BRIEF COMMUNICATION
https://doi.org/10.1038/s41893-019-0304-4

nature sustainability

Tradeoffs between groundwater conservation and air pollution from agricultural fires in northwest India

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Air pollution imposes enormous public health and economic burdens in northwest India. Groundwater conservation policies appear to be exacerbating the crisis by concentrating agricultural burning in the late fall with a 39% higher peak fire intensity occurring when meteorological conditions favour poor air quality. Reconciling food security, resource depletion and environmental quality tradeoffs is necessary for achieving sustainable development in the breadbasket region of India.

South Asia megacities are global hotspots for poor air quality[1], and catastrophic spikes in air pollution are increasingly common in northwest India in the fall season following cessation of the monsoon rains[2]. Haze in the capital region of New Delhi brings the city to a standstill through travel delays, school closings and illnesses. These impacts are not transitory: in 2015, India had an estimated 1.09 million deaths from air pollution, costing the economy 3% of gross domestic product[3]. Fine particulate matter ($PM_{2.5}$) in New Delhi is of particular concern, with average levels occasionally exceeding 700 $\mu g\,m^{-3}$ (Supplementary Fig. 2). As a consequence, an estimated 16,000 premature deaths are caused every year in the New Delhi capital region, with an aggregate reduction in life expectancy of 6 years[1,4,5].

Air pollution in New Delhi has significantly worsened since 2000[6,7]. The main sources of pollution are vehicle emissions, construction, industry and the burning of wood, coal and crop residues. During late October and early November, rice crop residue burning from the adjacent states of Punjab and Haryana contributes 25–70% of the $PM_{2.5}$ pollution in New Delhi[2,8,9]. These states compose the 'breadbasket' of India, where yields of rice and wheat are the highest in South Asia[10]. With the advent of combine harvesting in the 1980s, in situ burning of rice residues became the method of choice for accelerating the turn-around time between crops to ensure timely wheat planting and maintenance of yield potential[11]. Since the alternative practice of incorporating residues into soil is both time consuming and costly[12], there are strong incentives for burning. Despite laws that ban the practice, approximately 23 million tonnes of rice residues are burned annually in Punjab and Haryana[12], with $PM_{2.5}$ dominating the pollution load[10].

Air pollution is not the only critical sustainability issue confronting agriculture in the northwest. Groundwater depletion from irrigating rice poses a central threat to national food security[13,14]. Attempts to replace rice with less water-demanding crops have failed because of subsidies favouring rice, such as free electricity for irrigation, assured output markets and minimum support price guarantees[15]. More success has been had in compelling farmers to change agronomic practices. Historically, most rice was transplanted before the onset of monsoon. The Punjab Preservation of Subsoil Water Act and the Haryana Preservation of Subsoil Water Act (hereafter, the groundwater acts) were promulgated in March 2009 and prohibit transplanting before 10 June—a date that was subsequently adjusted to 20 June. Simulation studies suggest that groundwater depletion is significantly reduced through the groundwater acts[16].

In this analysis, we use time series satellite data to develop first inferences about the implications of groundwater conservation policies on air quality in northwest India, as mediated by changing patterns of rice production and agricultural burning. For the six rice seasons before the groundwater acts, an average of 86% of the rice area in Punjab and Haryana was planted on or before 28 June. The influence of the acts is clear, with less than 40% of the total rice area planted on or before 28 June since 2009 (Supplementary Fig. 1). Rice harvest has shifted accordingly. Before 2009, approximately 40% of the rice crop in Punjab was harvested by 26 October, but thereafter this declined to 14% (Fig. 1). Changes in Haryana were less pronounced since aromatic rice varieties are common and transplanted later. In aggregate, we document an 8-d harvest delay (mean Julian date: 313 versus 305) that is accompanied by a more concentrated distribution (s.d.: 8 versus 10 d).

Following the groundwater acts, residue burning declined within the last fortnight of October but significantly increased in the first three weeks of November (Fig. 2a). Before the acts, maximum occurrence was on 24 October at 490 fires per day. After implementation of the acts, this increased to 681 fires per day, peaking around 4 November. Groundwater act implementation is associated with a concentration of crop residue burning into a narrower window, later in the season, and with a peak intensity that is 39% higher.

