pollution is also high[9]—practise agricultural crop-residue burning (ACRB).

Banned in November 2015 by the National Green Tribunal,[10] ACRB is still widely practised due to weak enforcement of the ban, political economy issues and lack of alternatives to burning among poor farmers.[11] In Punjab alone, an estimated 44–51 million metric tonnes of residue are burned each year, with rice being the primary source.[12] Winds carry suspended particles hundreds of miles, generating a thick cloud of smog above northern India visible by satellite. Recently, the contribution of ACRB in north-western India to air pollution in Delhi has been quantified, with estimates ranging between 7 and 78% of $PM_{2.5}$ enhancements during the burning season being attributable to ACRB.[13] Moreover, previous work has shown that ACRB results in an unrecoverable decrease in pulmonary function among children aged 10–13 years.[14] Among different sources of outdoor air pollution, ACRB was responsible for an estimated 66 200 deaths in 2015 in India.[6] In addition to affecting human health, ACRB deteriorates soil fertility, releases greenhouse gases that contribute to global warming and results in the loss of biodiversity.[11]

The Indian government has demonstrated an interest in combatting air pollution and respiratory illness but so far has fallen short in addressing the air-quality crisis. India was the first country to develop national targets aimed at reducing deaths from non-communicable diseases (NCDs) including respiratory illness, by 2025, following the WHO's Global Action Plan for the Prevention and Control of NCDs 2013–2020.[15] However, a major barrier to further political action against crop burning is the lack of rigorous evidence linking this practice to health outcomes. To our knowledge, there are no available estimates of the economic costs and societal disease burden associated with crop burning. Therefore, we sought to estimate the risk of acute respiratory infection (ARI) attributable to crop burning, among other socio-demographic and household factors, and to quantify the costs to society of this practice.

Methods

Outcome variable

Data on ARI were obtained from the fourth round of India's District Level Household Survey (DLHS-4)[16]—a national demographic health survey sampled to be representative at district and state levels. Data were used from households in three Indian states—Haryana (in northern India), Andhra Pradesh and Tamil Nadu (both in southern India)—interviewed between September 2013 and February 2014, the two southern states serving as comparators without ACRB. In DLHS-4, household heads were asked whether any household member had suffered from an illness in the previous 15 days. If the response was 'yes', information on illness type was collected for affected persons. For individuals who had reported symptoms of ARI in the previous 15 days, a follow-up question was asked about whether and where the individual received medical treatment. Our primary outcome was seeking treatment for ARI in the previous 15 days at a private or public medical facility among those who also reported ARI symptoms.

Explanatory variables

Data on ACRB were obtained from the National Aeronautics and Space Administration (NASA) Moderate-Resolution Imaging Spectroradiometer (MODIS) Terra satellite Fire Information for Resource Management System (FIRMS) database.[17] The MODIS fire locations provide daily information on spatial and temporal fire distribution. Each hotspot/active fire detection represents the centre of a 1-km^2 area. Using Global Positioning System coordinates and Arc Geographic Information System software (Environmental Systems Research Institute), we mapped the fires to state district centroids and boundaries. The number of fires recorded by MODIS were counted and summed by district and day. Thus, the primary explanatory variable used in the study was the number of fires recorded per district per day from 1 September 2013 to 28 February 2014—a timeframe selected to be inclusive of the period before and after peak ACRB. Additional risk factors from DLHS-4 included age, sex, urban or rural residence, education in years, access to electricity, source of cooking fuel (biomass or other), whether a water-purification method was used, water-drainage infrastructure (open or closed drain), number of rooms in the home and whether the kitchen was inside the home. Motor-vehicle congestion was measured using an index ranging from 0 to 1 for the number of vehicles per square kilometre at the district level, using data from India's 2011 Census.[18] The index was constructed as [(vehicle density in district J – minimum vehicle density in sample)/vehicle density range]. A value of 0 implies that the district has the lowest vehicle density among all districts in the sample. A value of 1 is typical of congested urban districts.

A secondary contributor to poor air quality in northern India is the burning of firecrackers during the Hindu festival of lights, Diwali, which occurs between mid-October and mid-November.[19] In Delhi, the time around Diwali is associated with sharp increases in concentrations of respirable particulate matter, total suspended particulate matter, sulphur dioxide and surface ozone.[20–22] Thus, we examined the period after Diwali—3–10 November in 2013—as an additional ARI risk factor.

Data merging

Individual-level data from DLHS-4 were merged with MODIS data on the number of fires, by district and survey date. The merged data set was a high-frequency panel with daily temporal and spatial variations on exposure to ACRB at the district level. Since ARI was reported for the previous 15 days, data were merged using a recall-adjusted survey date (interview date minus 7 days). The final sample size was 252 539 individuals.

Visualization of ACRB and ARI co-occurrence

MODIS data on the number of fires were mapped for Haryana—a state known for endemic ACRB. Reported treatment seeking for ARI and ACRB occurrence was plotted on a shared timescale to determine whether the two independently observed time series moved in tandem during the study period. Separate plots were constructed for Haryana (high occurrence of ACRB) vs southern states (low occurrence of ACRB).

