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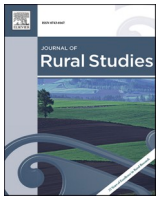

Farmer perspectives on crop residue burning and sociotechnical transition in Punjab, India

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ABSTRACT

Burning rice stubble is a common practice for millions of farmers across the Indo-Gangetic Plains. Though burning represents a low input, cost-effective strategy of crop residue management (CRM), it produces harmful air pollution, and it releases greenhouse gasses. Large-scale transition to no-burn CRM in northwest India will require social and technological change. We analyze data from 60 focus group discussions and 24 interviews with farmers and key actors related to agriculture in Punjab, and we discuss our findings using a sociotechnical systems framework. Farmers and key informants alike illustrate the complexity of CRM, highlight the diversity of machinery used in rice-wheat cropping, and identify a multi-level and unequal policy landscape that constricts the time available to implement no-burn CRM between harvesting rice and sowing wheat crops. Farmer responses reveal mistrust and uncertainty regarding current incentives for no-burn CRM, including subsidies for purchasing no-burn CRM machinery and fines for burning. Nonetheless, farmers support new long-term price subsidies for alternate rice varieties, crops, and fuel. In addition to cost-reduction measures, farmers and key informants voice support for local demonstrations of no-burn CRM, promoting agricultural services through social organizations, and being free to choose how to best reduce or eliminate burning on their fields. In contrast to studies that consider individual farmers' willingness to accept payment for reduced burning, our findings emphasize the importance of considering the political and technological aspects of CRM in Punjab. Respondents acknowledge the importance of improving individual incentives while working through local organizations to provide wider access to no-burn CRM technology and address information asymmetries.

1. Introduction

Crop residue burning is a global concern. Agriculture is a significant contributor to total global greenhouse gas (GHG) emissions (Bennetzen et al., 2016; Crippa et al., 2021) and directly produces 10 to 12% of global anthropogenic GHG emissions (Tongwane and Moeletsi, 2018). Within the sector, crop residue burning is an important contributor and a threat to air quality and human health (Li et al., 2016; Santiago-De La Rosa et al., 2018; Lan et al., 2022). It releases substantial amounts of carbon dioxide, methane and other pollutants that produce negative environmental and human health impacts (Abdurrahman et al., 2020). In northwest India, a critically important agricultural region, crop residue burning is particularly prevalent (Lan et al., 2022).

The production of rice and wheat in northwest India contributes to national food security, regional economies, and the livelihoods of millions of farmers. India is the second largest producer of rice and wheat in the world (Singh et al., 2018), and 13.5 Mha of the Indo-Gangetic plains in northwestern India is covered by rice or wheat cropping systems, accounting for more than 85% of the total region (Jat et al., 2024). In the state of Punjab, in northwest India, agriculture employs over one third of the state's 29.9 million residents and approximately 83% of its gross cropped area dedicated to cereals including rice and wheat (Gulati et al.,

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2021). However, the dominance of rice-wheat agriculture in Punjab is associated with declining groundwater resources and extensive crop residue burning (Abdurrahman et al., 2020; Agarwala et al., 2022).

Policy, climate, and water availability combine to promote crop residue burning in Punjab. In 2009, the state government implemented the Preservation of Subsoil Water Act that restricts when the sowing and transplantation of rice crops is allowed, in order to avoid usage of groundwater irrigation during hot summer months (Tripathi et al., 2016). Though it appears that these regulations have reduced the depletion of groundwater resources, a growing body of evidence demonstrates that it has increased the burning of crop residues (Balwinder-Singh et al., 2019). In Punjab, farmers have between ten and twenty days to harvest rice, manage unwanted crop residues left after harvesting rice, and sow wheat (Shyamsundar et al., 2019). Preferences for high-yield, long-duration paddy varieties that receive a minimum support price contribute to this reduced time period (Gupta, 2019). Due to the short amount of time between paddy harvesting and wheat sowing, limited external market uses of crop residues, and rural labor shortages, farmers often turn to full or partial burning to prepare their fields for sowing wheat in October or November. Crop residue burning generates several negative externalities, including reduced air quality in increased carbon dioxide emissions (Cusworth et al., 2018; Agarwala et al., 2022). Due to the importance of rice-wheat agriculture in Punjab, facilitating a transition from crop residue burning to no-burn crop residue management (CRM) is critical (Shyamsundar et al., 2019; Keil et al., 2021).

