ENVIRONMENTAL RESEARCH
FOOD SYSTEMS

CrossMark

OPEN ACCESS

RECEIVED
21 August 2023

REVISED
20 January 2024

ACCEPTED FOR PUBLICATION
6 February 2024

PUBLISHED
29 February 2024

PAPER

Mitigating agricultural residue burning: challenges and solutions across land classes in Punjab, India

P P Krishnapriya[1,8,*], Subhrendu K Pattanayak[1], E Somanathan[2], Alwin Keil[3], M L Jat[4,5], H S Sidhu[6] and Priya Shyamsundar[7]

[1] Sanford School of Public Policy, Duke University, 201 Science Drive, Durham, NC 27708, United States of America
[2] Economics and Planning Unit, Indian Statistical Institute, Delhi Centre, 7, S. J. S. Sansanwal Marg, New Delhi, Delhi 110016, India
[3] Unique Land Use GmbH, Schnewlinstrasse 10, 79098 Freiburg, Germany
[4] CIMMYT, G2, B Block, National Agricultural Science Centre Complex (NASC), Dev Prakash Shastri Marg, New Delhi, Delhi 110012, India
[5] Resilient Farm & Food Systems Program, International Crops Research Institute for Semi-Arid Tropics, Patancheru, Telangana 502324, India
[6] Punjab Agricultural University, Ferozepur Rd, Ludhiana, Punjab 141027, India
[7] The Nature Conservancy, Arlington, VA 22203, United States of America
[8] This work was completed by the author prior to joining Amazon.
[*] Author to whom any correspondence should be addressed.

E-mail: krishnapriya.perumbillissery@duke.edu

Keywords: agricultural residue burning, social networks, India, mulching, technology adoption

Supplementary material for this article is available online

Abstract

India faces significant air quality challenges, contributing to local health and global climate concerns. Despite a national ban on agricultural residue burning and various incentive schemes, farmers in northern India continue to face difficulties in curbing open-field burning. Using data from 1021 farming households in rural Punjab in India, we examine the patterns and drivers of the adoption of no-burn agriculture, particularly for farmers who mulch instead of burning crop residue. We find a growing trend in no-burn farming practices among farmers between 2015 and 2017, with the highest adoption rates among large farmers compared to medium and small farmers. Our findings suggest that access to equipment and learning opportunities may increase the likelihood of farmers using straw as mulch instead of burning it. Specifically, social learning appears to increase the likelihood of farmers embracing no-burn practices relative to learning from extension agencies. Furthermore, the form of learning depends on farm size. While large and medium farmers exhibit a variety of learning strategies, small farmers primarily self-learn. These results underscore the importance of a multiprong policy that provides sufficient access to equipment and a combination of learning platforms that enabling farmers from different land classes to adopt no-burn technologies.

1. Introduction

For decades, agricultural residue burning has plagued several regions of the world (Pant 2013, Shyamsundar *et al* 2019, Haider 2013). Seasonal agricultural fires cause spikes in emissions of black carbon and particulate matter, creating severe short-term and irreversible long-term threats to health and the environment (Ramanathan and Carmichael 2008, Gupta *et al* 2016), and contributing to both immediate (Agarwal *et al* 2013, Gupta *et al* 2016) and delayed health costs (Rangel and Vogl 2019, Singh *et al* 2019). However, in the absence of binding regulations and low private costs associated with burning, farmers in many parts of the world continue to burn agricultural residue (Tan-Soo and Pattanayak 2019).

In this paper, we seek to understand how and why farmers who contribute to seasonal agricultural fires may change their land use practices. We examine paddy residue burning in the Indo-Gangetic plains of north-west India, a region that is important because it ensures food security in India by producing large quantities of food crops. The vast majority of farmers in this region grow paddy and wheat in an annual two-crop production system. Because of the narrow time interval between harvesting paddy and sowing wheat, farmers burn paddy straw as an easy way to clear and prepare their fields for the next crop (Singh *et al* 2019, Keil *et al* 2021). Specifically, farmers in the state of Punjab, where most of burning occurs, burn about 19 metric tons of paddy residue (Chaba 2018). This form of residue burning is associated with a 43% increase in seasonal aerosols in the Indo-Gangetic plains (Jethva *et al* 2019) and is estimated to have contributed to 66, 200 air pollution-related deaths in India in 2015 (GBD MAPS 2018). This problem may have been exacerbated by COVID-19, causing significant increases in burning in 2020 (60%) relative to previous years (Ravindra *et al* 2022).

While much has been written about the problems related to agricultural residue burning such as environmental and health impacts (Huang *et al* 2022, Lan *et al* 2022, Mor *et al* 2022), far less is known about potential solutions. We focus on the factors that influence farmers' decisions to use paddy straw as mulch instead of burning (Sidhu *et al* 2015). Other no-burning options include the incorporation of residue into the topsoil often using tilling equipment. Overall, mulching can help farmers increase soil moisture, decrease weed growth, and replenish soil nutrients (Enegi *et al* 2008, Singh and Sidhu 2014). Farmers' choice of mulching depends in part on access to and familiarity with a cost-cutting machine called the *Turbo Happy Seeder* (Shyamsundar *et al* 2019, Jat and Sidhu 2021, Keil *et al* 2021). Turbo Happy Seeders are tractor-mounted machines that allow farmers to sow wheat despite the presence of standing paddy stubble, eliminating the need to get rid of paddy residue before sowing of wheat (Sidhu *et al* 2015). Because farming is an evolving dynamic activity in the Indo-Gangetic plains, farmers learn about the use of alternatives to conventional practices through a variety of different channels. In general, agricultural learning can occur through demonstration and training provided by extension services, media communications, and social networks, or through self-learning through practice on their land (Singh *et al* 2010, Meera *et al* 2017, Thakur and Chander 2018, Kumar 2019, Marenya and Usman 2021). In recent years, the Indian Government has sought to subsidize several pieces of no-burn equipment (Nirmal 2019) and invest in information dissemination and training programs (Ravindra *et al* 2022). However, outcomes associated with these different learning channels can vary because of how they affect farmers' uptake and use of new knowledge (Garforth *et al* 2004, De Janvry *et al* 2016). Given this background, we assess whether easing supply constraints and improving farmer capacity can contribute to the better adoption of an economically and environmentally promising no-burn strategy.

In our region of interest, Punjab, the average farm size is 3.62 ha, with some 86% of operational landholding being less than 2 ha of land (Agriculture Census 2015-16 2020). Thus, for any no-burn strategy to spread across the state, it must appeal to all types of farmers. From a policy and political perspectives, it is important to understand how land class differences may affect efforts to not burn. Typically, in contrast to small holders, large and medium farmers have better information and more capital or are willing to test the use of different practices on small land parcels. To understand the linkages between land use decisions and land classes, we expand on earlier work by Keil *et al* (2021) to see how no-burn mulching differs across small, medium, and large farmers.