Estimating the association between ACRB and ARI

Associations between risk factors and reported ARI were assessed through unadjusted and mutually adjusted generalized linear models (GLMs), as ARI satisfies the epidemiologic 'rare disease assumption'.[23] To test for the association of ACRB with ARI, for individual i belonging to household h in district s and survey date t, we ran GLM models using Equation (1):

$$ARI_{ihst} = \alpha + ACRB_{st}\beta 1 + X_{ihst}\Omega + \epsilon_{ihst}. \quad (1)$$

In the unadjusted model, $ACRB_{st}$ and each risk factor in X_{ihst} were individually related to ARI, whereas, in the mutually adjusted model, all risk factors were considered simultaneously. $ACRB_{st}$ is the daily district-level exposure to intense ACRB, X_{ihst} is the set of risk factors that an individual was exposed to and ϵ_{ihst} is the individual-specific error term. The relative risk ratio $\beta 1$ represents the ratio of the risk (probability) of ARI in the exposed group to the risk of ARI in the reference group.[24] Exposure to pollution from ACRB was deemed intense if the household member was interviewed on a day when MODIS detected 100 or more fires (the top quintile of fires per day per district) in their district of residence.

Sensitivity analyses

To test the sensitivity of our estimates from Equation (1), we ran regressions on sub-samples of young children (under 5 years), the elderly (over 60 years) and place of residence (rural vs urban). Using Equation (1), we also estimated models using the natural logarithm of the number of fires per day in a district as a continuous explanatory variable to obtain the marginal effect of a 1% increase in daily fire occurrence.

Health and economic benefits to society from crop burning

In estimating the disease burden attributable to ACRB, we considered the total population in three Indian states likely to be affected by this practice: Haryana, Punjab and Delhi. These states were chosen based on previous ACRB studies[11,14,25] and from satellite images of the fires (Figure 1). Maps showing district-level population density, population of young children and urbanization in the studied states can be found in Supplementary Figure 1, available as Supplementary data at *IJE* online.

Four steps were taken to estimate the direct disease burden attributable to ACRB and firecracker burning. First, the total estimated number of cases of ARI that would be averted if exposure to these risk factors were eliminated in the population, or the population attributable fraction (PAF), was calculated using the 'punaf' STATA routine.[26] Second, state-specific DALY rates attributable to ARIs were obtained for Haryana, Punjab and Delhi from India state-level Disease Burden Initiative Collaborators.[9] Third, these DALY rates were multiplied by our estimated PAF values for ACRB or firecrackers and by state population to estimate total DALYs attributable to these two risk factors in each state. For Punjab, to account for the higher incidence of ACRB in this state relative to Haryana, the DALY rates were apportioned based on the ratio of percentage area burned in Punjab relative to Haryana (67% in Punjab vs 29% in Haryana, i.e. 2.3 times).[11] Fourth, total DALYs saved were converted to per-year economic benefits by multiplying the state-specific per-capita gross domestic product (GDP) by the total DALYs attributable to ACRB and firecrackers.[27] For firecrackers, we also subtracted US$1 billion (US$200 million per year over 5 years)—the estimated loss in revenue from the sale of firecrackers during Diwali.[28] Benefits were compounded for 5 years using a 3% discount rate, as is standard practice when accounting for financial returns at a future date.[29]

Results

Crop burning in Haryana during October and November in 2013 was most intense in the northern districts and was primarily practised in districts where paddy cultivation was also practised (Figure 2).

Figure 1. Typical crop-residue-burning episode and affected geographical area. State borders are overlaid on a MODIS satellite image from 5 November 2012. Active fires are shown as dots (NASA 2012).

The frequency of reported ARI symptoms in Haryana closely paralleled the number of fires observed by the MODIS satellite in this state, with ARI symptoms being more frequently reported in urban than in rural areas (Figure 3). In south Indian states (Andhra Pradesh and Tamil Nadu), where ACRB is not practised and firecracker burning during Diwali is much less prevalent, ARI frequency and the number of fires were low.

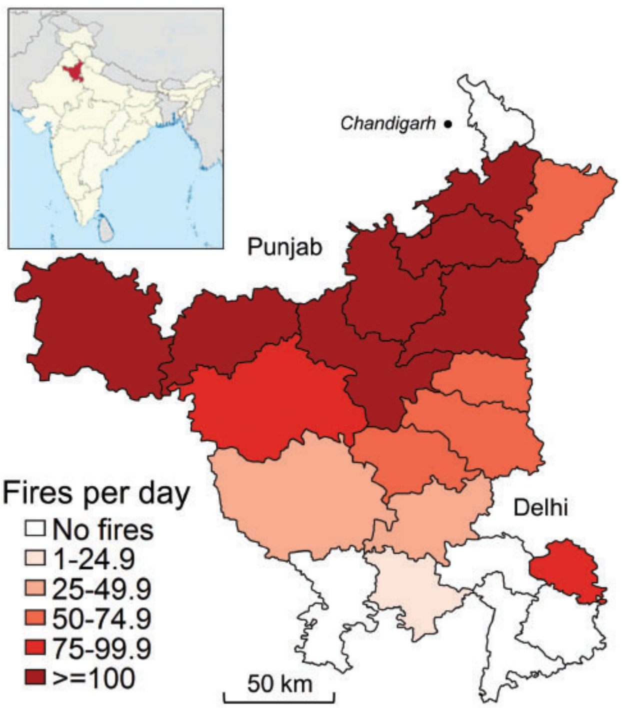

Figure 2. Average number of fires per day during October and November 2013 in districts in Haryana. Fire data from NASA-MODIS-FIRMS, 2013.[17]

In Haryana, 5.4% of surveyed individuals reported suffering from ARI symptoms in the previous 15 days, whereas the reported ARI symptoms in southern states were only 0.1% (Table 1). Among those who reported suffering from ARI, 83% also reported receiving treatment for ARI at a private or public medical facility. Whereas high-intensity fire exposure was virtually absent in south India, 17.5% of individuals in Haryana lived in a district where 100 or more fires per day were observed by satellite. In Haryana, compared with southern states, more households cooked with biomass (15.3 vs 0.2%) and drained water into an open drain (90.6 vs 70.4%) and fewer households treated water before drinking (15.8 vs 26.9%).

