

Environmental Research Letters



LETTER

OPEN ACCESS

RECEIVED
25 January 2020

REVISED
9 June 2020

ACCEPTED FOR PUBLICATION
17 July 2020

PUBLISHED
6 October 2020

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Post-monsoon air quality degradation across Northern India: assessing the impact of policy-related shifts in timing and amount of crop residue burnt

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Keywords: earth observation, air quality, agriculture, crop residue burning, Indo-Gangetic Plain, groundwater, policy

Supplementary material for this article is available [online](#)

Abstract

The past decade has seen episodes of increasingly severe air pollution across much of the highly populated Indo-Gangetic Plain (IGP), particularly during the post-monsoon season when crop residue burning (CRB) is most prevalent. Recent studies have suggested that a major, possibly dominant contributor to this air quality decline is that northwest (NW) Indian rice residue burning has shifted later into the post-monsoon season, as an unintended consequence of a 2009 groundwater preservation policy that delayed the sowing of irrigated rice paddy. Here we combine air quality modelling of fine particulate matter (PM_{2.5}) over IGP cities, with meteorology, fire and smoke emissions data to directly test this hypothesis. Our analysis of satellite-derived agricultural fires shows that an approximate 10 d shift in the timing of NW India post-monsoon residue burning occurred since the introduction of the 2009 groundwater preservation policy. For the air quality crisis of 2016, we found that NW Indian CRB timing shifts made a small contribution to worsening air quality (3% over Delhi) during the post-monsoon season. However, if the same agricultural fires were further delayed, air quality in the CRB source region (i.e. Ludhiana) and for Delhi could have deteriorated by 30% and 4.4%, respectively. Simulations for other years highlight strong inter-annual variabilities in the impact of these timing shifts, with the magnitude and even direction of PM_{2.5} concentration changes strongly dependent on specific meteorological conditions. Overall we find post-monsoon IGP air quality to be far more sensitive to meteorology and the amount of residue burned in the fields of NW India than to the timing shifts in residue burning. Our study calls for immediate actions to provide farmers affordable and sustainable alternatives to residue burning to hasten its effective prohibition, which is paramount to reducing the intensity of post-monsoon IGP air pollution episodes.

1. Introduction

Outdoor air pollution is the world's greatest environmental health risk (WHO 2020), and fine particulate

matter (PM_{2.5}) is its most harmful component and a leading cause of morbidity and premature death across much of South Asia (Landrigan *et al* 2018). In India, 1.24 million premature deaths and 26%

of global disability-adjusted life years (DALYs) were attributable to air pollution in 2017 (Balakrishnan *et al* 2019). Seasonal crop residue burning (CRB) in the northwest (NW) agricultural states of Punjab and Haryana is a major source of PM_{2.5} air pollution in north India (Kaskaoutis *et al* 2014, Lohan *et al* 2018). Transport of these emissions along the Indo-Gangetic Plain (IGP), can cause impacts on hundreds of millions of citizens (Vadrevu *et al* 2015), including in the National Capital Territory (NCT) of Delhi (population 20 million).

The high yield rice-wheat cropping system operated across NW India (Davis *et al* 2018) means CRB occurs twice per year, in April–May (wheat stubble) and October–November (rice straw). There is evidence that the severity of post-monsoon episodes of poor air quality across northern India is worsening (Sarkar *et al* 2018) and this has led state governments to enforce state-wide bans prohibiting CRB. However, for many farmers at present there are few affordable alternative options to open field burning for removing this material, so the practice remains widespread. During the post-monsoon months of 2016 for example, CRB in Punjab and Haryana has been implicated in the severely amplified ‘smog’ episode that was experienced across the IGP (Jethva *et al* 2018). At this time, when rice residue burning is most prevalent, PM_{2.5} concentrations at locations in Delhi NCT can reach 500 $\mu\text{g m}^{-3}$ (Chowdhury *et al* 2019). The US Environmental Protection Agency considers any concentration above 300 $\mu\text{g m}^{-3}$ to be ‘hazardous’ for everyone, and high enough to sometimes prompt emergency condition alerts.

Whilst deteriorating air quality related to CRB has become a central environmental concern (Bhuvan-shwari *et al* 2019), it is not the only cause of environmental degradation in NW India. Since the mid-70s, an assured income achievable by farmers through the governmental initiative of ‘minimum support price’ for rice, combined with the provision of subsidised power for some farmers, has allowed those with even modest incomes to access personal irrigation systems (Bhargava 2018). The groundwater used by these irrigation systems enabled paddy rice to be sown several months before the onset of the Indian southwest (SW) monsoon, allowing the crop to mature earlier when pests are typically less prevalent. It also enabled earlier winter planting of the subsequent ‘Rabi’ wheat crops, helping farmers counteract the effects of a less than ideal winter growing season (Mahajan *et al* 2009). Unfortunately, the resulting extensive groundwater extraction has led to a water crisis in the NW Indian states (Famiglietti 2014), with evidence that the water table could be lowered in a way that could threaten the nation’s future food requirements (Rodell *et al* 2009, Macdonald *et al* 2016). To counter this possibility, the Governments of Punjab and Haryana instituted the ‘Sub-Soil Water Act’ (SSWA)

of 2009 to limit further groundwater decline (Singh 2009). The SSWA essentially altered the prescribed timing of paddy rice planting to the fields, moving it closer to the onset of the SW monsoon (late June) to reduce the reliance on groundwater irrigation. This shift also delayed the post-monsoon rice harvest, and is thought to have had the unintended consequence of delaying the post-harvest period of rice residue burning (Liu *et al* 2019, Jethva *et al* 2019). Sawlani *et al* (2019) have suggested that a shift to later CRB may have exacerbated post-monsoon air quality crises across the IGP by releasing smoke into more stable atmospheric conditions that typically exist further into November (Singh and Kaskaoutis 2014), and it has even been suggested that the later burning may be the dominant cause (Singh *et al* 2019). Other potential drivers include increases in the amount of residue burnt and/or changes in other air pollution sources such as vehicular or construction emissions. It remains critical to disentangle these various contributions to the worsening air quality so that any future agricultural policy adjustments can account for such changes. Here we use a combination of air quality modelling and satellite observations to identify the shifts in timing in post-monsoon vegetation growth and CRB that the SSWA has engendered, and to quantify what impact this timing shift has had on PM_{2.5} concentrations across the IGP. We also use a long-term satellite data time series to examine any changes in CRB magnitude over the last 15 years. Our specific objectives are to: 1. Quantify how spatial and temporal patterns of post-monsoon CRB have changed across NW India since the implementation of the 2009 SSWA, 2. Determine the extent to which this CRB currently contributes to the air quality of Delhi and other IGP cities, 3. Test how shifts in post-monsoon CRB timing related to the 2009 SSWA have impacted this contribution, and 4. Explore the possible impacts of any further CRB delays.