2. Methods

2.1. Sampling and data

We use data from a primary survey of 1021 farming households from 52 villages in Punjab, India, conducted in 2018. This survey generated information from a relatively 'normal' year as the last several years have been disrupted by the COVID-19 epidemic (Ravindra *et al* 2022) and political unrest in response to National Farm Bills (Behl 2022). The sample for this survey applied a stratified random sampling strategy to ensure the coverage of paddy farmers who lived in 'high' and 'low' residue burn districts and had access to different zero-till equipment (see Keil *et al* (2021) for details on sampling and survey). Because residue from coarse paddy varieties (in contrast with Basmati paddy) are generally burned (Gupta 2014), first, we identified coarse paddy growing districts (administrative areas) in Punjab. Second, we categorized these districts into high and low-residue-burning categories using remote sensing data from the Government of Punjab on agricultural fires (Keil *et al* 2021). Third, to enable variation and ensure ease of data collection in each category, we chose two districts that were geographically adjacent to each other. Therefore, our sample was drawn from the Ludhiana and Sangrur districts in the high residue burning category, and Patiala and Fatehgarh Sahib in the low residue burning category, as shown in figure 1.

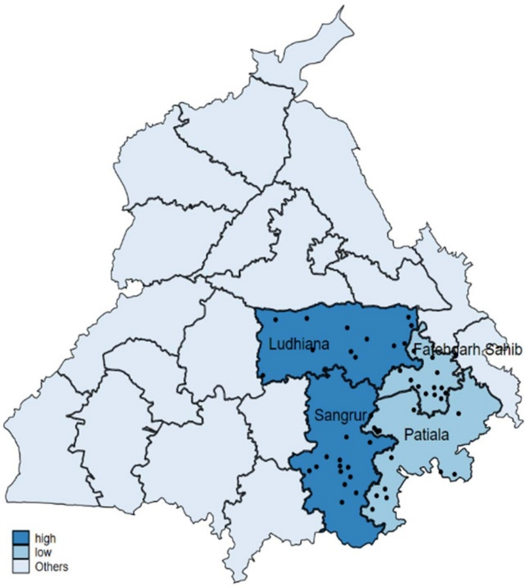

Figure 1. Location and sample.
Notes: selected villages are represented by •. *Source*: Punjab Remote Sensing Centre data 2017, Statistical Abstract of Punjab 2016, Basmati Survey Report APEDA Volume I 2017.

Fourth, in each of the identified districts, we selected 13 villages with access to no-burn equipment (*Happy Seeder*) based on a census of 64 villages. The census across the four districts enabled us to identify villages with at least one user of the *Happy Seeder*. Finally, to identify farming households for the survey, we drew a stratified random sample of farm households from each village. We over-sampled a limited number of farmers who undertook no-till conservation agricultural practices, including the use of *Happy Seeder*, yielding 1021 households. This was important because we needed to ensure that there were enough farmers in our sample who used the *Happy Seeder* to enable mulching instead of burning straw.

Our sample includes small (0–3 ha), medium (3–7 ha) and large (7+ ha) farmers. In high-residue-burn districts (Sangrur and Ludhiana), the shares of large, medium, and small farmers in our sample were 35.57%, 45.54%, and 18.89% respectively. In low-residue-burn districts (Patiala and Fatehgarh Sahib), the shares of large, medium, and small farmers in our sample were 40.88%, 36.40%, and 22.72% respectively.

All farmers in our sample cultivated paddy in the *Kharif* (monsoon) season and wheat in the *Rabi* (winter) season. We obtained household-level data on all seeding and residue management techniques used by farmers for the survey year and the preceding two years. We leverage these recall data to learn about the possible channels of self-learning. In addition, household-level data recorded details about yield and household-specific farmer characteristics.

Figure 2 shows how the farmers in our sample use broadly four ways to combine seeding techniques and residue management methods: (1) burning all the residue, (2) partial residue burning that requires removing and burning loose residue left after harvesting, while sometimes incorporating the remaining lower parts of the straw, (3) incorporating all residue into the soil using machines such as the *Rotavator*, and (4) mulching the fields with residue using mainly the *Happy Seeder*. Farmers combine land preparation (till and no-till), seeding (line-sowing, conventional, zero-till drill, and *Happy Seeder*), and residue management techniques (burning, partial burn, incorporation, and mulch). While the rest of the paper focuses on understanding decisions related to the *Happy Seeder* use for mulching lands, we model land use decisions in the Methods section by accounting for different land management practices.

2.2. Empirical methods

First, we use sample means to describe farming patterns and dynamics in our study site. Second, we use statistical analysis to assess the drivers of farmers' decisions to adopt a no-burn mulching strategy and how land is allocated to mulching by different farmer land classes.

While no-burn mulching is the primary issue of policy interest, farmers who choose to mulch their lands select this strategy from a set of residue management choices (figure 2). Thus, we model farmer decisions

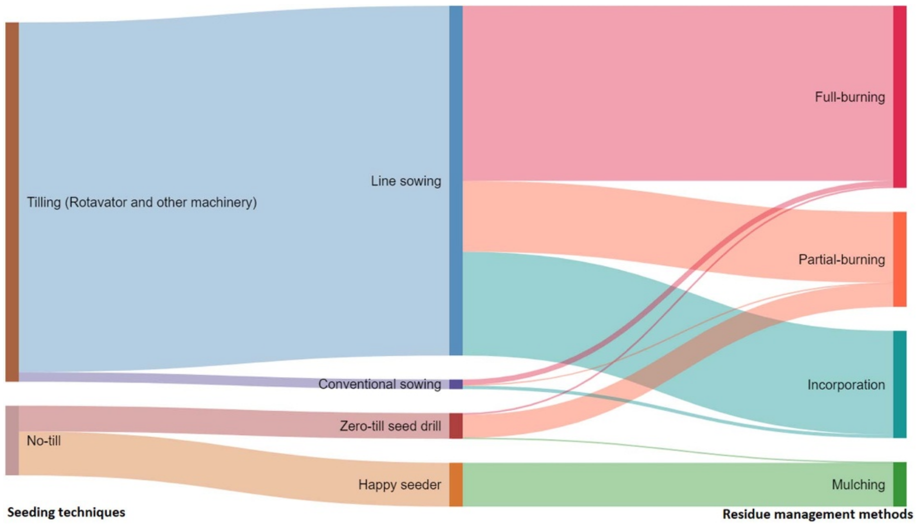

Figure 2. Land preparation for the wheat crop, sowing and residue management by farm households in the study area. Farmers use different combinations of land preparation (till and no-till), seeding (line, conventional, zero-till drill, and *Happy Seeder*), and residue management (burning, partial burn, incorporation, and mulch) techniques. More than half the farmers who till their lands burn residue, while a smaller fraction incorporate residue into soils. Most farmers, who do not till, forgo burning by mulching their residue.
Note: computations are based on weighted observations to correct for the over-sampling of farmers not tilling the farm in the sample. *Source*: survey data collected in Punjab from July to August 2018.