Living in a district with intense ACRB was the leading risk factor for ARI, with ≥100 fires per day in the district being associated with a 3-fold higher risk of ARI in the mutually adjusted model (adjusted risk ratio, 95% confidence interval: 2.99, 2.77 to 3.23) (Figure 4). Other risk factors included the week after Diwali (2.45, 2.21 to 2.72), being less than 5 years of age (2.21, 2.17 to 2.61), living in a district with high motor-vehicle congestion (1.96, 1.71 to 2.23), draining water into open drains (1.91, 1.73 to 2.11), using biomass for cooking (1.73, 1.58 to 1.90), living in

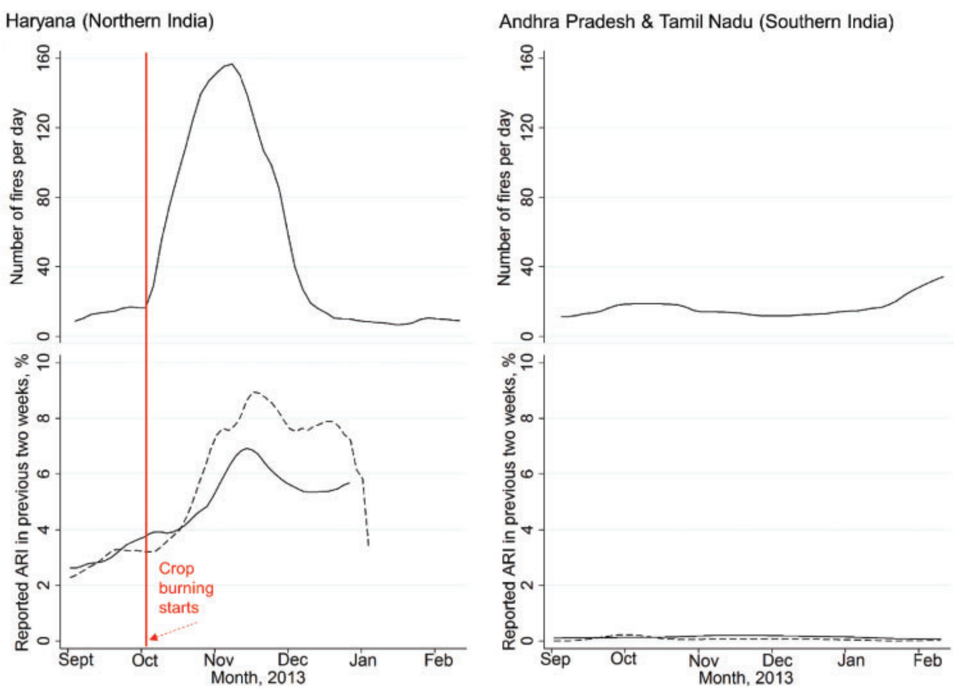

Figure 3. Temporal association between incidence of agricultural crop-residue burning and acute respiratory infection among Indians. Dashed lines in lower two panels indicate urban areas and solid lines indicate rural areas. Data on number of fires were sourced from NASA-MODIS-FIRMS.[17] Data on reported ARI were sourced from Indian DLHS-4.[16] ARI, acute respiratory infection.

Table 1. Summary statistics for Indians surveyed in three states between September 2013 and February 2014

	Haryana	Andhra Pradesh and Tamil Nadu	All
N	90 327	162 212	252 539
Outcome[a]			
Reported ARI in previous 2 weeks, %	5.4	0.1	2.0
N	4832	224	5056
Treatment seeking by those who reported ARI			
Treatment at a private facility	76.5	52.7	75.5
Treatment at a public facility	6.5	35.7	7.8
Treatment at home	3.5	3.1	3.4
No treatment	9.0	1.8	8.7
N	90 327	162 212	252 539
Exposure			
Days when district had 100 or more fires, %	17.5	0.0	6.3
1–7 days after Diwali, %	7.6	0.0	2.7
Covariates			
Children less than 5 years of age, %	8.0	7.1	7.4
Adults 60 years and older, %	10.1	12.4	11.6
Females, %	46.8	51.5	49.8
Urban residence, %	41.5	42.5	42.1
Less than 5 years of education, %	47.9	50.8	49.7
Motor-vehicle index	0.2	0.1	0.1
Household has electricity, %	97.2	98.6	98.1
Cooks with biomass, %	15.3	0.2	5.6
Treats water before drinking, %	15.8	26.9	23.0
Drains water into open drain, %	90.6	70.4	77.6
Fewer than two rooms in house, %	39.7	46.1	43.8
Kitchen is inside house, %	69.3	69.4	69.4

Data were taken from the fourth round of the District Level Household Survey (International Institute for Population Sciences 2015) other than days when the district had 100 or more fires, which were derived from NASA-MODIS-FIRMS data (National Aeronautics and Space Administration).

[a]Only individuals who reported ARI in the previous 2 weeks and sought treatment at a private or public medical facility were classified as having the outcome of interest.