New Delhi's pollution 'airshed' in the late autumn extends northwest to Haryana and Punjab[2,8,9]. Seasonal $PM_{2.5}$ trends strongly correlate with residue burning in the airshed[2,8,9,17], and also with meteorological conditions that favour pollution[18]. After the groundwater acts, the period of maximum burning shifted to the first fortnight of November (Fig. 2a) when temperatures in New Delhi are 3 °C lower and winds are weaker compared with the second fortnight of October (Supplementary Fig. 3). These conditions favour atmospheric stability and discourage the dispersion of air pollution. Consequently, average daily $PM_{2.5}$ concentrations in November were 29% higher after the groundwater acts (Fig. 2b). In relative and absolute terms, the increase in November was significantly higher than in any other month (Supplementary Fig. 4), suggesting that agricultural fires rather than temporal emission trends from other

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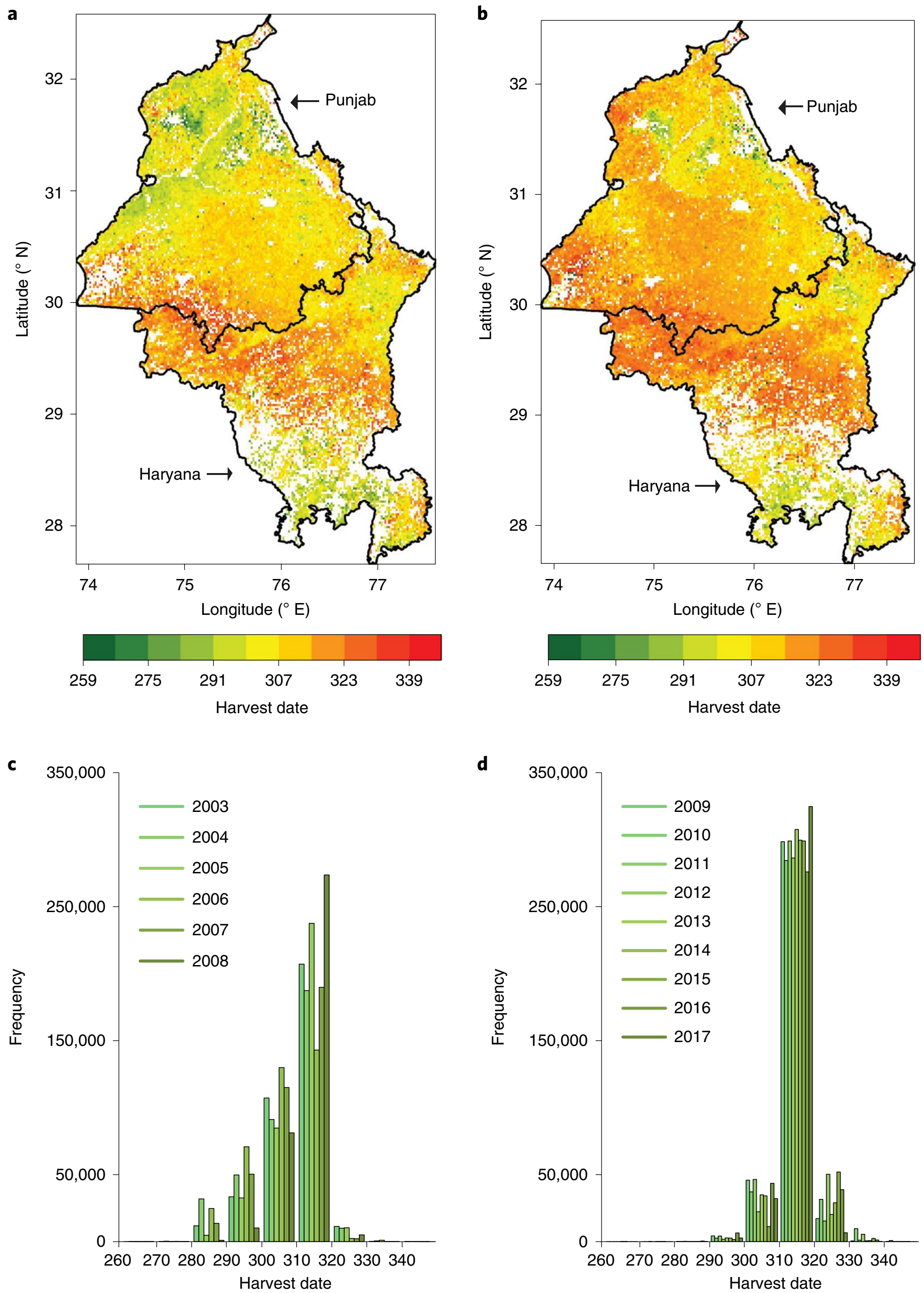

Fig. 1 | Rice harvesting dates. a,**b**, Rice harvesting dates (day of year) in Punjab and Haryana before (**a**; 2003–2008) and after (**b**; 2009–2017) implementation of the groundwater acts. **c**,**d**, Date-wise frequency distributions by year for 2003–2008 (**c**) and 2009–2017 (**d**).

economic sectors are principally responsible for deteriorating air quality following the monsoon. It is important to note that total rice area increased by 10%, and aggregate rice production by 11%, in the period after implementation of the acts, ostensibly increasing the pollution load from burning. In contrast, while rainfall and maximum and minimum daily temperatures were very similar before and after implementation of the acts, wind speed significantly increased in the later period, which probably improved air quality, ceteris paribus. Additional air pollution monitoring and modelling efforts are required at the regional scale to confirm our results by disentangling the relative contribution of agricultural burning to air quality in the context of dynamic climate factors, including changes in regional air circulation patterns[19], while accounting for emission sources from different economic sectors.