using the multinomial probit (MNP) framework to estimate the probability of a farmer choosing a particular residue management method as shown in equation (1)

$$P(y_{nil} = k|x) = \text{Prob}\left(V^k_{nil} + \varepsilon^k_{nil} > V^j_{nil} + \varepsilon^j_{nil}\right) \text{ for all } k \neq j \ldots \quad (1)$$

where $P(y_{nil} = k)$ represents the probability of the residue management method y_{nil} being chosen by farming household n in village i and district l. Here, $k = \{0, 1, 2, 3, 4\}$ such that the values 0, 1, 2, 3, and 4 indicate full-burning of residue, partial burning of the residue by line-sowing farmers, partial burning by zero-till seed drill users, residue incorporation by line-sowing farmers, and mulching by *Happy Seeder* users respectively. As these choices must be mutually exclusive for the estimation, we restrict our sample to farmers who exclusively practice one of these five methods. We exclude farmers practicing conventional broadcasting of seeds because this sub-sample of farmers is extremely small. A farmer's decision to choose any particular residue management option k depends on the utility they obtain from this choice. Here, utility is modeled to include a non-stochastic part, $V^k_{nil} = \beta' x_{nil}$, based on x_{nil}: observed farmer and the farmer household characteristics, and other sets of explanatory variables relating to the alternative k:, and a stochastic term, ε^k_{nil}, based on any unobserved characteristics, and is distributed normally with a mean vector of zero and covariance matrix Ω (Train 2009). We also include district-level fixed-effects and cluster the standard errors at village-level, i.

Because we are particularly interested in the farmers' decision to mulch, our explanatory variables, x_{nil}, include variables such as age of the farmer, if the farmer had completed 10th-grade education, age of household head, if the head had completed 10th-grade education, farmers' self-assessment of risk-taking behavior, operational land holding (total owned, rented, shared, and mortgaged in area under Rabi crops), number of tractors owned (given their role in many land preparation and sowing activities) access to *Happy Seeders* and indicators of different channels farmers use to learn about no-burn strategies. We include an indicator for the presence of service providers of zero-till machines such as *Happy Seeders* in the village to account for equipment access. Farmer learning channels include whether the farmer received any information on agricultural issues from (a) agricultural extension services, or (b) television (extension- and media-based learning), (c) whether camps promoting no-burning were organized in the farmer's village (village-level demonstration and learning), (d) whether the farmer's social network included *Happy Seeder* users (social learning), and (e) yield from mulched land in the previous year (an indicator of self-learning). We do not estimate equation (1) by the landholding class because the sub-samples by landholding classes are simply too small.

In addition to understanding the choice not to burn residue, farmers also make decisions on how much land to allocate to different land and residue management strategies. Given our focus on mulching as an alternative to residue burning, we examined farmland allocated for *Happy Seeder* use. Additionally, noting the heterogeneity in farm sizes, we assess whether small, medium, and large farmers make similar land allocation decisions. We use an ordinary least squares (OLS) model to examine the amount of land z_{nil} that farmers in 2017 mulched using *Happy Seeders* as follows:

$$z_{nil} = \alpha_0 + X_{nil}\alpha_1 + \gamma_l + u_{nil} \ldots . \quad (2)$$

Equation (2) is estimated using four specifications: (a) the whole sample of farmers, who used one of the five methods of seeding and residue management, (b) the sample of small farmers, (c) the sample of medium farmers, and (d) the sample of large farmers. Similar to equation (1), we assess the influence of access to *Happy Seeders* and learning strategies on land allocation. We control for district indicator variables, γ_l, and other observable covariates, as in equation (1), while clustering the standard errors at the village level, *i*, in each of the model specifications.

3. Results

3.1. The dynamics of residue management

Data from the field indicate an increasing trend in no-burn agricultural practices in the four districts of the study area (figure 3). Recall data suggest that the share of farmers practicing no-burn residue management methods has steadily increased, with a disproportionate increase in 2017. Between 2015 and 2017, the percentage of farmers who fully burned their residue reduced from 62.6% to 42%. Thus, approximately 21.4% of our sample switched from full burning to incorporation (13%), mulching (∼5%) and partial burning (3%) during this three-year period.

To understand the shifts in burning patterns by land class, we classified farming households into small (0–3 ha), medium (3–7 ha), and large (7+ ha) farmer categories. In our sampled villages, about 20% of the farmers were large (7+ ha), 42% were medium (3–7 ha) and 38% were small farmers (0–3 ha).

Figure 3 shows that the number of farmers mulching or incorporating agricultural residue has steadily increased across small, medium, and large farmers. Between 2015 and 2017, the share of farmers using no-burn mulching strategies among small farmers increased from 4.8% to 7.3%, while for medium and large farmers, the shares of farmers using no-burn mulching went up from 7.2% to 12.0% and from 8.2% to 13.8% respectively.

In addition to learning through their own efforts, farmers learn about no-burn strategies through other channels. Eighty-two percent of the households in our sample belonged to villages exposed to no-burning promotion camps by various extension agencies. Farmers also received information on agricultural issues, including no-burn strategies, from television (17%), and extension services (34%). Approximately 23% of the farmers reported being part of a network of farmers, where at least one farmer used the *Happy Seeder.* Only 17 of the 52 villages reported the presence of a service provider of zero-till machines such as *Happy Seeders* in their villages (table A1 in the appendix). There were no significant differences among small, medium, and large farmers in terms of their exposure to various learning opportunities and village-level access to *Happy Seeder* service providers.

3.2. Understanding no-burn practices

Figure 4 graphically presents the average marginal effect estimates from the MNP, identifying different factors that affect the probability of farmers choosing mulching, given the different options they face. This analysis confirms that the village-level availability of machinery such as *Happy Seeders* is a critical driver for reducing agricultural fires. For example, a service provider of zero-till machines such as *Happy Seeders* in a village increases the probability of mulching by about 8.7% points, relative to the probability of fully burning the residue. We also find that obtaining information agricultural extension services increases the probability of mulching by 4% points, while the presence of at least one network member using *Happy Seeders* is associated with an almost 12% points increase in the probability. If you had a higher yield (10 g ha^{-1}) on your farm, you are more likely to continue mulching (2.6% points more) and less likely to incorporate (0.5% points) or partially burn residue (1% points) in the following year. As mentioned before, we also control for other household characteristics. While the age and education of the farmer appear to be positively associated with higher probabilities of mulching, an inverse relationship is seen between the probability of mulching

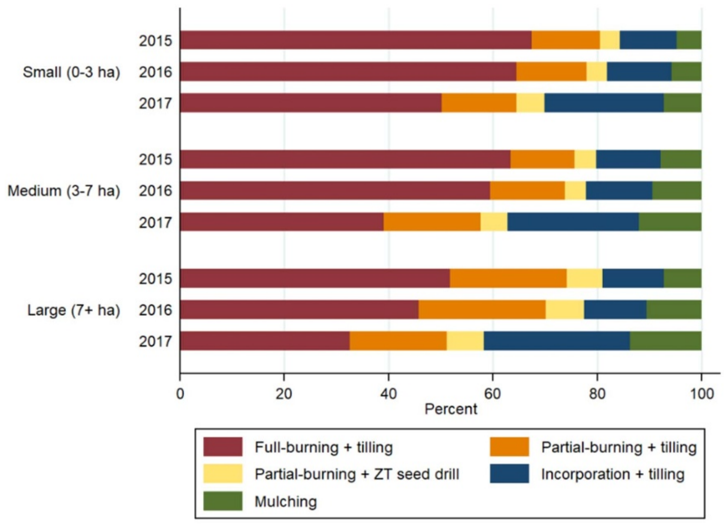

Figure 3. Residue management methods across farmers by land ownership based on recall data suggests an increase in adoption of no-burn practices between 2015 and 2017 among all land classes. Computations are based on weighted observations to correct for the over-sampling of farmers not tilling the farm in the sample. *Source*: survey data collected in Punjab from July to August 2018.