2. Materials and method

2.1. Datasets

To assess state-wide long-term (2003 to 2018) changes in cropping patterns and residue burning across NW India, we used vegetation index and active fire (AF) information derived from observations made by the Moderate Resolution Imaging Spectroradiometer (MODIS) operating on the Aqua satellite. Maps and state-wide time series of the enhanced vegetation index (EVI, Huete *et al* 2002, Jiang *et al* 2008) and land surface water index (LSWI, Chandrasekar *et al* 2010) were produced at 0.05° resolution from the daily surface reflectance MODIS MYD09CMG Version 6 product. Corresponding data on state-level crop area and production for the states of Punjab, Haryana and Rajasthan, was extracted from official

statistics collected by the Department of Agriculture, Cooperation and Farmers Welfare, Government of India (<http://agricoop.nic.in/>). We used the Aqua MODIS Collection 6 MYD14 1 km AF products (Giglio *et al* 2016) to calculate daily summed fire radiative power (FRP) at the same 0.05° resolution as a measure of fire emissions magnitude (Wooster *et al* 2005, Kaiser *et al* 2012). Though individual CRB fires are typically small, the MODIS AF products can miss some fires when there are too few burning concurrently in an area (Vadrevu and Lasko 2018). However, the long MYD14 data record is highly consistent and considered very suitable for examining CRB fire trends over large areas (Jethva *et al* 2018, Cusworth *et al* 2018, Liu *et al* 2019, Vadrevu *et al* 2019). For the purpose of air quality modelling (section 2.2) it was considered more important to detect as many of the CRB areas as possible. Therefore we used higher spatial resolution 375 m AF data derived from observations made by the Visible Infrared Imaging Radiometer Suite (VIIRS) sensor operating onboard the Suomi NPP satellite, taking the matching FRP measurements from the companion 750 m VIIRS I-Band observations to avoid sensor saturation over more intensely burning fires (Zhang *et al* 2017). See SI for further description of dataset quality control and processing.

2.2. Modelling changes in PM_{2.5} exposure due to post-monsoon CRB

To calculate CRB influences on ambient PM_{2.5} concentrations across northern India, we used a combination of the Weather Research and Forecasting model (WRF 3.9.1, Skamarock *et al* 2008) and the Community Multi-scale Air Quality model (CMAQ 5.0.2, Byun *et al* 2006), fed with standard all-source emissions inventories enhanced with our VIIRS-derived AF data (see figure S1 (<https://stacks.iop.org/ERL/15/104067/mmedia>) for the modelling framework employed). The WRF model was set up in the ‘all-India’ domain, horizontally divided into 9672 grids of 36 km x 36 km and vertically divided in 25 layers up to a height of 19.5 km. Meteorological fields were extracted from Interim European Centre for Medium Range Weather Forecasting Re-Analysis (ERA-Interim) 6-hourly daily fields (Berrisford *et al* 2011). Combined with MODIS land-use land-cover classification, these datasets were fed into the WRF model, output of which was used as meteorological input for the CMAQ modelling system.

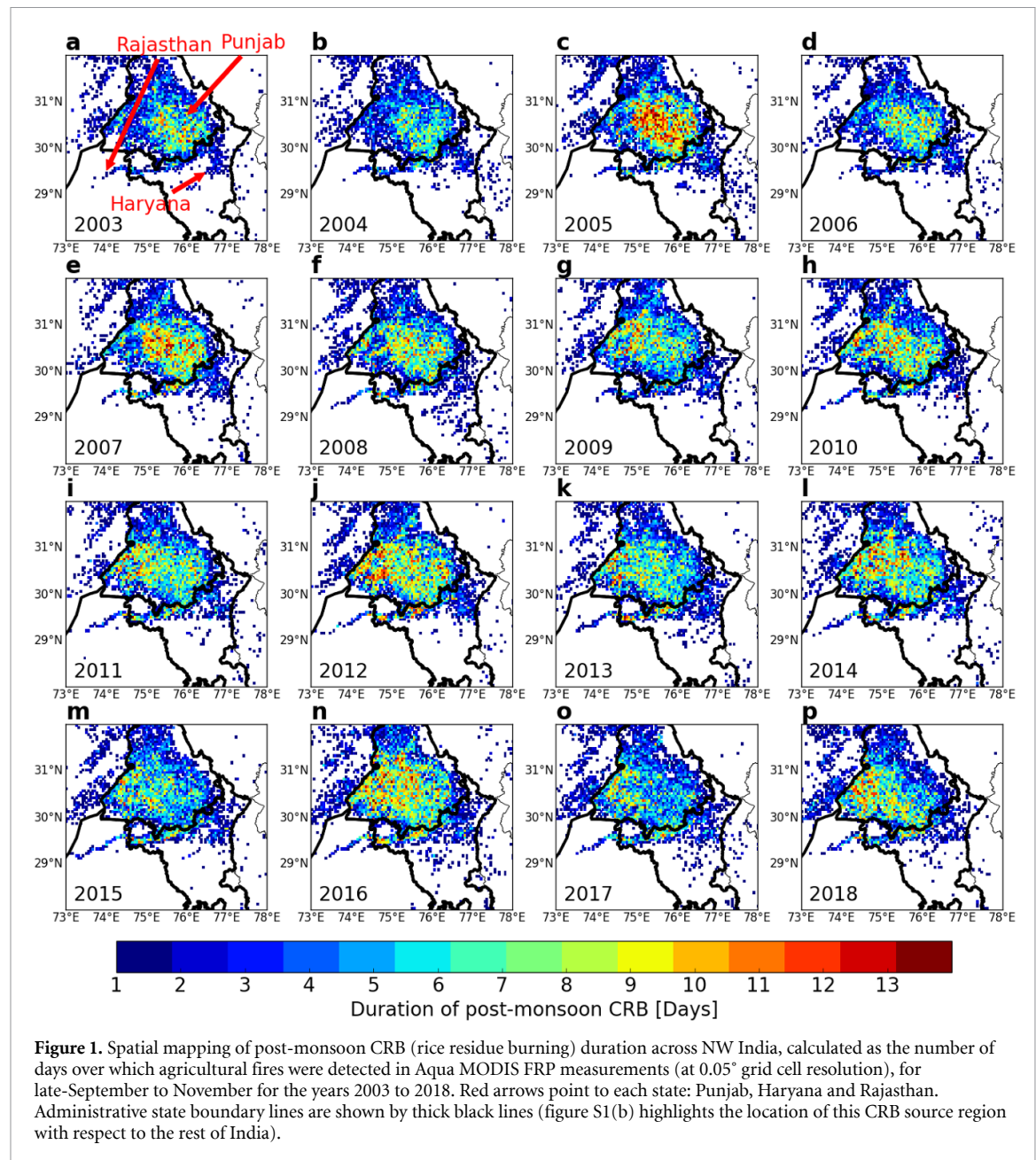
2.2.1. Emission inventories

The standard emissions inventory used in our study was developed by TERI (2018), in which emissions for 2016 were calculated using International Institute for Applied Systems Analysis (IIASA) Greenhouse Gas—Air Pollution Interactions and Synergies (GAINS)