Our analysis suggests that temporal changes in burning are a prime contributor to the air quality crisis in northwest India. The apparent tension between groundwater conservation and enhancing regional air quality is not necessarily a zero-sum game, but it is also clear that there are no simple solutions at the nexus of food security, resource depletion and environmental quality. A sensible approach for overcoming tradeoffs will embrace agronomic technologies, such as the Happy Seeder, that permit crop establishment into residues without burning[20], along with management adjustments such as encouraging the cultivation of shorter-duration

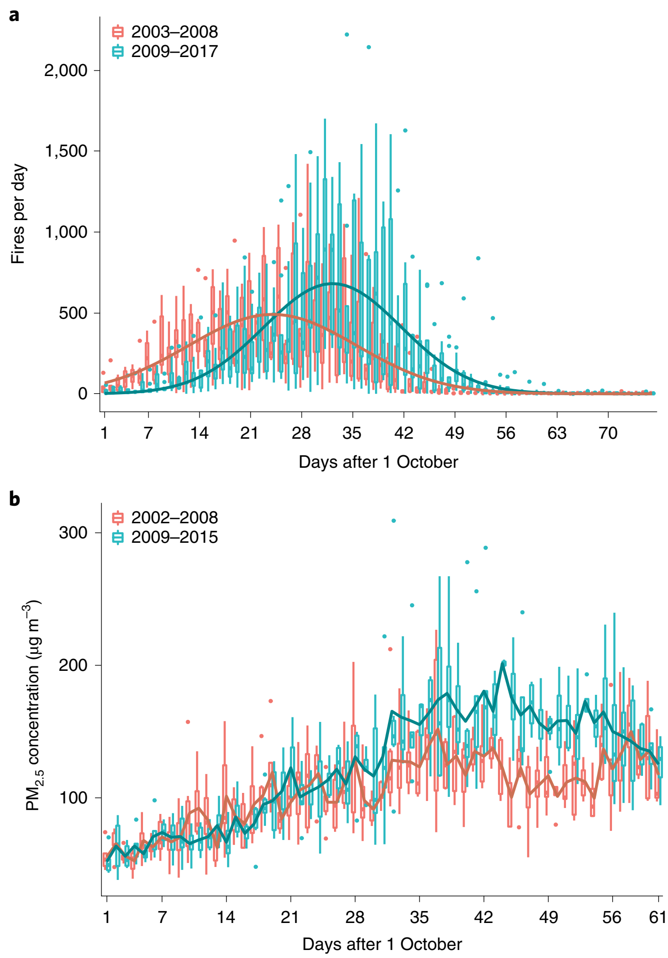

Fig. 2 | Fires and $PM_{2.5}$ concentrations. a, Active fires in Punjab and Haryana, before (2003–2008) and after (2009–2017) the groundwater acts, following the rice harvest. Regression curves generalize the relationship between date and fire occurrence. **b**, $PM_{2.5}$ for New Delhi after 1 October before (2002–2008) and after (2009–2015) the groundwater acts. For both graphs, the line within each box represents the median, and the lower and upper boundaries of the box indicate the first and third quartiles, respectively. Error bars (whiskers) represent 1.5× the interquartile range, with data points above or below this shown as outliers.

rice varieties so that the burning patterns are more dispersed and less concentrated in November. Energy production and other off-farm uses for crop residues are also probable candidates to provide part of the solution. At the same time, new approaches to water conservation[21] are emerging that, if appropriately incentivized through measures such as full pricing of energy, would probably reduce the policy imperatives to prohibit earlier rice establishment.

The Government of India has recently launched a US$157 m (October 2018 exchange rate) initiative to discourage burning through agricultural machinery innovations. While this and the other aforementioned interventions hold significant promise, deeper structural changes may also be warranted. The current policy environment encourages productivity maximization of cereals and, consequently, very high levels of residue production. If these policies are changed because tradeoffs cannot be resolved, companion efforts will be needed to facilitate sustainable intensification in areas such as the Eastern Gangetic Plain, where water resources are relatively abundant and closer coupling of crop–livestock systems provides a diverse set of end uses for crop residues.