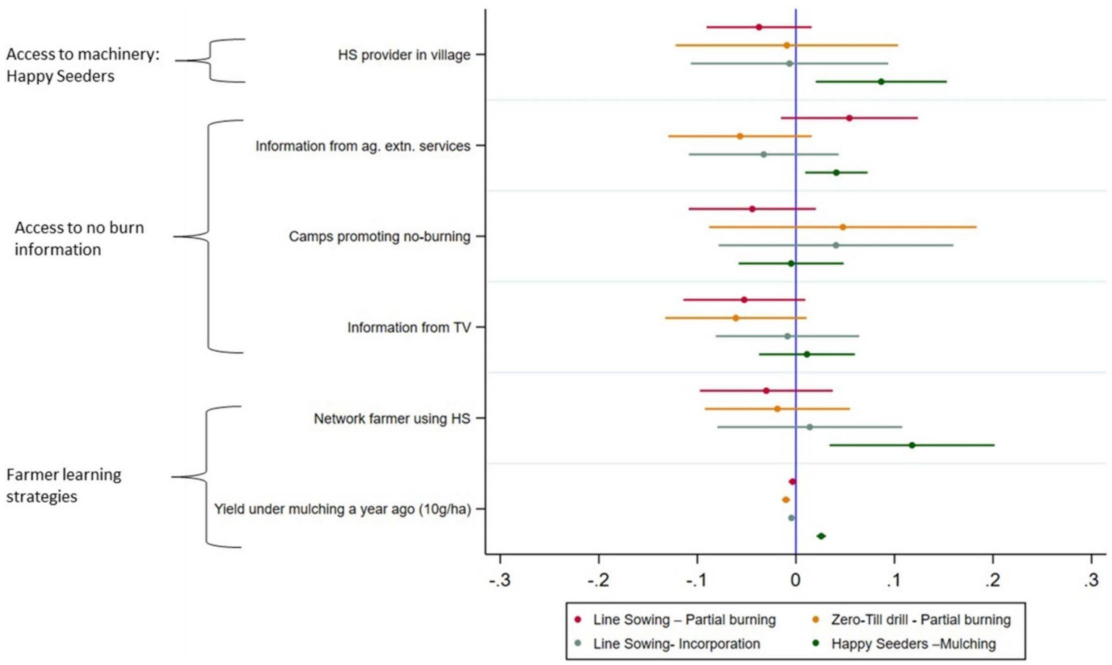

Figure 4. Marginal effects from multinomial probit estimations of different residue management strategies used by farmers. *Notes*: the horizontal axis represents marginal effects in terms of percentage points. The vertical blue line represents zero percentage points. The horizontal line around the point estimates represents the 95% confidence intervals, robust standard errors are clustered at the village level. We interpret the point estimates to be significantly different from zero when their confidence intervals do not intersect the vertical blue line. *Source*: survey data collected in Punjab from July to August 2018.

and the age and education of the household head. We do not find risk-taking behavior or tractor ownership to be significantly associated with mulching. Detailed estimates are presented in table A2 in the appendix.

Next, using OLS regressions (figure 5), we find that the expansion of land area under mulching using *Happy Seeders* occurs through (a) extension services providing information on no-burn practices, (b) peer learning through the other farmers who use *Happy Seeders*, and (c) learning-by-doing, or in this case, by mulching on their own land. Furthermore, there was substantial variation among the different landholding classes in the drivers of land area expansion under no-burn agricultural residue management practices. It is

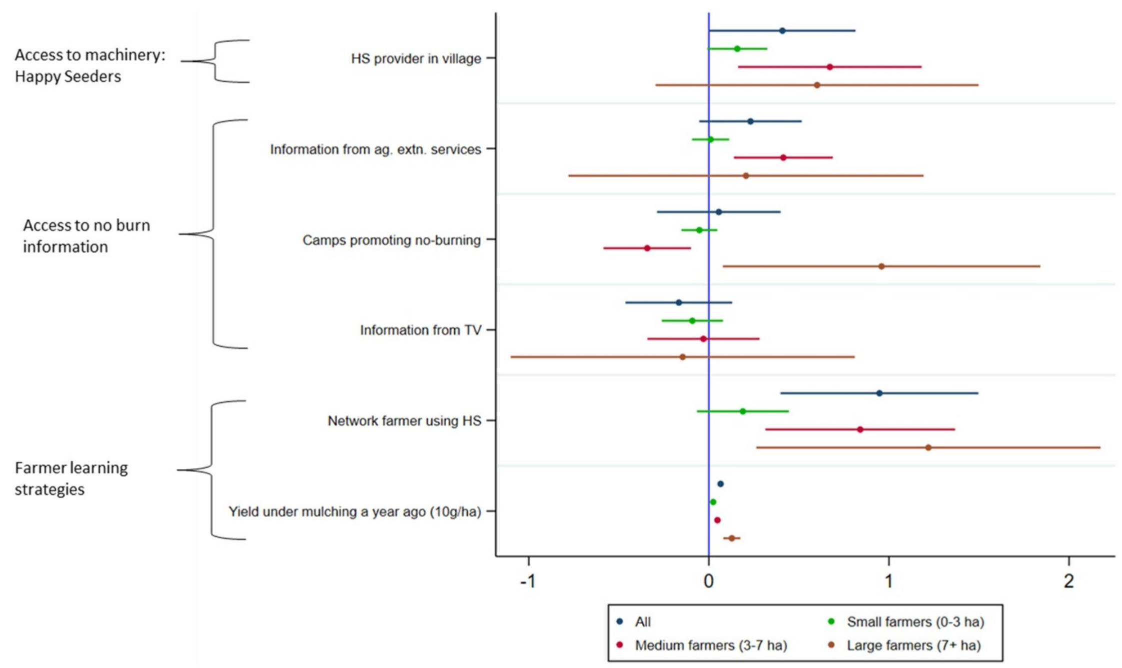

Figure 5. OLS estimates for land under *Happy Seeder* use in Punjab by farm size: small farmers (0–3 ha), medium farmers (3–7 ha), and large farmers (7+ ha) and the total sample.
Notes: the horizontal axis represents marginal effects in terms of percentage points. The vertical blue line represents zero percentage points. The horizontal line around the point estimates represents the 95% confidence intervals, robust standard errors are clustered at the village level. We interpret the point estimates to be significantly different from zero when their confidence intervals do not intersect the vertical blue line. *Source*: survey data collected in Punjab from July to August 2018.