Asia model (Amann *et al* 2011). The sectors included encompass industry, transport, residential, power, non-energy sources (e.g. crematoria burning, municipal waste refuse burning), the fuel categories of biomass, coal, gasoline, diesel, LPG, natural gas, and other petroleum products (heavy oil, fuel oil). Certain emission sources like natural dust, construction, fire-crackers and road dust are not included due to a limited availability of national level data. Spatial and temporal allocation of the CRB emissions, calculated from crop yield and agricultural statistics from TERI (2018), were conducted according to the 2016 daily VIIRS FRP data. Emissions from neighbouring countries falling into the study domain were taken from IIASA’s GAINS Asia model. The pollutants from outside the domain, i.e. the international boundary conditions, were accounted for using the Model for Ozone And Related chemical Tracers (MOZART) chemical transport model (Emmons *et al* 2010). Thereafter the CMAQ model was run for the all-India scale for a 2016 case study, and the modelled PM_{2.5} concentrations validated against *in situ* observations from the Central Pollution Control Board (SI section 5).

2.2.2. Modelling CRB timing scenarios

Our modelling framework was used to evaluate the air quality impacts of three CRB timing scenarios: Scenario A—the ‘baseline’ where CRB timing was based directly on daily VIIRS AF observations; Scenario B—in which the timing of these emissions were shifted earlier to represent the situation prior to implementation of the 2009 SSWA, and Scenario C—in which CRB was moved later to represent a situation in which rice harvesting could be further delayed, due to future SSWA amendments or a delayed SW monsoon withdrawal and zero CRB mitigation. Section 3.2 describes how the changes in the CRB timing, pre- and post-SSWA introduction, were determined. Only the timing of the fire emissions was adjusted in each scenario modelled based on these findings—not their absolute magnitude. The emissions from other sectors were also kept constant. This approach enables the impact of CRB timing to be examined explicitly, in contrast to approaches that directly compared pre- and post-SSWA satellite-derived AF and PM_{2.5} concentrations (Chowdhury *et al* 2019, Singh *et al* 2019), which can make it challenging to decouple changes in CRB amount, or the growth in sources such as vehicular traffic occurring over the same period (GOI 2017). A further set of experiments were conducted where different meteorological regimes and residue burning magnitudes were used in the model to explore sensitivities beyond that of CRB timing.

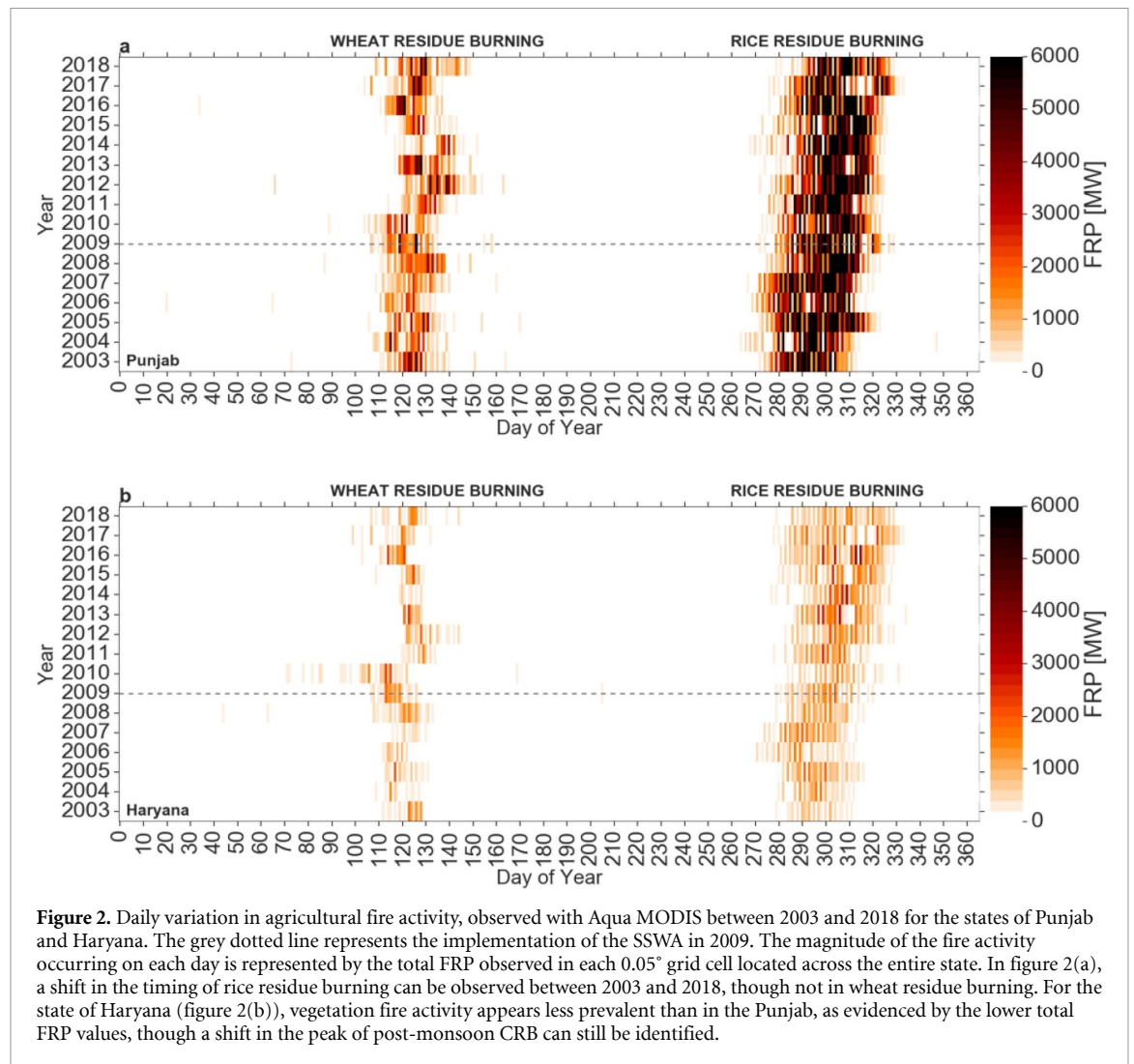


3. Results

3.1. Spatial and temporal changes in post-monsoon CRB

Figure 1 presents maps of post-monsoon CRB duration derived from daily Aqua MODIS AF detections. Prior to 2009, post-monsoon CRB lasted as much as 13 d in central and south-eastern Punjab, and closer to 5 d across north-western Punjab and northern Haryana (figures 1(a) to (f)). After 2009, post-monsoon CRB became more prevalent across Punjab and most of its western districts (figures 1(g) to (p)), lasting up to 11 d. Shorter duration (<5 d) burn periods were concentrated towards the north-eastern districts. Post-2009, CRB also appears to have become more pronounced across northern Haryana and northern Rajasthan districts, lasting as long as