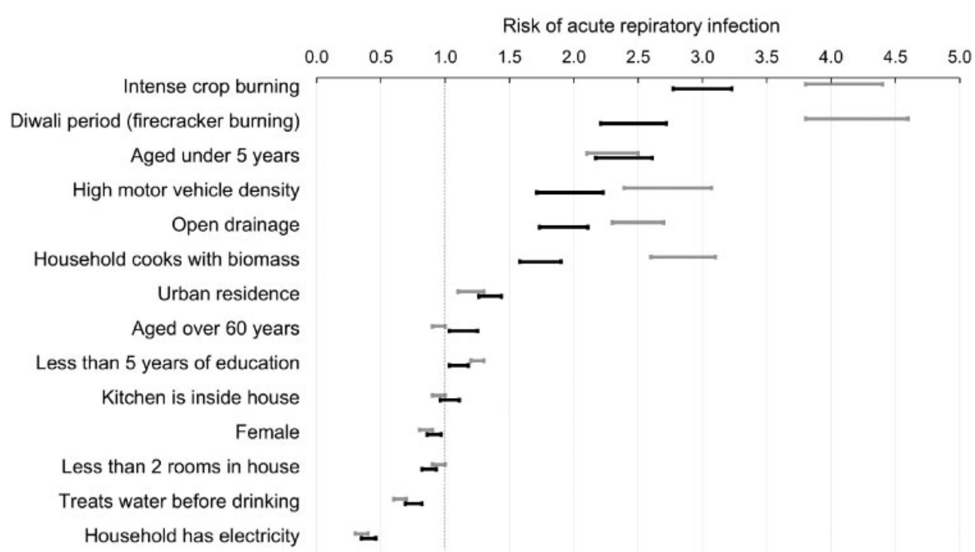

Figure 4. Risk of acute respiratory infection among multiple determinants. 95% confidence intervals are shown for unadjusted (grey) and mutually adjusted (black) risk ratios. The dashed vertical line at 1.0 on the x-axis indicates no risk difference between groups. The mutually adjusted model was adjusted for all other factors shown. Data were taken from DLHS-4[16] other than living in intense crop-burning district (100 or more fires per day), which was derived from NASA-MODIS-FIRMS data,[17] and vehicle density, which was derived from India Census 2011 data.[18]

urban areas (1.35, 1.26 to 1.44) and being 60 years or older (1.14, 1.03 to 1.25). Protective factors included having access to electricity (0.40, 0.35 to 0.46), treating water before drinking (0.75, 0.69 to 0.82), having fewer than two rooms in the house (0.87, 0.82 to 0.93) and being female (0.92, 0.86 to 0.97).

Analysis on subgroups (Table 2) showed that children under 5 years old are at particularly high risk of ARI from ACRB (3.65, 3.06 to 4.34) and open drainage (2.85, 2.14 to 3.80). The elderly were particularly susceptible to ARI associated with firecracker burning (2.53, 1.84 to 3.49) and cooking with biomass (1.92, 1.44 to 2.55). Individuals residing in urban areas were at a higher risk of ARI from ACRB and Diwali, whereas those in rural areas were at greater risk of ARI from open drains and cooking with biomass. Morever, children and elderly living in urban areas were at a higher risk for ARI associated with ACRB than those living in rural areas. When looking at sex differences in risk factors of ARI, motor-vehicle congestion was a stronger risk factor among females (2.18, 1.80 to 2.64) than among males (1.78, 1.49 to 2.14). Similarly, cooking with biomass was a greater risk factor for females (1.84, 1.61 to 2.12) compared with males (1.64, 1.44 to 1.86). Results using a continous explanatory variable to measure ACRB were similar (Supplementary Table 1, available as Supplementary data at *IJE* online).

We estimated that 14.4% of all ARI cases were attributable to ACRB and 6.6% are attributable to burning firecrackers in 2013 (Table 3). For Haryana, Punjab and Delhi combined, the total number of DALYs averted from eliminating ACRB was estimated to be 14.9 million years, valued at US$152.9 billion for 5 years. DALYs averted by eliminating firecrackers were estimated at 4.2 million years, valued at US$35.7 billion for 5 years.

Discussion

Our study has three novel findings. First, exposure to outdoor air pollution from intense ACRB. firecracker burning and motor vehicles are three leading risk factors for ARI in northern India. Second, children under 5 years old are at high risk for ARI from ACRB, whereas other leading household-level risk factors for ARI are exposure to open drains, cooking with biomass and urban residence. Third, the DALY benefits attributable to complete ACRB and firecracker abatement in three states in northern India are estimated at 14.9 and 4.2 million years, respectively, valued at 1.7% of India's GDP—about US$190 billion cumulative for 5 years.

Apart from ACRB and firecrackers, open drainage and the use of biomass for cooking fuel were associated with higher ARI, whereas access to electricity and water filtration were protective factors. We also found a small protective effect of having fewer rooms in the house; this may just reflect poverty and the fact that poor households have lower healthcare-seeking practices and thus were not classified as having ARI in our analyses. The coefficients were in the expected direction[1,3,14,22,30–39] and the relative magnitude of the effects is important for policy focus. Programmes and policies must simultaneously address indoor and outdoor pollution, through a combination of bans and agricultural subsidies; increasing access to improved cooking fuels like liquefied petroleum gas, electrification and promotion of induction cooking stoves; and the construction of improved drainage systems for households. In addition, behavioural-change communication campaigns for the promotion of water treatment and reduction of firecracker use are likely to strengthen macro-level policies and outcomes.

We found a relatively stronger effect of outdoor air pollution (crop burning, firecrackers, motor vehicles) on ARI compared with indoor air pollution (cooking with biomass). Recently, a large-cluster randomized–controlled trial in Malawi found no benefit of switching to cleaner cooking stoves on child pneumonia.[40] The authors suggest that daily exposure to pollution from other sources may have negated the effect of the intervention, which only targeted indoor pollution. There is a large ongoing effort by the central Indian government to expand the use of liquid petroleum gas for cooking to 80% of households by 2019[41] and it will be of interest to assess the impact of these policy efforts on health outcomes in the next few years.