unclear whether small farmers increase mulching in response to the presence of a Happy Seeder provider (statistically significant at the 10% but not 5% level) or a network farmer using a Happy Seeder (not statistically significant at the 10% level). For them, only the self-learning channel appeared to be positively associated (at 5% statistical significance level) with expanding mulching on their farms. In contrast, medium-sized farmers responded to agricultural extension services, self-learning, and peer learning when making mulching choices. For large farmers, peer and self-learning strategies, and camps that promote no-burn technology were also associated with the expansion of land under mulching (at 5% statistical significance level). It is worth noting that farmers in 40 of the 52 villages reported camps being held in their villages, of which 27 villages did not have a service provider of zero-till machines such as *Happy Seeders*. In the absence of village-level access to *Happy Seeders*, fewer small and medium-sized farmers use these machines compared to large farmers. Televised information has little impact on land allocated to mulching strategies. In addition, the age and education of the heads of the household also matter in decisions related to expanding land that is mulched. Notably, among small and medium farmers, the more educated and older the household head, the less likely it is that land area under mulching will expand; with the opposite being true for large farmer households. In contrast, the age and education of household heads seem to be negatively associated with the expansion of land under mulching for small and medium-sized farmers, while an inverse relationship exists for large farmers. We do not find risk-taking behavior to be significantly associated with mulching. Tractor ownership is positively correlated with the expansion of land under mulching for large farmers, while it is the reverse for medium-sized farmers (table A3 in the appendix).

4. Discussion

While the social costs associated with burning agricultural residue significantly exceed farmers' private costs (Tan-Soo and Pattanayak 2019, Singh *et al* 2019), farmers usually only consider the costs they directly bear. Our analyses identify options that reduce farmers' private costs, making it easier for them to adopt no-burn strategies.

While there are several proposed alternative methods for disposing of paddy residue by burning, our analysis reinforces the importance of access to new mulching technologies such as *Happy Seeders* (Kumar *et al* 2015, Hellin *et al* 2021). Although the Government of India subsidizes several many no-burn agricultural machines, farmers are still unable to access these machines at the right time sufficiently (Watts 2018, Kapil 2020). Given machinery costs, access is better provided through service provision rather than ownership. Service provision is growing, but slowly relative to farmer needs (Kurinji and Prakash 2021).

Extension services in the form of information, demonstrations, and training on no-burn strategies and machinery are critical for the adoption of new agricultural practices (Hellin *et al* 2021). Our findings suggest that, while farmers learn from extension agencies, social learning is three times as important in increasing the use of no-burn mulching practices. Consistent with the literature (Kolady *et al* 2021), we also find that farmers learn from their own experiences, which along with peer learning and formal training and information dissemination, helps in reducing the uncertainties and misconceptions associated with new technologies (De Janvry *et al* 2016).

We, however, find some critical differences across land classes. While there appears to be steady growth in the use of *Happy Seeders* among all land classes during 2015–2017; in 2017, only 7.3% of the small farmers and 12% of medium farmers used *Happy Seeders*, whereas the share of large farmers who used these machines was 13.8%. Smaller farmers are likely to be slower to adopt *Happy Seeders* partly because they cannot afford or access these machines. To offset upfront costs, the national government initiated a series of subsidies, and the Punjab state government made no-burn farm machinery rent-free at custom hiring centers in 2020 (Chaba 2020). However, cost is not the only barrier. *Happy Seeders* require tractors with a capacity of 65 hp, whereas most tractors used in this region have a lower capacity. Additionally, Happy Seeders are less effective unless combine harvesters, the machine used for harvesting paddy, include an attachment called the super straw management system (super SMS). Collectively, these economies of scale impose further barriers to adoption of no-burn technologies (Tribune 2019, Kumar 2021). By contrast, medium sized farmers are open to multiple forms of learning, ranging from formal extension services to peer-learning to self-learning.

Our research leads to at least two dilemmas regarding how to reduce agricultural fires in the Indo-Gangetic plains. First, farmers are beginning to use new technologies (*super seeders, smart seeders* and *PUSA bio-decomposers*) that have entered the market to mitigate residue burning. Furthermore, *ex-situ* measures, like the baling of residue for energy production, are gaining momentum, supported by government subsidies (Khanna 2023). The cumulative impact of these measures may be contributing to reductions in fire counts in 2023 (Haq 2023). Still, residue burning continues to persist, presenting substantial costs. This may be because there is limited and mixed evidence on the impact of these new machines on profits and bio-mass reductions (Chaudhary *et al* 2021, Gupta *et al* 2021, Schukraft 2021) and uncertainty over the ability of power plants to utilize baled residue.

Second, and more importantly, binding regulations are important for reducing the incidence of agricultural residue burning. Our data suggest that the multi-pronged approach adopted by the central and state governments in India to promote alternatives to residue burning—subsidy provision, information dissemination, market development, and regulations (Hellin *et al* 2021)—appears to be moving the agricultural system in the right direction. This progress is further supported by the efforts of various non-profits and universities, who are demonstrating and communicating the benefits of no-burn technologies. However, trends in residue burning can only be verified through careful analyses of fire information, and setbacks are to be expected from COVID and recent political upheavals (Ravindra *et al* 2022). Further evidence is needed to understand how regulations complement or substitute learning acquired through information, training, and demonstration programs.

5. Conclusion

Our analysis suggests three empirical patterns: first, increased access to no-till and no-burn machines such as *Happy Seeders* is positively associated with an increased probability of mulching, thereby reducing burning. Second, three forms of learning are positively associated with farmers choosing to mulch paddy residue and the decision to expand the area under mulching: information through extension services, peer-learning from social networks, and self-learning. However, farmer-oriented village camps, a common way of providing extension services (Mukherjee and Maiti 2016), are not as ineffective for small and medium farmers. The first three channels also led to the expansion of land area under *Happy Seeders* over time. Third, the efficacy of different adoption drivers varies across landholding classes. For small farmers, we find that testing no-burn mulching on their own land is the only factor influencing the expansion of cultivable land under *Happy Seeders*. In contrast, for medium and large farmers, peer learning also matters, whereas agricultural extension services only influence medium-sized farmers. While our estimates in each size class are representative of Punjab and are internally valid, the proportion of large farms in our data may be larger than the true proportion in the state.[9] Additionally, these insights gained from Punjab may lack external validity across Indian farmers as the sample does not represent farmers across India. However, they can be readily applied to interventions related to no-burn strategies in the Indo-Gangetic plains.