10 d. These increasing fire signatures observed across multiple states converge into a ‘fire belt’ covering the Ghaggar-Hakra palaeochannel, a fluvial incised valley extending south-westwards from Haryana and into Rajasthan (Singh *et al* 2017), and appears to indicate that farmers growing rice in this region are burning more residue as time goes on. Changes in annual state-wide fire count and FRP for the post-monsoon burning period (figure S2), and the growth in the spatial extent and duration of burning shown in figure 1 demonstrates that rice residue burning activity has expanded (between 4 and 11 d) across all three states. This is in line with the significant increases in rice (and wheat) production reported over the last decade across NW India, particularly across Punjab and Haryana. The increased yields have been supported by the popularisation



of mechanised ‘combine’ harvesters, which have the disadvantage of typically leaving more residue in the fields compared to manual harvest approaches (FAO 2019). State-wide agricultural statistics for 2003 to 2016 (figure S3) highlight that the amount of rice residue generated in Punjab, Haryana and Rajasthan, calculated using a residue-to-crop ratio of 1.59 (Sharma and Kumar, 2016), increased by 30%, 60% and 120% respectively over this period. Whilst the percentage growth is lowest in Punjab, the absolute residue amount here is approximately $4 \times$ that in Haryana and $60 \times$ that in Rajasthan, demonstrating the dominance of Punjab as the primary source of CRB emissions in the post-monsoon burning season.

3.2. Post-monsoon CRB timing shifts

Temporal changes in state-wide CRB timing and source strength across Punjab and Haryana were quantified using Aqua MODIS FRP data (figure 2). Across Punjab (figure 2(a)), rice residue burning signatures (mid-October, day 270 onwards) were stronger and lasted longer (close to 40 d in most years) compared to those of wheat residue burning

(mid April, day 110 onwards, typically lasting 30 d). A distinct shift in the starting date of rice residue fires can be observed, moving from the end of September (day 270) in 2003 to the first week of October (day 280) by 2018. This matches delays in the harvesting of rice, which is identified in the corresponding time series of Aqua MODIS vegetation indices (figure S4). Across all years, rice residue burning was completed by mid to late November (day 330), in time for the sowing of wheat in late November. Similar to Punjab, rice residue burning in Haryana (figure 2(b)) started in mid October (day 290) and continued for longer each year. No such timing shifts were observed in the wheat residue burning period (mid April, day 110 onwards). State-wide integrated timing shifts of post-monsoon rice residue burning were calculated from aggregated (mean) time series of daily FRP for the state of Punjab for: 1. 2003 to 2008 when abundant irrigation took place unrestricted by Government legislation, 2. 2009 to 2013 after the introduction of the 2009 SSWA when paddy transplantation occurred on 10th June or later (GOP 2018), and 3. 2014 to 2017 when Government of Punjab policy updates meant paddy transplantation

moved to 15th June. The same shifts were calculated for Haryana, but for just two time periods reflecting pre- and post-SSWA implementation since no post-2013 legislation change occurred (GOH 2009). Fits to these data (figure S5) indicate that on average, the peak of post-monsoon rice residue burning in Punjab shifted later by 9 ± 1 d between 2009 and 2017 compared to 2003–2008, and that in Haryana by 11 d. These shifts agree with a 10 d delay in the peak of vegetation greenness observed during the monsoon ‘Kharif’ rice growing season (figure S4), and the post-monsoon CRB shifts ascertained by Jethva *et al* (2019). Whilst the CRB timing shifts are synonymous with delayed harvesting of rice, it is important to note that in Punjab the timing changes occurred even before implementation of the SSWA, although the shift became more pronounced after 2009. Furthermore, in terms of overall emission magnitude, post-monsoon FRP totals reached a maximum of 167 GW in the pre-SSWA era (2003 to 2008) over Punjab (figure S5(a)) which then increased by 19% between 2009 and 2013, and by 40% between 2014 and 2017. For Haryana, a FRP total of 19 GW in the pre-SSWA era (figure S5(b)) is observed, which increased by 57% between 2009 and 2018 in the period following implementation of the SSWA.

3.3. Variability of $PM_{2.5}$ related to CRB timing shifts: A 2016 case study

3.3.1. $PM_{2.5}$ concentrations in Delhi

In 2016, post-monsoon burning of rice residue was reported to have contributed significantly to one of the most intense air pollution episodes recorded across the IGP (Sawhani *et al* 2019, Jethva *et al* 2019, Mukherjee *et al* 2020). Our air quality modelling (section 2.2) was used to simulate a number of scenarios and show how the ~ 10 d shift in peak post-monsoon CRB timing associated with the SSWA introduction (section 3.2) may have impacted this event. For Scenario A (the baseline), the peak of fire emission was based on the peak in daily VIIRS AF counts (7th November 2016), whereas for Scenario B and C it was shifted 10 d earlier and later, respectively. For all three 2016 scenarios, we compared the simulated daily absolute ambient $PM_{2.5}$ concentrations and the CRB contribution (%) for Delhi (figure 3). For the baseline scenario, modelled $PM_{2.5}$ concentrations peak in the first week of November at between $150 \mu\text{g m}^{-3}$ and $200 \mu\text{g m}^{-3}$, with CRB emissions contributing on average 40 %, a similar finding to Cusworth *et al* (2018) and Bray *et al* (2019). For Scenario B i.e. earlier fires without implementation of the SSWA, the modelled $PM_{2.5}$ concentration profile shifts backwards but maintains a similar intensity and shape as the baseline Scenario A. Although a $\sim 20 \mu\text{g m}^{-3}$ reduction in peak $PM_{2.5}$ concentration is observed, the timing shifts do not

change the number of days [55 d] in which Delhi’s modelled $PM_{2.5}$ concentration exceeds the national 24 h ambient air quality standard of $60 \mu\text{g m}^{-3}$, nor the time-integrated exposure of the population. However, for Scenario C, the peak $PM_{2.5}$ concentration could have been $\sim 50 \mu\text{g m}^{-3}$ higher, with the number of days of air quality threshold exceedance increased to 59 d, and a total integrated $PM_{2.5}$ exposure increase by 36%.