In our subgroup analyses, we found that motor-vehicle congestion was a larger risk factor for ARI in women compared with men. This finding is in line with literature suggesting that women may be more susceptible to pollutants compared with men for biological and social reasons.[42,43] We also found that firecracker burning was a stronger risk factor in urban compared with rural areas, but that open drainage was a stronger risk factor in rural areas compared with urban areas. These findings are as expected, given relatively intense firecracker burning and less open drainage in urban centres compared with rural areas.

Our findings are in line with previous investigations reporting on exposure to environmental air pollution and respiratory health. Wildfires, which are becoming increasingly common with climate change, have been shown to have a broad range of negative population-level health impacts, including respiratory infection.[44] A few studies have reported more frequent hospital visits for respiratory infections following wildfires in the USA and Canada.[45–48] A study in Australia showed that an increase in PM_{10} of 10 μgm^{-3} was associated with a 15% increase risk of

Table 2. Relative risk models for acute respiratory infection on population subgroups

	Children (<5 years)		Elderly (>59.9 years)		Rural		Urban		Females		Males	
	ARR	95 % CI	ARR	95 % CI	ARR	95 % CI	ARR	95 % CI	ARR	95 % CI	ARR	95 % CI
Intense ACRB, 0/1	3.646	[3.06, 4.34]	2.982	[2.34, 3.80]	2.913	[2.63, 3.22]	3.245	[2.88, 3.65]	3.076	[2.75, 3.45]	2.929	[2.64, 3.25]
Diwali week, 0/1	2.037	[1.56, 2.65]	2.532	[1.84, 3.49]	2.042	[1.76, 2.37]	2.949	[2.54, 3.42]	2.526	[2.16, 2.95]	2.397	[2.08, 2.76]
District vehicle index, 0–1	1.625	[1.16, 2.27]	1.807	[1.16, 2.81]	2.886	[2.45, 3.40]	1.002	[0.80, 1.26]	2.182	[1.80, 2.64]	1.784	[1.49, 2.14]
Exposed to open drain, 0/1	2.848	[2.14, 3.80]	1.636	[1.25, 2.13]	2.444	[2.09, 2.86]	1.558	[1.37, 1.77]	1.789	[1.56, 2.06]	2.025	[1.76, 2.33]
Cooks with biomass, 0/1	1.303	[1.03, 1.65]	1.918	[1.44, 2.55]	1.769	[1.59, 1.97]	1.216	[0.96, 1.54]	1.844	[1.61, 2.12]	1.639	[1.44, 1.86]
Urban residence, 0/1	1.511	[1.29, 1.76]	1.260	[1.03, 1.54]					1.423	[1.29, 1.56]	1.291	[1.18, 1.41]
Kitchen is inside house, 0/1	1.139	[0.95, 1.37]	1.156	[0.92, 1.45]	1.036	[0.94, 1.14]	0.990	[0.87, 1.12]	1.005	[0.90, 1.12]	1.049	[0.95, 1.16]
Female, 0/1	0.834	[0.72, 0.97]	0.901	[0.74, 1.09]	0.880	[0.81, 0.96]	0.956	[0.87, 1.05]				
Fewer than two rooms in house, 0/1	0.768	[0.65, 0.91]	0.954	[0.78, 1.17]	0.890	[0.81, 0.97]	0.890	[0.80, 0.99]	0.849	[0.77, 0.94]	0.898	[0.82, 0.98]
Treats drinking water, 0/1	0.663	[0.54, 0.82]	0.775	[0.61, 0.99]	0.553	[0.47, 0.65]	0.868	[0.78, 0.96]	0.771	[0.68, 0.87]	0.739	[0.66, 0.83]
Has electricity, 0/1	0.348	[0.25, 0.49]	0.383	[0.26, 0.57]	0.409	[0.35, 0.48]	0.344	[0.27, 0.44]	0.422	[0.34, 0.52]	0.377	[0.31, 0.46]
Below 5 years of education, 0/1			0.793	[0.63, 0.99]	1.159	[1.05, 1.28]	1.040	[0.93, 1.16]	1.183	[1.07, 1.31]	1.036	[0.94, 1.14]
Children (<5 years), 0/1					2.152	[1.90, 2.43]	2.745	[2.39, 3.15]	2.128	[1.86, 2.43]	2.633	[2.32, 2.98]
Elderly (> 59.9 years), 0/1					1.104	[0.97, 1.26]	1.175	[1.01, 1.36]	1.031	[0.89, 1.19]	1.233	[1.08, 1.41]
N	18 760		29 282		146 163		106 376		125 866		126 673	

ARR, mutually adjusted risk ratio, i.e. adjusted for all other factors shown; CI, confidence interval. Data were taken from DLHS-4 (International Institute for Population Sciences 2015) other than intense ACRB (days when district had 100 or more fires), which was derived from NASA-MODIS-FIRMS data (National Aeronautics and Space Administration).

Table 3. Economic benefits of government actions to abate agricultural crop-residue burning and burning of firecrackers

Row		Haryana		Punjab		Delhi		Total	
		ACRB	Firecrackers	ACRB	Firecrackers	ACRB	Firecrackers	ACRB	Firecrackers
1	DALY rates for ARI per 1000 population[a]	1311	1311	887	887	799	799		
2	State population, millions[b]	25.4	25.4	27.7	27.7	16.8	16.8		
3	Proportion of ARI cases attributed to risk factor[c]	0.14	0.06	0.33	0.06	0.14	0.06	0.14	0.07
4	DALYs saved by eliminating risk factor, million years[d]	4.79	1.96	8.14	1.45	1.93	0.79	14.85	4.20
5	Per-capita state GDP, US$/person[e]	2637.26	2637.26	1739.67	1739.67	4575.16	4575.16		
6	Economic value of DALYs saved per yr, US$ billion/yr[f]	12.62	4.17	14.16	1.52	8.82	2.61	35.60	8.31
7	Economic value of DALYs saved over 5 yrs, US$ billion[g]	54.20	17.91	60.79	6.54	37.87	11.22	152.86	35.67