Methods

Rice area and phenology. We used 13 years (2003–2017) of Moderate Resolution Imaging Spectroradiometer (MODIS) 16-day L3 composite enhanced vegetation index (EVI) data at 250 m resolution. By combining data from the National Aeronautics and Space Administration's Terra (MOD13Q1) and Aqua (MYD13Q1) satellites, EVI estimates were compiled at 8-d intervals for Punjab and Haryana. EVI data were then smoothed for each pixel using TIMESAT's Savitzky–Golay filter, resulting in growth curves for the monsoon season that were used to derive estimates of establishment, maturity, field duration and maximum growth.

An analysis mask to segregate rice areas was developed in two steps. First, high-productivity pixels were identified as those exceeding an EVI threshold of 0.5 during the monsoon cropping season. Then, field duration criteria (rice ranges: 112–152 d in Punjab and Haryana) were used to segregate rice from other crop types and permanent vegetation. Good correspondence ($r^2 = 0.75$, coefficient of determination) was found between rice area predictions and government statistics at the district level. The derived rice mask delimited all subsequent analyses.

Following the methods developed by Boschetti et al.[22], we estimated relative differences in crop establishment dates (herein referred to as planting) before and after implementation of the groundwater acts by assessing when each rice pixel achieved 10% of maximum EVI on the ascending limb of the growth curve; actual transplanting was likely to be 2–3 weeks before our estimates. We then calculated when a pixel declined to 10% of peak EVI on the descending limb of the growth curve, to assess differences in crop maturity, herein referred to as harvest.

Fire data. MODIS-C6 active fire data (1 km² spatial resolution) were analysed from 1 October 2003 to 31 December 2017 for rice areas in Punjab and Haryana. Fires per day were estimated by counting active fire pixels, with 'low confidence' (that is, <30%) active fire pixels excluded from the analysis. MODIS active fire data probably underestimate the number of actual fires because most agricultural fires are small and short in duration; additionally, there could be multiple fires occurring within each pixel[23]. Observations from newer satellite platforms such as the Visible Infrared Imaging Radiometer Suite (VIIRS) suggest that the number of active fires is probably five- to tenfold higher than suggested by the MODIS data[24]. VIIRS was launched at the end of 2011; hence, there were not sufficient historical data to use VIIRS in our analysis.

Measured $PM_{2.5}$ data. Ground-based air quality monitoring data were averaged across 27 stations in the New Delhi region.

Satellite-estimated $PM_{2.5}$ data. To complement the limited availability of historical ground monitoring data, daily estimates of $PM_{2.5}$ from 2003–2015 were evaluated from a MODIS-based dataset developed with methods detailed by Kumar et al.[25]. Data are available at a spatial resolution of 5 km and predicted by a regression model that associates MODIS-derived aerosol optical depth with ground-based air pollution data.

Statistical tests. Means separation for meteorological factors, fire occurrence, crop phenology and $PM_{2.5}$ concentrations was conducted with one-way analysis of variance, with statistical significance established at $P < 0.05$.

Data availability

MODIS EVI data were acquired from the NASA Land Data Products and Services portal: https://lpdaac.usgs.gov/products/mod13q1v006/. MODIS active fire data were acquired from the Fire Information for Resource Management System: https://firms.modaps.eosdis.nasa.gov/download/. Measured $PM_{2.5}$ data for New Delhi were acquired from the National Ambient Air Quality Monitoring Network that aggregates information from 27 air quality monitoring stations that are distributed across the capital region. Year-wise daily data are available from the Government of India (note: filter results for 'Delhi'): https://data.gov.in/catalog/historical-daily-ambient-air-quality-data. Satellite-estimated $PM_{2.5}$ data for New Delhi were acquired from the University of Miami: http://precise.miami.edu/index_delhi.php. Rice yield data for Punjab and Haryana were compiled from various Government of India sources: https://aps.dac.gov.in/APY/Public_Report1.aspx, https://nfsm.gov.in/ReadyReckoner/NFSMRR/NFSM_AllocationReleases2018.pdf and http://esaharyana.gov.in/en-us/Economic-Survey-of-Haryana-2016-17-English. Weather data for New Delhi were acquired from the Indian Agricultural Research Institute: http://www.iari.res.in/index.php?Itemid=1033&id=402&option=com_content&view=article. Political boundaries depicted in our maps are distributed as spatial data by GADM (www.gadm.org).

Received: 28 October 2018; Accepted: 1 May 2019;
Published online: 17 June 2019

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Author contributions
B.-S. and A.J.M. conceptualized the study and were the principal drafters of the manuscript. A.K.S. developed the analytical methods and conducted the geospatial analyses. B.G. contextualized the research within broader frameworks for sustainable intensification, and contributed to the manuscript accordingly.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary information is available for this paper at https://doi.org/10.1038/s41893-019-0304-4.

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