3.3.2. $PM_{2.5}$ concentrations across the IGP

The impact of post-monsoon CRB timing changes show a similar pattern of effects for cities located across the IGP to those observed in Delhi (figure 4). To capture influences of short-term $PM_{2.5}$ enhancements, we focused on the 30 d period around the time of maximum $PM_{2.5}$ concentration (thus capturing both the elevation to, and the dissipation from, the peak $PM_{2.5}$ concentration). To capture changes related to the CRB timing of each scenario, we quantify:

- Mean (percentage) difference in modelled $PM_{2.5}$ calculated across the peak concentration in the early fire Scenario B ± 15 d, and that centered on the peak $PM_{2.5}$ concentration in the baseline Scenario A ± 15 d ($\Delta BA_{PM_{2.5}}$).
- Mean (percentage) difference in modelled $PM_{2.5}$ calculated across the peak concentration in late fire Scenario C ± 15 d, and that centered on the peak $PM_{2.5}$ concentration in baseline Scenario A ± 15 d ($\Delta CA_{PM_{2.5}}$).

Earlier CRB activity results in modest reductions ($<6\%$) in modelled $PM_{2.5}$ concentrations compared to the baseline ($\Delta BA_{PM_{2.5}}$) across Delhi and other cities in the IGP (figure 4(b)). In the case of later fires, increases in $PM_{2.5}$, compared to the baseline, are observed (i.e. a positive $\Delta CA_{PM_{2.5}}$) and some are very significant, particularly close to the CRB source region (up to 31%, Ludhiana) and downwind of Delhi (up to 21%, Lucknow). These results indicate that SSWA-related shifts in CRB timing did not contribute significantly to the severity of the 2016 post-monsoon air quality event. However, under the meteorology and CRB emissions of 2016, had the fires have been delayed by a further 10 d, the increased air quality impact could have been highly significant.

3.4. Impact of meteorological conditions and CRB emission on $PM_{2.5}$ concentrations

Air quality impacts in Delhi from residue burning sources, as well as local air pollution sources, are sensitive to weakened north-westerly winds and/or reductions in the height of the boundary layer (Tiwari *et al* 2013, Mukherjee *et al* 2020, Beig *et al* 2020). We evaluated this sensitivity, and that to the absolute residue burning emissions magnitude, using a

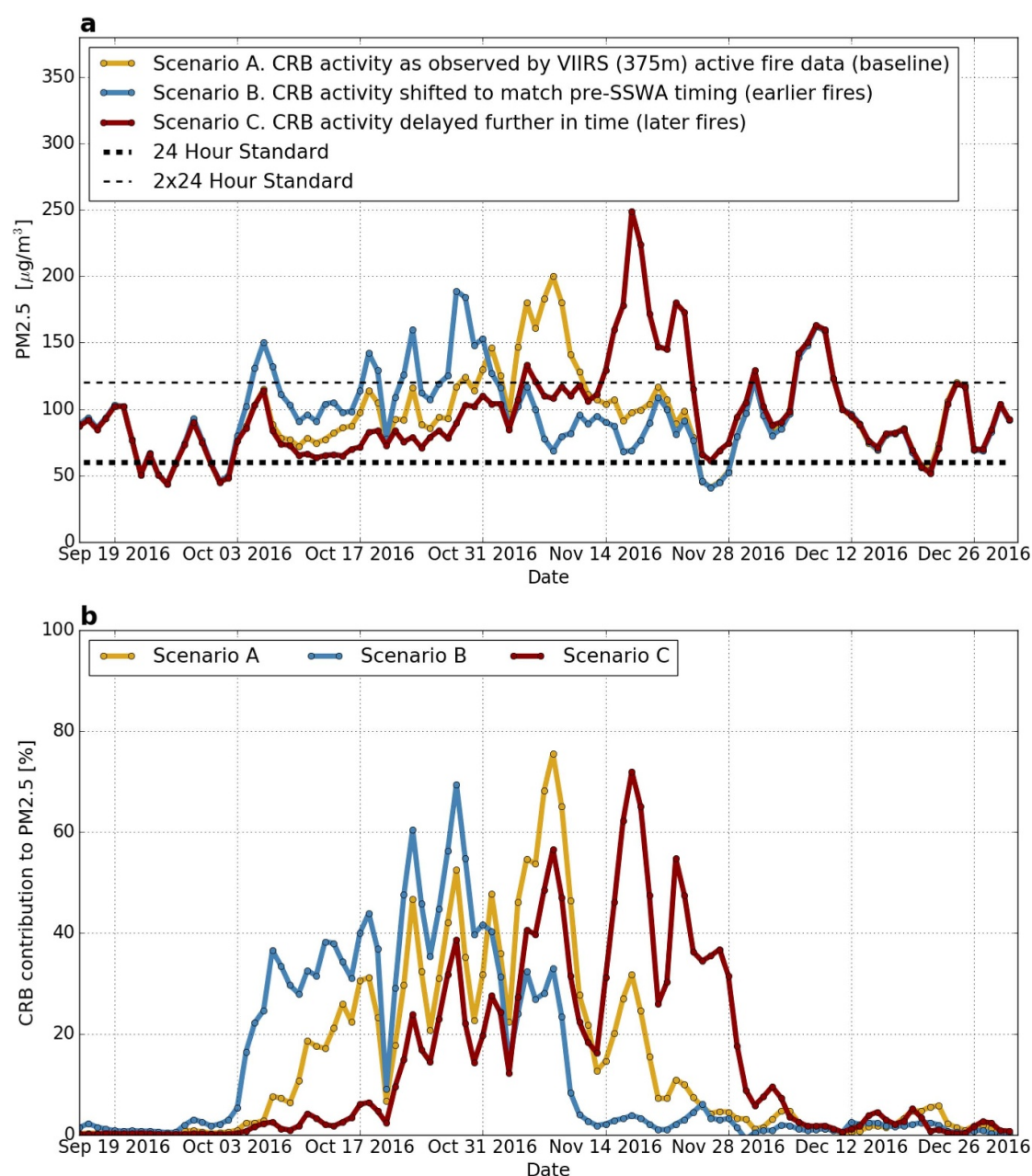
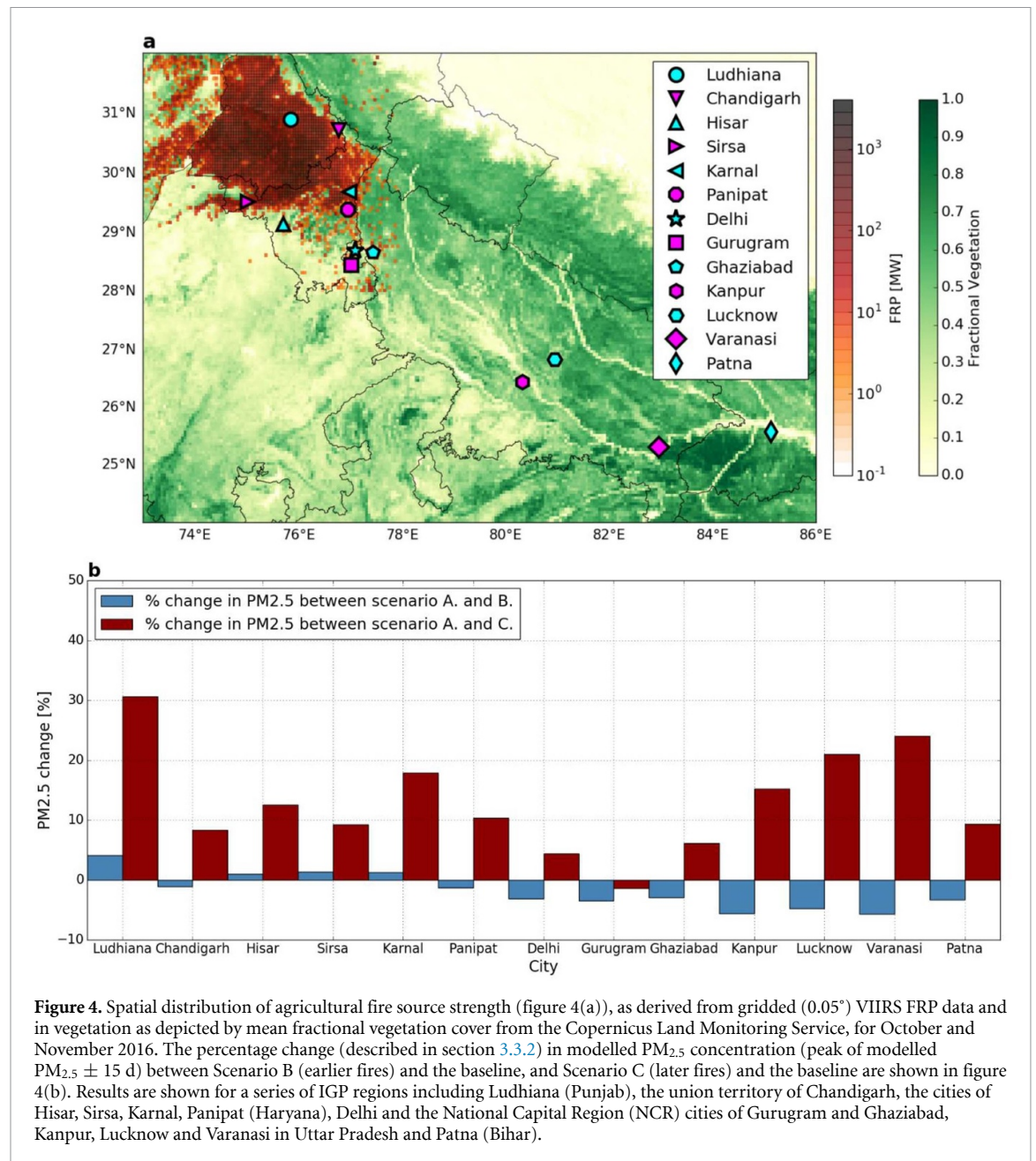