[a]From Figure 4 in Dandona *et al.* (2017).
[b]From Indian Population Census 2011 (Office of the Registrar General & Census Commissioner 2011).
[c]From PUNAF after estimating Equation (1), with the PAR for Punjab multiplied by 2.3 to account for higher ACRB in Punjab relative to Haryana (Lohan *et al.* 2018).
[d]Row 1 × Row 2 × Row 3.
[e]From NITI Aayog (National Institution for Transforming India 2017).
[f]Row 4 × Row 5. One billion in economic benefits subtracted due to losses faced by firecracker industry (KV Lakshmana 2017).
[g]From Row 6 for 5 years discounted at 3% per year.
DALY, disability-adjusted life years; GDP, gross domestic product.

respiratory infection among indigenous people living in dry areas with frequent vegetation fires.[49] Second-hand tobacco smoke has also been related to ARI. The odds of hospital admission for ARI were 1.55 times higher in children under 2 years of age who were exposed to second-hand tobacco smoke compared with children who were not.[50] Respiratory infections were found to be the single greatest contributor to the global burden of disease attributable to second-hand smoke in children under 5 years of age.[51] Others have looked at ambient particulate-matter concentration (from multiple sources) as a predictor of respiratory outcomes. A meta-analysis of four studies in areas with relatively low average annual $PM_{2.5}$ concentrations ($12–25\,\mu gm^{-3}$, compared with $153\,\mu gm^{-3}$ in Delhi during the study period[52]) found a 12% increased risk of ARI in children under 5 years of age per $10\,\mu gm^{-3}$ increase in $PM_{2.5}$.[53] A long-term study in the USA found that a 1-interquartile range increase in ozone predicted a 4% increase in respiratory infection among children aged 0–4 years.[54] Given that most studies relating poor air quality to respiratory health come from developed countries with much lower ambient concentrations of pollutants as well as less poverty and better health services, direct comparison to the currently studied population in northern India may be limited.

Our study has several strengths. First, to our knowledge, this is the only study to systematically estimate the effect of exposure to ACRB on ARI in India. Second, we leveraged two high-resolution data sets: crop-burning data from MODIS and data on reported ARI among all age groups of men and women in Haryana from DLHS-4, which has a large sample size, is representative at the district level and were collected when ACRB peaks. Third, we accounted for a comprehensive set of risk factors in our mutually adjusted statistical model, thus our study provides an important benchmark in examining the relative contribution of these risk factors for ARI. Fourth, we provide the first available estimates of ACRB abatement in terms of DALYs and US dollars.

Our study is not without limitations. First, the DLHS survey was not conducted in Punjab—the state with the highest incidence of ACRB in October—thus we could not estimate the contribution of ACRB on ARI in that state. Second, to our knowledge, high-frequency, high-resolution data on particulate-matter concentration in the ambient air of Haryana or Punjab are not available; consequently, we could not estimate the dose–response function linking ACRB and the resulting increase in air pollution to health outcomes. Third, in our mutually adjusted models, we controlled for other factors that may also increase outdoor air pollution. However, it is possible that we missed some factors, such as a fall in the ambient temperature, which may worsen the effect of air pollution on population health. Fourth, the effects of firecracker burning were estimated by specifying a dummy variable for the week after Diwali. The independent effects of firecracker burning would ideally be estimated in the absence of ACRB to avoid confounding, but this was not possible due to co-occurrence of these events. Therefore, our estimate of the contribution of firecracker burning is likely biased. Finally, we note that low variability in the district vehicle index in the urban sample prevents us from being able to accurately examine the effect of motor-vehicle density on ARI in cities, and data at a higher spatial resolution would allow better risk assessment in this case.

Conclusion

We found that living in an area where crop burning is practised was a leading risk factor for respiratory disease in northern India. Whereas the total burden of diseases from air pollution declined between 1990 and 2016 due to efforts to reduce the burning of solid fuel for household use, outdoor air pollution increased by 16.6%.[6] We found that ACRB leads to over US$30 billion losses in economic value every year and a 3-fold risk of ARI to those exposed in the general population. Any investments made for the abatement of ACRB are likely to be highly favourable in terms of their return on investment, when compared with other public-health interventions or actions.[55,56] ACRB is a growing problem in India and in other countries.[3,39,57,58] The promotion of sustainable economic development should include investments to stop crop burning.

Supplementary data

Supplementary data are available at *IJE* online.