These results offer several insights into why farmers in Punjab adopt no-burn technologies such as mulching using *Happy Seeders* for government and non-government agencies seeking to diminish residue burning in the Indo-Gangetic plains. Such interventions should reduce the barriers that farmers face in accessing no-burn farm equipment and service providers; promote social networking and learning for medium and large farmers (for example, by creating social networking opportunities as many farmers have smartphones); direct investment in small farmers' lands (such as using smallholdings as field demonstration sites); and focus extension services on medium farmers, who make up the majority of the farming community in the region.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

Acknowledgments

We also acknowledge partners associated with the Indian Statistical Institute, Borlaug Institute for South Asia, The Nature Conservancy (TNC) and International Maize and Wheat Improvement Center (CIMMYT), who served as advisors and helped launch data collection efforts in Punjab, India, and Duke University for providing post-doctoral research support.

Funding

This paper is part of a NatureNet Postdoctoral Research Grant sponsored by TNC. Data collection was supported by Grants received from the Nature Conservancy (TNC) and the International Maize and Wheat Improvement Center (CIMMYT).

Author contribution statement

P P Krishnapriya: conceptualization, formal analysis, investigation, writing—original draft, visualization. Subhrendu K Pattanayak: conceptualization, supervision, writing—review & editing. E Somanathan: conceptualization, supervision, writing—reviewing, funding acquisition. Alwin Keil: investigation, writing—reviewing, and funding acquisition. M L Jat: writing—reviewing, funding acquisition. H S Sidhu: writing—reviewing. Priya Shyamsundar: conceptualization, supervision, writing—original draft, writing—review & editing, funding acquisition.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this study.

Ethical compliance

The research involving human participants was reviewed and approved by the CIMMYT Ethics in Research Policy of the CIMMYT Internal Research Ethics Committee ('IREC'). The Rules used for the assessment were international standards in terms of CIMMYT Policy. Application number: IREC 2018.005. Date of resolution: 24 July 2018.

[9] Punjab, where our study area is located, the average farm size was 3.62 ha (Agriculture Census 2020), which is much higher than the rest of India. Specifically, in Punjab, the shares of marginal (below 1 ha), small (1–2 ha), semi-medium (2–4 ha), medium (4–10 ha), and large farm holdings (10 ha and above) were 14.1%, 18.9%, 33.7%, 27.9%, and 5.3% (computed using data from table 2, Agricultural Census of India 2015–16, Phase 1,2019). Lastly, it is worth noting that if we combine marginal and small farmer shares for Punjab, the total is 33%, which is close to our share of small (0–3 ha) farmers, 38%. Comparing the proportion of medium and large farmers is not straightforward because our classification of small (0–3 ha), medium (3–7 ha), and large (7+ ha) differs from the definition used in the census.

Appendix

Table A1. Average characteristics of farming households in the sample.

Characteristics	Average
Cultivable area: operational land holding (in ha)	4.9 (3.9)
Yield under mulching a year ago (kg ha^{-1})	4.6 15.1
Camps promoting no-burning (*d*)	0.8 (0.4)
Information from TV (*d*)	0.2 0.4
Information from agricultural extension services (*d*)	0.3 (0.5)
Social network members using HS (*d*)	0.2 (0.4)
Happy Seeder and other ZT service provider in village (*d*)	0.4 (0.5)
Respondent's age (in years)	51.4 (10.8)
Respondent completing grade 10 (*d*)	0.4 (0.49)
Head's age (in years)	51.5 (10.8)
Head completing grade 10 (*d*)	0.42 (0.49)
Risk averse in growing wheat (1–5)	2.6 (0.8)
Number of tractors owned	0.8 (0.4)
N	1021

Notes: standard deviations in parentheses, (*d*) is an indicator variable taking the value 0 or 1; computations are based on weighted observations to correct for the over-sampling of farmers not tilling the farm in the sample. *Source*: survey data collected in Punjab from July to August 2018.

Table A2. Marginal effects from multinomial probit estimations.

	Line sowing — partial burning	Zero-till drill — partial burning	Line sowing — incorporation	Happy Seeders — mulching
Total area under Rabi crops (ha)	0.002	0.007	−0.004	0.004
	(0.002)	(0.004)	(0.004)	(0.003)
Yield under mulching a year ago (10 g ha^{-1})	−0.003	−0.010***	−0.005***	0.026***
	(0.002)	(0.002)	(0.002)	(0.002)
Camps promoting no-burning (*d*)	−0.044	0.048	0.041	−0.005
	(0.033)	(0.069)	(0.061)	(0.027)
Information from TV (*d*)	−0.052*	−0.061*	−0.009	0.011
	(0.032)	(0.037)	(0.037)	(0.025)
Information from agricultural extension services (*d*)	0.054	−0.057	−0.033	0.041**
	(0.035)	(0.037)	(0.039)	(0.016)
Network farmer using HS (*d*)	−0.030	−0.019	0.014	0.118***
	(0.034)	(0.038)	(0.048)	(0.043)
HS and other ZT provider in the village (*d*)	−0.037	−0.009	−0.006	0.087**
	(0.027)	(0.058)	(0.051)	(0.034)
Age of respondent	0.015***	−0.044***	−0.039***	0.022***
	(0.005)	(0.014)	(0.013)	(0.006)
Respondent education: completed grade 10 (*d*)	−0.040***	−0.177	−0.231	0.310***
	(0.009)	(0.146)	(0.146)	(0.075)
Age of HH head	−0.013***	0.044***	0.040***	−0.023***
	(0.004)	(0.014)	(0.013)	(0.006)
HH head education: completed grade 10 (*d*)	−0.042***	0.182	0.293	−0.236***
	(0.008)	(0.203)	(0.201)	(0.058)
Risk taking behavior	0.000	−0.014	−0.013	−0.010
	(0.012)	(0.017)	(0.019)	(0.009)
# of tractors owned	−0.027	0.015	0.017	−0.002
	(0.017)	(0.037)	(0.031)	(0.021)
District fixed effects	Yes	Yes	Yes	Yes
N	931	931	931	931
Log pseudolikelihood	−1077.11	−1077.11	−1077.11	−1077.11

Notes: robust standard errors clustered at the village level in parentheses; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$; (*d*) is an indicator variable taking the value 0 or 1. *Source*: survey data collected in Punjab from July to August 2018.

Table A3. OLS estimates for land under Happy Seeder use in Punjab.