Figure 3. Time series of post-monsoon CRB smoke emissions impacts over Delhi under different CRB timing scenarios for 2016. Figure 3(a) shows the absolute daily mean ambient PM_{2.5} concentration, and figure 3(b), the CRB contribution (in %). Simulated PM_{2.5} data from the baseline Scenario A (mustard line), along with that of Scenario B (earlier fires than currently experienced, blue line) and C (later fires than currently experienced, maroon line) are shown.

series of additional model experiments each driven by ERA-Interim meteorological fields for 2016 to 2018. The withdrawal of the SW monsoon from NW India was consistent between these 3 years (table S2). The model experiments were run with fixed boundary conditions, fixed atmospheric emissions from all other sectors, and fixed timing and spatial distribution of CRB fires (remaining consistent with the three scenarios used for 2016). However, for the 2017 and 2018 simulations, the fires were located spatially according to VIIRS AF detections of 2016 and the absolute CRB emissions magnitude of each year were adjusted according to changes in total FRP observed by Aqua MODIS (figure S2(b)). Across

Punjab, Haryana and Rajasthan collectively, this corresponded to total emissions reductions of 41% and of 29% in 2017 and 2018 respectively—further indicating the unusual magnitude of the 2016 CRB period.

Table 1 shows results from these experiments, which each used a different years CRB emission amount ('E') or meteorological condition ('M'). The numbers '16', '17' and '18' refer to the year of meteorology and CRB emissions used for each experiment. For each scenario and for the ± 15 d period around the time of maximum PM_{2.5} concentration observed from October to November, we again report $\Delta\text{CA}_{\text{PM}_{2.5}}$ and $\Delta\text{BA}_{\text{PM}_{2.5}}$ as well as:



- The importance of CRB emissions to overall ambient PM_{2.5} concentrations (CRB % contribution), calculated from the total modelled PM_{2.5} concentration of each scenario compared to that of the same exact scenario but with zero fire emissions.
- The mean PM_{2.5} concentration ($\overline{PM_{2.5}}$).

3.4.1. Constant CRB emissions with varied timing and meteorological regime

Table 1 shows that higher $\overline{PM_{2.5}}$ concentrations ($>177 \mu\text{g m}^{-3}$) for Scenario A (baseline) were observed over Delhi in E16M17 and E16M18 (compared to the $122.5 \mu\text{g m}^{-3}$ of E16M16). Over Ludhiana, $\overline{PM_{2.5}}$ exceeded $193 \mu\text{g m}^{-3}$ in E16M17 and E16M18 compared to E16M16 ($121.6 \mu\text{g m}^{-3}$).

A similar pattern was found for Kanpur. Concentrations were higher in the E16M17 and E16M18 experiments that experienced lower wind speeds (i.e. less dispersive conditions, see figure S6) related to local meteorological stability, promoting the near-surface accumulation of air pollutants.

In the case of the earlier (Scenario B) CRB fires, changes in PM_{2.5} compared to the baseline ($\Delta\text{BA}_{\text{PM}_{2.5}}$) are generally not that large, and unlike for 2016 do not show reductions in each city. Thus our modelling shows that CRB timing shifts observed since the 2009 SSWA are not universally driving up post-monsoon air pollution across northern India, as has been suggested by Chowdhury *et al* (2019), Singh *et al* (2019) and Sawlani *et al* (2019). In the case of the later (Scenario C) CRB fires, the $\Delta\text{CA}_{\text{PM}_{2.5}}$ metric is also quite variable between experiments. A

Table 1. CRB % contribution, $\overline{PM}_{2.5}$, $\Delta BAPM_{2.5}$ and $\Delta CAPM_{2.5}$ (see section 3.3.2 for description of calculations) reported for Delhi, Ludhiana and Kanpur for a set of model experiments in which CRB emissions and meteorology regimes were adjusted with respect to the years 2016 to 2018.