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References

1. Ferkol T, Schraufnagel D. The global burden of respiratory disease. *Annals ATS* 2014;**11**:404–06.
2. GBD 2015 LRI Collaborators, Forouzanfar M, Rao PC *et al*. Estimates of the global, regional, and national morbidity, mortality, and aetiologies of lower respiratory tract infections in 195 countries: a systematic analysis for the Global Burden of Disease Study 2015. *Lancet Infect Dis* 2017;**17**:1133–61.
3. Chen J, Li C, Ristovski Z *et al*. A review of biomass burning: emissions and impacts on air quality, health and climate in China. *Sci Total Environ* 2017;**579**:1000–34.
4. Adar SD, Sheppard L, Vedal S *et al*. Fine particulate air pollution and the progression of carotid intima-medial thickness: a prospective cohort study from the multi-ethnic study of atherosclerosis and air pollution. *PLoS Med* 2013;**10**:e1001430.
5. Bentayeb M, Simoni M, Baiz N *et al*. Adverse respiratory effects of outdoor air pollution in the elderly. *Int J Tuberc Lung Dis* 2012;**16**:1149–61.
6. Health Effects Institute. *Burden of Disease Attributable to Major Air Pollution Sources in India*. Boston, MA: Health Effects Institute, 2018.
7. India State-Level Disease Burden Initiative Air Pollution Collaborators. The impact of air pollution on deaths, disease burden, and life expectancy across the states of India: the Global Burden of Disease Study 2017. *Lancet Planet Health* 2019;**3**: E26–E39.
8. WHO. *WHO Global Urban Ambient Air Pollution Database (Update 2016)*. Geneva, Switzerland: World Health Organization.
9. Dandona L, Dandona R, Kumar GA *et al*. Nations within a nation: variations in epidemiological transition across the states of India, 1990–2016 in the Global Burden of Disease Study. *Lancet* 2017;**6736**:1–24.
10. Vasudeva V. Punjab farmers defy ban on stubble burning. *The Hindu*. 2017. https://www.thehindu.com/news/national/other-states/punjab-farmers-defy-ban-on-stubble-burning/article19872262.ece (15 September 2018, date last accessed).
11. Lohan SK, Jat HS, Yadav AK *et al*. Burning issues of paddy residue management in north-west states of India. *Renew Sustain Energy Rev* 2018;**81**:693–706.
12. Ministry of New & Renewable Energy G of I. *Biomass Resource Atlas of India*. Bangalore, India: CGPL, Indian Institute of Science, 2017.
13. Cusworth DH, Mickley LJ, Sulprizio MP *et al*. Quantifying the influence of agricultural fires in northwest India on urban air pollution in Delhi, India. *Environ Res Lett* 2018;**13**:044018.
14. Awasthi A, Singh N, Mittal S, Gupta PK, Agarwal R. Effects of agriculture crop residue burning on children and young on PFTs in North West India. *Sci Total Environ* 2010;**408**:4440–45.
15. WHO. Global action plan for the prevention and control of noncommunicable diseases 2013–2020. *World Health Organ* 2013; **102**.
16. International Institute for Population Sciences. *District Level Household Survey 2012–2013 (DLHS-4)*. Mumbai, India: International Institute for Population Sciences, 2015.
17. National Aeronautics and Space Administration. *Fire Information for Resource Management System*. USA: LANCE NASA, 2018.
18. Office of the Registrar General & Census Commissioner. *Population Enumeration Data (Final Population)*. New Delhi, India: ORGI DDU, 2011.
19. Kulshrestha UC, Nageswara Rao T, Azhaguvel S, Kulshrestha MJ. Emissions and accumulation of metals in the atmosphere due to crackers and sparkles during Diwali festival in India. *Atmos Environ* 2004;**38**:4421–25.
20. Ganguly ND. Surface ozone pollution during the festival of Diwali, New Delhi, India. *J Earth Sci India* 2009;**2**:224–29.
21. Mandal P, Prakash M, Bassin JK. Impact of Diwali celebrations on urban air and noise quality in Delhi City, India. *Environ Monit Assess* 2012;**184**:209–15.