Area under Happy Seeders (ha)	All	Small farmers (0–3 ha)	Medium farmers (3–7 ha)	Large farmers (7+ ha)
Total area under Rabi crops (ha)	0.215***	0.218***	0.190*	0.214**
	(0.063)	(0.073)	(0.104)	(0.095)
Yield under mulching a year ago (10 g ha^{-1})	0.065***	0.024***	0.047***	0.127***
	(0.008)	(0.003)	(0.008)	(0.024)
Camps promoting no-burning (*d*)	0.055	−0.053	−0.342***	0.959**
	(0.171)	(0.050)	(0.121)	(0.439)
Information from TV (*d*)	−0.167	−0.092	−0.030	−0.146
	(0.148)	(0.085)	(0.155)	(0.476)
Information from agricultural extension services (*d*)	0.231	0.009	0.413***	0.206
	(0.142)	(0.051)	(0.137)	(0.491)
Network farmer using HS (*d*)	0.947***	0.189	0.840***	1.219**
	(0.274)	(0.127)	(0.262)	(0.476)
HS provider and other ZT provider in the village (*d*)	0.408**	0.158*	0.672**	0.601
	(0.202)	(0.083)	(0.254)	(0.447)
Age of respondent	0.035*	0.026***	0.041**	−0.072*
	(0.018)	(0.006)	(0.020)	(0.037)
Respondent education: completed grade 10 (*d*)	0.228	0.542***	1.525**	−5.655**
	(0.484)	(0.186)	(0.663)	(2.563)
Age of HH head	−0.026	−0.030***	−0.033*	0.077*
	(0.017)	(0.006)	(0.017)	(0.041)
HH head education: completed grade 10 (*d*)	−0.035	−0.482**	−1.377**	5.693**
	(0.485)	(0.194)	(0.650)	(2.623)
Risk taking behavior	0.052	0.017	−0.213	0.370
	(0.120)	(0.035)	(0.141)	(0.392)
# of tractors owned	0.048	−0.031	−0.427*	2.126*
	(0.220)	(0.059)	(0.255)	(1.071)
District fixed effects	Yes	Yes	Yes	Yes
Constant	−1.772**	−0.168	−0.528	−5.545***
	(0.722)	(0.284)	(1.070)	(1.374)
N	1021.000	350.000	425.000	246.000
R^2	0.449	0.521	0.567	0.525
Adjusted R^2	0.440	0.498	0.550	0.492

Notes: robust standard errors clustered at the village level in parentheses; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$; (*d*) is an indicator variable taking the value 0 or 1. *Source*: survey data collected in Punjab from July to August 2018.

ORCID iDs

P P Krishnapriya https://orcid.org/0000-0002-8441-941X
Subhrendu K Pattanayak https://orcid.org/0000-0003-2021-5511
E Somanathan https://orcid.org/0000-0003-3746-5779
Alwin Keil https://orcid.org/0000-0002-8085-7279
Priya Shyamsundar https://orcid.org/0000-0001-8368-8581

References

Agarwal R, Awasthi A, Singh N, Mittal S K and Gupta P K 2013 Epidemiological study on healthy subjects affected by agriculture crop-residue burning episodes and its relation with their pulmonary function tests *Int. J. Environ. Health Res.* **23** 281–95

Agricultural Census of India 2015–16 2019 (Phase 1) All India report on number and area of operational holdings *Department of Agriculture, Cooperation & Farmers Welfare, Ministry of Agriculture & Farmers Welfare* (Government of India) (available at: https://agcensus.nic.in/document/agcen1516/T1_ac_2015_16.pdf)

Agriculture Census 2020 All India report on agriculture census 2015–16 *Department of Agriculture, Cooperation & Farmers Welfare, Ministry of Agriculture & Farmers Welfare* (Government of India) (available at: https://agcensus.nic.in/document/agcen1516/ac_1516_report_final-220221.pdf)

Behl N 2022 India's farmers' protest: an inclusive vision of Indian democracy *Am. Polit. Sci. Rev.* **116** 1141–6

Chaba A A 2018 No respite from crop stubble burning in Punjab *The Indian Express* (available at: https://indianexpress.com/article/india/no-respite-from-crop-stubble-burning-in-punjab-5255640/)

Chaba A A 2020 Explained: why Punjab rent waiver on farm machines will not help much *The Indian Express* (available at: https://indianexpress.com/article/explained/punjab-farmers-stubble-burning-machines-on-rent-6717113/)

Chaudhary S, Singh V P, Chandra S, Singh T P, Singh S P and Durgue S A 2021 Effect of wheat establishment methods and rice residue levels on yield and economics of rice and wheat under rice-wheat cropping system *J. Pharm. Innov.* **10** 423–7 (available at: www.researchgate.net/profile/Shubham-Durgude/publication/353907234_Effect_of_wheat_establishment_methods_and_rice_residue_levels_on_yield_and_economics_of_rice_and_wheat_under_rice-wheat_cropping_system/links/6117e4881ca20f6f862250c8/Effect-of-wheat-establishment-methods-and-rice-residue-levels-on-yield-and-economics-of-rice-and-wheat-under-rice-wheat-cropping-system.pdf)

De Janvry A, Sadoulet E and Rao M 2016 *Adjusting extension models to the way farmers learn* FERDI Policy Brief No. B159 (available at: http://hdl.handle.net/10419/269761)

Egrinya Eneji A, Inanaga S, Li X, An P, Li J, Duan L and Li Z 2008 Effectiveness of mulching vs. incorporation of composted cattle manure in soil water conservation for wheat based on eco-physiological parameters *J. Agron. Crop Sci.* **194** 26–33

Garforth C, Rehman T, McKemey K, Tranter R, Cooke R, Yates C and Dorward P 2004 Improving the design of knowledge transfer strategies by understanding farmer attitudes and behaviour *J. Farm Manage.* **12** 17–32 (available at: www.researchgate.net/profile/Peter-Dorward/publication/233692469_Improving_the_Design_of_Knowledge_Transfer_Strategies_by_Understanding_Farmer_Attitudes_and_Behaviour/links/546cd3f50cf2193b94c5780b/Improving-the-Design-of-Knowledge-Transfer-Strategies-by-Understanding-Farmer-Attitudes-and-Behaviour.pdf)

GBD MAPS Working Group 2018 Burden of disease attributable to major air pollution sources in India *Special Report 21* (MA: Health Effects Institute)

Gupta A, Singh P, Singh G, Sekhon B S and Sodhi G P S 2021 On farm testing of rice residue management techniques for wheat (Triticum aestivum L.) establishment in Punjab *Indian J. Ext. Educ.* **57** 85–88

Gupta R 2014 Low-hanging fruit in black carbon mitigation: crop residue burning in South Asia *Clim. Change Econ.* **5** 1450012

Gupta S, Agarwal R and Mittal S K 2016 Respiratory health concerns in children at some strategic locations from high PM levels during crop residue burning episodes *Atmos. Environ.* **137** 127–34

Haider M Z 2013 Determinants of rice residue burning in the field *J. Environ. Manage.* **128** 15–21

Haq Z 2023 Farm fire cases on the decline, Parliament told *Hindustan Times* (available at: www.hindustantimes.com/india-news/farm-fire-cases-on-the-decline-parliament-told-101702489750674.html)

Hellin J, McDonald A, Jat M L, Shyamsundar P and Singh A K 2021 Mitigating agriculture's contribution to air pollution in India *Lancet Planet Health* **5** e186

Huang T, Ma J, Song S, Ling Z, Macdonald R W, Gao H and Mao X 2022 Health and environmental consequences of crop residue burning correlated with increasing crop yields midst India's green revolution *npj Clim. Atmos. Sci.* **5** 81

Jat M L and Sidhu H S 2021 Seeding happy, cleaning air: farmers adopting non-burn tech give hope *DownToEarth Blog* (available at: www.downtoearth.org.in/blog/agriculture/seeding-happy-cleaning-air-farmers-adopting-non-burn-tech-give-hope-77729)