Delhi	Scenario A (current CRB timing)			Scenario B (earlier CRB timing)			Scenario C (later CRB timing)		
	Run Name	CRB contri- bution (%)	$\overline{PM}_{2.5}(\mu g\ m^{-3})$	CRB contri- bution (%)	$\overline{PM}_{2.5}(\mu g\ m^{-3})$	$\Delta BA_{PM_{2.5}}$ (%)	CRB contri- bution (%)	$\overline{PM}_{2.5}(\mu g\ m^{-3})$	$\Delta CA_{PM_{2.5}}$ (%)
	E16M16	41.4	122.2	42.1	115.1	-3.2	43.4	126.7	4.4
	E16M17	30.9	183.9	25.2	168.1	-1.7	35.7	172.8	-1.3
	E16M18	28.1	177.0	26.5	173.7	14.6	31.0	171.3	9.7
	E17M16	35.2	101.2	32.2	94.5	-5.6	35.5	102.1	1.2
	E17M17	22.5	167.4	16.7	156.0	-4.0	25.9	149.5	-4.1
	E18M18	22.8	160.6	21.5	160.5	14.8	25.3	156.4	6.7
Ludhiana									
		Scenario A			Scenario B			Scenario C	
	Run Name	CRB contri- bution (%)	$\overline{PM}_{2.5}(\mu g\ m^{-3})$	CRB contri- bution (%)	$\overline{PM}_{2.5}(\mu g\ m^{-3})$	$\Delta BA_{PM_{2.5}}$ (%)	CRB contri- bution (%)	$\overline{PM}_{2.5}(\mu g\ m^{-3})$	$\Delta CA_{PM_{2.5}}$ (%)
	E16M16	56.2	121.6	57.9	115.5	4.1	61.6	144.2	30.7
	E16M17	40.6	193.4	35.6	191.6	18.0	46.1	179.1	1.5
	E16M18	37.7	199.7	36.2	183.2	-0.7	45.4	181.2	-8.3
	E17M16	43.9	94.8	45.7	89.0	0.4	49.6	109.3	24.1
	E17M17	29.8	169.9	25.4	157.5	-2.5	32.5	169.2	2.9
	E18M18	30.7	169.8	27.5	166.7	11.6	38.2	154.3	-0.1
Kanpur									
		Scenario A			Scenario B			Scenario C	
	Run Name	CRB contri- bution (%)	$\overline{PM}_{2.5}(\mu g\ m^{-3})$	CRB contri- bution (%)	$\overline{PM}_{2.5}(\mu g\ m^{-3})$	$\Delta BA_{PM_{2.5}}$ (%)	CRB contri- bution (%)	$\overline{PM}_{2.5}(\mu g\ m^{-3})$	$\Delta CA_{PM_{2.5}}$ (%)
	E16M16	27.4	91.4	25.2	82.2	-5.7	28.6	103.5	15.2
	E16M17	18.9	122.1	13.3	114.2	-2.8	18.0	118.9	-0.8
	E16M18	19.5	118.2	15.7	110.5	-2.6	17.7	113.2	-1.9
	E17M16	22.6	82.4	18.5	80.8	1.4	26.7	93.1	14.4
	E17M17	14.5	115.6	10.1	111.0	-2.4	13.5	113.3	-1.1
	E18M18	16.3	112.7	13.3	106.9	-2.1	17.1	110.6	2.7

4.4% increase in $\overline{PM_{2.5}}$ is seen in Delhi, 30.7% in Ludhiana and 15.2% Kanpur for the E16M16 run, but when using the meteorology from other years (E16M17 and E16M18), such a consistent increase is not observed (i.e. E16M17 in Delhi and Ludhiana). In some cases, $PM_{2.5}$ concentrations even decrease (i.e. E16M17 Delhi, E16M18 Ludhiana and E16M17 Kanpur), demonstrating that under fixed emissions scenarios CRB timing has varying impacts on the air quality of cities located both in the CRB source region, and downwind across the IGP. In particular, the local meteorology (i.e. reductions in low-level wind speed, 2 metre air temperature and planetary boundary layer (PBL) height) existing at the time of peak CRB emissions plays an important role in regulating $PM_{2.5}$ enhancements.

3.4.2. Varying CRB emissions with varied timing but constant meteorological regime

Modelled ambient $PM_{2.5}$ for Scenario A using the same 2016 meteorology but reduced CRB emissions (i.e. comparing E16M16 to E17M16 in table 1) show that the $PM_{2.5}$ contributions coming from CRB decrease accordingly, for example from 41.4% to 35.2% over Delhi. A CRB emissions reduction of 41% ('E16' vs. 'E17') generates a 17.2% reduction in $\overline{PM_{2.5}}$ over Delhi, a 22.1% reduction over Ludhiana and a 9.8% reduction over Kanpur. Over all cities and in most experiments, compared to Scenario A (current fire timing), CRB $PM_{2.5}$ contributions for Scenario B (early fires) tend to be lower and those of Scenario C (later fires) tends to be greater, though all changes remain below an absolute magnitude of 5%. Similar findings are observed for the scenarios based on the 2017 meteorology and changed CRB emissions (i.e. for the E16M17 and E17M17 runs) with $\overline{PM_{2.5}}$ always larger when CRB emissions are higher. These results suggest that significant increases in CRB magnitude over the past 15 years (figure S2), which is corroborated by similarly increased crop production (Jethva *et al* 2019), are likely to be responsible for the increasing severity of post-monsoon air pollution episodes. Additional drivers may come from increases in other sources, for example industrial activities or vehicle ownership, which has grown over the last 15 years in the NCR (GOI 2017). Compared to these effects, the impact of the later CRB timing induced by the 2009 SSWA legislation appears to be minimal, and indeed can sometimes decrease as well as increase air quality problems depending on the meteorological conditions of the time. For example, Sawlani *et al* (2019) and Takigawa *et al* (2020) report how calmer meteorology (i.e. reduced wind speed and lower PBL height) induce enhancements in $PM_{2.5}$ from CRB and local sources. In our model experiments for both 2017 and 2018, the increased occurrence of low wind speeds ($<2 \text{ m s}^{-1}$) limited the natural dispersion of pollutants

and made $\overline{PM_{2.5}}$ typically higher for the same CRB emissions and timing in these years compared to 2016.