22. Perrino C, Tiwari S, Catrambone M, Torre SD, Rantica E, Canepari S. Chemical characterization of atmospheric PM in Delhi, India, during different periods of the year including Diwali festival. *Atmos Pollut Res* 2011;**2**:418–27.
23. Schmidt CO, Kohlmann T. When to use the odds ratio or the relative risk? *Int J Public Health* 2008;**53**:165–67.
24. Northridge ME. Public health methods—attributable risk as a link between causality and public health action. *Am J Public Health* 1995;**85**:1202–204.
25. Subramanian M. Can Delhi save itself from its toxic air? *Nature* 2016;**534**:166–69.
26. Newson R. *PUNAF: Stata Module to Compute Population Attributable Fractions for Cohort Studies Fractions and Other Scenario Comparisons*. Boston, USA: Boston College Department of Economics, 2016.
27. Brown DW. Economic value of disability-adjusted life years lost to violence: estimates for WHO Member States. *Rev Panam Salud Publica* 2008;**24**:203–09.
28. Lakshmana KV. SC ban on firecrackers: industry stares at Rs 1, 000-crore loss, layoffs. *The Hindustan Times*. 2017. https://www.hindustantimes.com/india-news/sc-ban-on-firecrackers-industry-stares-at-rs-1–000-crore-loss-layoffs/story-zctMTeZ16DaPf4O5DWggJI.html (15 September 2018, date last accessed).
29. Shekar M, Dayton Eberwein J, Kakietek J. The costs of stunting in South Asia and the benefits of public investments in nutrition. *Matern Child Nutr* 2016;**12**:186–95.
30. Zheng X, Ding H, Jiang L *et al*. Association between air pollutants and asthma emergency room visits and hospital admissions in time series studies: a systematic review and meta-analysis. *PLoS One* 2015;**10**:e0138146.
31. Jayachandran S. Air quality and early-life mortality: evidence from Indonesia's wildfires. *J Human Resources* 2009;**44**:916–54.
32. Singh P. *Seasonal Exposure to Wildfires: Child Weight Outcomes for India*. New Delhi, India: India Statistical Institute, 2017, pp. 1–28.
33. Zhang L, Liu Y, Hao L. Contributions of open crop straw burning emissions to PM2.5 concentrations in China. *Environ Res Lett* 2016;**11**:014014.
34. Page CM, Patel A, Hibberd PL. Does smoke from biomass fuel contribute to anemia in pregnant women in Nagpur, India? A cross-sectional study. *PLoS One* 2015;**10**:e0127890.
35. Zhou Y, Zou Y, Li X *et al*. Lung function and incidence of chronic obstructive pulmonary disease after improved cooking fuels and kitchen ventilation: a 9-year prospective cohort study. *PLoS Med* 2014;**11**:e1001621.
36. Cançado JED, Saldiva PHN, Pereira LAA *et al*. The impact of sugar cane-burning emissions on the respiratory system of children and the elderly. *Environ Health Perspect* 2006;**114**:725–29.
37. Schei MA, Hessen JO, Smith KR, Bruce N, McCracken J, Lopez V. Childhood asthma and indoor woodsmoke from cooking in Guatemala. *J Expo Sci Environ Epidemiol* 2004;**14**:S110–17.
38. Gurung A, Bell ML. Exposure to airborne particulate matter in Kathmandu Valley, Nepal. *J Expo Sci Environ Epidemiol* 2012;**22**:235–42.
39. Liu LS. *Exposure and Health Assessments of the Effects of Agricultural Field Burning in Young Adults with Asthma Living in Pullman Washington*. Seattle, Washington: University of Washington, 2005.
40. Mortimer K, Ndamala CB, Naunje AW *et al*. A cleaner burning biomass-fuelled cookstove intervention to prevent pneumonia in children under 5 years old in rural Malawi (the Cooking and Pneumonia Study): a cluster randomised controlled trial. *Lancet* 2017;**389**:167–75.
41. Times of India. PM Modi: 10 crore LPG connections given in 4 years against 13 crore in 6 decades. *India News—Times of India*. https://timesofindia.indiatimes.com/india/pm-modi-10-crore-lpg-connections-given-in-4-years-against-13-crore-in-6-decades/articleshow/64350785.cms (15 September 2018, date last accessed).
42. Butter ME. Are women more vulnerable to environmental pollution? *J Hum Ecol* 2006;**20**:221–6.
43. Clougherty JE. A growing role for gender analysis in air pollution epidemiology. *Environ Health Perspect* 2010;**118**:167–76.
44. Black C, Tesfaigzi Y, Bassein JA, Miller LA. Wildfire smoke exposure and human health: significant gaps in research for a growing public health issue. *Environ Toxicol Pharmacol* 2017;**55**:186–95.
45. Duclos P, Sanderson LM, Lipsett M. The 1987 forest fire disaster in California: assessment of Emergency Room visits. *Arch Environ Health* 1990;**45**:53–58.
46. Rappold AG, Stone SL, Cascio WE *et al*. Peat bog wildfire smoke exposure in rural North Carolina is associated with cardiopulmonary emergency department visits assessed through syndromic surveillance. *Environ Health Perspect* 2011;**119**:1415–20.
47. Henderson SB, Brauer M, MacNab YC, Kennedy SM. Three measures of forest fire smoke exposure and their associations with respiratory and cardiovascular health outcomes in a population-based cohort. *Environ Health Perspect* 2011;**119**:1266–71.
48. Reid CE, Jerrett M, Tager IB, Petersen ML, Mann JK, Balmes JR. Differential respiratory health effects from the 2008 northern California wildfires: a spatiotemporal approach. *Environ Res* 2016;**150**:227–35.
49. Hanigan IC, Johnston FH, Morgan GG. Vegetation fire smoke, indigenous status and cardio-respiratory hospital admissions in Darwin, Australia, 1996–2005: a time-series study. *Environ Health* 2008;**7**:42.
50. US Office on Smoking and Health. *The Health Consequences of Involuntary Exposure to Tobacco Smoke [Internet]. Heal. Consequences Involuntary Expo. to Tob. Smoke A Rep. Surg. Gen.* Centers for Disease Control and Prevention (US), 2006. http://www.ncbi.nlm.nih.gov/pubmed/20669524 (18 December 2018, date last accessed).
51. Oberg M, Jaakkola MS, Woodward A, Peruga A, Prüss-Ustün A. Worldwide burden of disease from exposure to second-hand smoke: a retrospective analysis of data from 192 countries. *Lancet (London, England)* 2011;**377**:139–46.
52. World Health Organization. *Ambient (Outdoor) Air Pollution in Cities Database 2014*. Geneva, Switzerland: WHO World Health Organization, 2014. https://www.who.int/phe/health_topics/outdoorair/databases/cities-2014/en/ (15 September 2018, date last accessed).
53. Mehta S, Shin H, Burnett R, North T, Cohen AJ. Ambient particulate air pollution and acute lower respiratory infections: a

systematic review and implications for estimating the global burden of disease. *Air Qual Atmos Health* 2013;**6**:69–83.

54. Darrow LA, Klein M, Flanders WD, Mulholland JA, Tolbert PE, Strickland MJ. Air pollution and acute respiratory infections among children 0–4 years of age: an 18-year time-series study. *Am J Epidemiol* 2014;**180**:968–77.
55. Hoddinott J, Alderman H, Behrman JR, Haddad L, Horton S. The economic rationale for investing in stunting reduction. *Matern Child Nutr* 2013;**9**:69–82.
56. Lomborg B. *Global Problems Smart Solutions: Costs and Benefits*. Cambridge, UK: Cambridge University Press, 2012.
57. Zhuang Y, Chen D, Li R *et al*. Understanding the influence of crop residue burning on $PM_{2.5}$ and PM_{10} concentrations in China from 2013 to 2017 using MODIS data. *Int J Environ Res Public Health* 2018;**15**:1504.
58. Stavrakou T, Müller JF, Bauwens M *et al*. Substantial underestimation of post-harvest burning emissions in the north china plain revealed by multi-species space observations. *Sci Rep* 2016;**6**:1–11.