Jethva H, Torres O, Field R D, Lyapustin A, Gautam R and Kayetha V 2019 Connecting crop productivity, residue fires, and air quality over northern India *Sci. Rep.* **9** 1–11

Kapil S 2020 'What other option do we have?': why stubble fires would not die. Down to Earth (available at: www.downtoearth.org.in/news/air/-what-other-option-do-we-have-why-stubble-fires-would-not-die-74174) (https://doi.org/10.1139/cjm-2020-0142)

Keil A, Krishnapriya P P, Mitra A, Jat M L, Sidhu H S, Krishna V V and Shyamsundar P 2021 Changing agricultural stubble burning practices in the Indo-Gangetic plains: is the Happy Seeder a profitable alternative? *Int. J. Agric. Sustain.* **19** 128–51

Khanna R M 2023 Punjab: ex situ management of paddy stubble set to get an impetus *The Tribune* (available at: www.tribuneindia.com/news/punjab/ex-situ-management-of-paddy-stubble-set-to-get-an-impetus-527490)

Kolady D, Zhang W, Wang T and Ulrich-Schad J 2021 Spatially mediated peer effects in the adoption of conservation agriculture practices *J. Agric. Appl. Econ.* **53** 1–20

Kumar A 2021 Why farmers are forced to choose stubble burning over Happy Seeder, a device that can help curb stubble burning? *The Quint* (available at: www.thequint.com/news/india/air-pollution-in-delhi-ncr-stubble-burning-in-punjab#read-more)

Kumar P, Kumar S and Joshi L 2015 *Socioeconomic and Environmental Implications of Agricultural Residue Burning: A Case Study of Punjab, India* (Springer Open) (available at: https://library.oapen.org/bitstream/handle/20.500.12657/27961/1/1002038.pdf)

Kumar S 2019 Social capital and diffusion of innovations: an analysis of farm households in rural Punjab *Agriculture Innovation Systems in Asia* (Routledge India) pp 253–75

Kurinji L S and Prakash S 2021 *Why Paddy Stubble Continues to Be Burnt in Punjab? Meeting Challenges with Solutions* (Council on Energy, Environment and Water)
Lan R, Eastham S D, Liu T, Norford L K and Barrett S R 2022 Air quality impacts of crop residue burning in India and mitigation alternatives *Nat. Commun.* **13** 6537
Marenya P P and Usman M A 2021 Community-embedded experiential learning and adoption of conservation farming practices in Eastern and Southern Africa *Environ. Dev.* **40** 100672
Meera S N, Gandhi R and Padaria R 2017 Accelerating impact through rice innovation systems: integrating knowledge, technology, and markets *The Future Rice Strategy for India* (Academic) pp 435–60
Mor S, Singh T, Bishnoi N R, Bhukal S and Ravindra K 2022 Understanding seasonal variation in ambient air quality and its relationship with crop residue burning activities in an agrarian state of India *Environ. Sci. Pollut. Res.* **29** 4145–58
Mukherjee A and Maity A 2016 My village my pride A concept towards better India *Indian Farming* **66** 2–5
Nirmal R 2019 Where are the Happy Seeders that Punjab's farmers were promised? *The Hindu BusinessLine* (available at: www.thehindubusinessline.com/economy/agri-business/where-are-the-happy-seeders-that-punjabs-farmers-were-promised/article30000119.ece#)
Pant K P 2013 *Monetary Incentives to Reduce Open-Field Rice-Straw Burning in the Plains of Nepal* (SANDEE) (available at: https://opendocs.ids.ac.uk/opendocs/bitstream/handle/20.500.12413/4406/1024_PUB_Final_Working_Paper_81_13_WEB.pdf?sequence=1)
Ramanathan V and Carmichael G 2008 Global and regional climate changes due to black carbon *Nat. Geosci.* **1** 221–7
Rangel M A and Vogl T S 2019 Agricultural fires and health at birth *Rev. Econ. Stat.* **104** 1–15
Ravindra K, Singh T and Mor S 2022 COVID-19 pandemic and sudden rise in crop residue burning in India: issues and prospects for sustainable crop residue management *Environ. Sci. Pollut. Res.* **29** 3155–61
Schukraft J 2021 Stubble Burning in India. *Effective Altruism Forum* (available at: https://forum.effectivealtruism.org/posts/s82X4ta6ucaPYRf9S/notes-stubble-burning-in-india)
Shyamsundar P *et al* 2019 Fields on fire: alternatives to crop residue burning in India *Science* **365** 536–8
Sidhu H S, Singh M, Singh Y, Blackwell J, Lohan S K, Humphreys E, Jat M L, Singh V and Singh S 2015 Development and evaluation of the Turbo Happy Seeder for sowing wheat into heavy rice residues in NW India *Field Crops Res.* **184** 201–12
Singh B, McDonald A J, Srivastava A K and Gerard B 2019a Tradeoffs between groundwater conservation and air pollution from agricultural fires in northwest India *Nat. Sustain.* **2** 580–3
Singh K, Peshin R and Saini S K 2010 Evaluation of the agricultural vocational training programmes conducted by the Krishi Vigyan Kendras (farm science centres) in Indian Punjab *J. Agric. Rural Dev. Trop. Subtrop.* **111** 65–77 (available at: http://nbn-resolving.de/urn:nbn:de:hebis:34-2010091334536)
Singh P, Dey S, Chowdhury S and Bali K 2019 Early life exposure to outdoor air pollution: effect on child health in India (available at: www.brookings.edu/wp-content/uploads/2019/03/Early-life-Exposure-to-Outdoor-air-pollution.pdf)
Singh Y and Sidhu H S 2014 Management of cereal crop residues for sustainable rice-wheat production system in the Indo-Gangetic plains of India *Proc. Indian Natl Sci. Acad.* **80** 95–114
Tan-Soo J S and Pattanayak S K 2019 Seeking natural capital projects: forest fires, haze, and early-life exposure in Indonesia *Proc. Natl Acad. Sci.* **116** 5239–45
Thakur D and Chander M 2018 Use of social media in agricultural extension: some evidences from India *Int. J. Sci. Environ. Technol.* **7** 1334–46 (available at: www.researchgate.net/profile/Devesh-Thakur/publication/326802477_USE_OF_SOCIAL_MEDIA_IN_AGRICULTURAL_EXTENSION_SOME_EVIDENCES_FROM_INDIA/links/5b63ff3daca272e3b6ac39f4/USE-OF-SOCIAL-MEDIA-IN-AGRICULTURAL-EXTENSION-SOME-EVIDENCES-FROM-INDIA.pdf)
Train K E 2009 *Discrete Choice Methods with Simulation* (Cambridge University Press)
Tribune 2019 Fitting combine harvesters with super SMS made compulsory *The Tribune* (available at: www.tribuneindia.com/news/archive/ludhiana/fitting-combine-harvesters-with-super-sms-made-compulsory-824376)
Watts A 2018 Co-op societies sans Happy Seeders despite 80% subsidy *The Tribune* (available at: www.tribuneindia.com/news/punjab/co-op-societies-sans-happy-seeders-despite-80-subsidy/669387.html)