4. Discussion and implications

Through analysis of satellite data and modelling, we have confirmed that rice residue burning contributes very significantly to ambient atmospheric $PM_{2.5}$ concentrations across the IGP during the post-harvest October to November period. During the 2016 air quality crisis for example, we find CRB to be responsible for more than 40% of the near-surface airborne $PM_{2.5}$ in Delhi. This contrasts with the situation of carbon monoxide (CO) air pollution in Delhi, for which Dekker *et al* (2019) found CRB to be only a limited contributor. We contend that this is at least in part down to the ratio of the rice residue burning CO and $PM_{2.5}$ emissions factors (g kg^{-1}), which Zhang *et al* (2015) show is around half that of tropical forest, savannah, and pasture maintenance fires. The result is that CRB influences on atmospheric $PM_{2.5}$ tend to be higher than on CO, in comparison to these other types of burn.

We show that the area and amount of residue burned has increased significantly over the past almost two decades—mirroring government statistics on increasing crop yields (figure S2 and S3). We have also found that the rice residue burning period has been delayed by 10 d since the introduction of the 2009 SSWA and the consequential delayed planting of paddy rice compared to the pre-SSWA period. Whilst modifying the date of paddy sowing has had the desired positive impact on the water table (Tripathi *et al* 2016), our modelling indicates that this has not had the unintended consequence suggested by Singh *et al* (2019) and Sawlani *et al* (2019) of significantly worsening air quality across northern India in the last decade (figure 4). Rather it is the increasing amount of residue being burned that is responsible—with additional year-to-year variability influenced by post-monsoon atmospheric dynamics (figures 1, 2, table 1). These results are strongly aligned with those of Ojha *et al* (2020) that showed reduced meteorological ventilation acting to confine air pollutants near the surface, when combined with increased CRB emissions, can lead to the widespread enhancements of $PM_{2.5}$ across the IGP.

Changes in SW monsoon behaviour, such as earlier onset and delayed withdrawal, as dictated by climate variability are expected in the future (Christensen *et al* 2014) and could impact future IGP air pollution. However, it may be wise to avoid further policy-driven delays to paddy sowing dates until such time as there is largescale uptake of CRB alternatives—such as the Happy Seeder, Super Straw

Management Systems and Paddy Straw Chopper-/Mulcher (Shyamsundar *et al* 2019)-since our modelling shows that another 10 d delay can sometimes result in large increases in $PM_{2.5}$ concentrations. Operational guidance released by the Ministry of Agriculture and Farmer Welfare actively promotes agricultural mechanisation for the *in situ* management of crop residue, which will act to support the farming community manage excessive residue in a timely fashion (Ravindra *et al* 2019). Ultimately, the halting of CRB would greatly aid the newly established National Clean Air Program (NCAP) (GOI 2019). The NCAP aims at reducing emissions from various sectors including agricultural residue burning. An interim target of 20%–30% reduction in annual PM concentration by 2024 has been suggested in the NCAP (using 2017 as a base year) with a continued focus on countering the frequency of intense post-monsoon air pollution episodes. This is particularly important as DALYS estimated at 149 thousand years in northern India could be prevented by halting CRB (Chakrabarti *et al* 2019).

5. Conclusions

Focusing on episodes of post-monsoon air pollution across the IGP, our results demonstrate how a combination of satellite data and atmospheric modelling can greatly aid the understanding of how drivers of agricultural productivity and poor air quality are coupled to changes in state government legislation. Our modelling approach helps separate influences not easily disaggregated when simply correlating different driving data (e.g. FRP) with measurements of air quality.

Our study provides evidence that the amount of rice residue burned in the NW Indian states of Punjab and Haryana exerts a very strong control on post-monsoon October to November air quality. Although the impact of agricultural burning emissions dissipates further from source regions, $PM_{2.5}$ enhancements can be observed right across the IGP. This and the specific post-monsoon meteorological conditions existing at the time of burning are the dominating factors controlling the severity of episodes of poor air quality. Increases in the number, spatial extent and total FRP of CRB fires up to 2018, and the different scenarios used in our simulations implicate increased residue burning as the main driver of the worsening concentrations of airborne $PM_{2.5}$ found during periods of poor air quality.

As suggested by Jethva *et al* (2019), we do find a significant (~ 10 d) shift in the timing of rice residue burning, in part related to the 2009 introduction of the groundwater preserving SSWA in Punjab and Haryana. However, our modelling shows that the magnitude, and even direction of $PM_{2.5}$ concentration change is not highly sensitive to this, and

is instead far more dependent on the specifics of the meteorological conditions prevailing at the time. Since reducing the amount of CRB always makes a consistent reduction to the $PM_{2.5}$ concentrations experienced across the IGP, rather than focus on the timing of residue burning, we recommend the implementation of adequate systems for the collection, storage and processing of agricultural residues to replace more polluting fuels in energy generation. Such policies can provide farmers with affordable alternatives to hasten the effective prohibition of CRB and thus reduce the very severe human health impacts that currently result from its continued growth.

Acknowledgments

This research used the ALICE High Performance Computing Facility at the University of Leicester. Authors are grateful to two anonymous reviewers who provided valuable and constructive comments. NASA and NOAA are thanked for access to the various satellite data used, some of which were processed on the JASMIN Super Data Cluster, operated by STFC on behalf of UKRI-NERC. We would like to thank the Ministry of Agriculture & Farmers Welfare, Government of India for their online archive of agricultural datasets, and the Department of Agriculture and Farmer Welfare, Government of Punjab and Government of Haryana, for making details of Acts and policies available online. We would like to express our gratitude to G.S. Dhillon and D. Sharma of the Department of Soil and Water Conservation, Punjab for additional information about the SSWA.

Funding

This research was completed with funding from the UK Science and Technology Facilities Council (STFC) through the Global Challenges Research Fund (GCRF) (ST/R00286X/1), and from the British Council and Indian Department of Science and Technology (DST) through the UK-India Education and Research Initiative (UKIERI) (IND/CONT/G/16-17/81). Aspects of this research were supported by a University of Leicester Quality-Related (QR) GCRF award, the UK National Environment Research Council (NERC) NC funding to NCEO (NE/R016518/1) and by the Leverhulme Centre for Wildfires, Environment and Society through the Leverhulme Trust (RC-2018-023).

Author contributions

HS led this research, conducted the analysis of state-level satellite datasets and model outputs, and generated the graphics of satellite and model datasets. TZ extracted and analysed active fire datasets and AM

extracted and analysed state-level agricultural datasets. SS, NS, and SA conceptualised and conducted the WRF-CMAQ model experiments with interpretation and input from MW, HS and HB. HS and MW wrote the paper with significant contributions, discussions and editing from SS, NS, SA, TZ, AM, SG, HB, SNT, RK, and SM.

Conflict of interests

The authors declare no competing interests.

Data availability

The data that support the findings of this study are available upon reasonable request from the authors.

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