Facilitating a transition to no-burn CRM in Punjab will require substantial changes within current agricultural production systems (Downing et al., 2022). A network of policies, mechanized agricultural practices, and climate patterns combine to make burning a widespread method for CRM in Punjab (Bikkina et al., 2019; Lan et al., 2022). Studies that evaluate farmers' willingness to accept payment to implement no-burn CRM (Jack et al., 2023; Lopes et al., 2023) or focus exclusively on farmer-specific actions may fail to evaluate the broader agricultural system in which farmers practice rice-wheat cropping in Punjab. In contrast to considering individual behavior, theories of sociotechnical systems focus on the relationships between policy, technology, and individual activities (Geels, 2004; Geels and Schot, 2007; Geels et al., 2016). As such, the literature on sociotechnical systems offers helpful insights for considering transition pathways related to no-burn CRM in Punjab (Loorbach et al., 2017).

2. Rice-wheat agriculture as a sociotechnical system

The multi-level perspective (MLP), a prominent framework within sociotechnical systems research, provides a useful analytic for understanding the relationships among policies, practices, and technologies that produce CRM. The MLP combines insights from the sociology of innovation, evolutionary economics, and institutionalism (Köhler et al., 2019) and emphasizes dynamic feedback between different components that compose systems characterized by social, political, and technological relationships. Specifically, the MLP identifies niches, sociotechnical regimes, and sociotechnical landscapes. Niches refer to small arenas of innovation where actors develop and diffuse alternative practices (Geels and Schot 2007). In contrast, sociotechnical regimes refer to practices that have been adopted widely and reinforced by a set of policy, market, or technological drivers referred to as the sociotechnical landscape. In short, the MLP helps identify social and policy relationships between a current regime of sociotechnical practice, such as crop-residue burning, and alternative practices or technologies, such as those that characterize no-burn CRM. Interpreting rice-wheat farming in Punjab using MLP helps to identify how policy, market, and technological drivers reinforce crop residue burning. It also aids in the identification of drivers that no-burn CRM must overcome for a sustainable transition.

Rice-wheat farming in Punjab is characterized by diverse farming practices, varied machine and seed technologies, technical assistance, credit, and price subsidies (Lohan et al., 2018; Shyamsundar et al., 2019). The cultivation of crops in Punjab is divided into *Kharif* and *Rabi* growing seasons. Rice is typically grown on paddy land during the *Kharif* season, beginning in June with harvest occurring in October or November. Wheat is typically grown during the *Rabi* season, when farmers sow it in November and harvest it in April. Thus, the end of October and the beginning of November mark an important transitional moment when farmers need to harvest rice, manage crop residues (i.e. paddy stubble), and sow wheat (Keil et al., 2021). Within this short window of time, farmers often turn to burning crop residues (Abdurrahman et al., 2020).

Within the sociotechnical system where crop residue burning is commonplace, no-burn CRM is characterized by a set of a niche practices encouraged through policy and financial incentives. Research across four districts in Punjab finds the use of alternate technologies to reduce burning among a small minority of farmers (Table 3, Keil et al., 2021), whereas ~59% of farmers report burning their fields completely or partially (Keil et al., 2021). According to the MLP, niche activities such as no-burn agricultural practices, can produce a sociotechnical transition if the landscape of policies, markets, and norms shifts behavior away from the prevailing regime. Using MLP theory, our analysis seeks to understand how no-burn agriculture interacts with the dominant sociotechnical regime and what aspects may need to change to facilitate a sustainable transition.

Assessing the social and technical relationships that produce CRM practices in Punjab offers a unique perspective for evaluating barriers and enabling conditions for a sustainable transition to regenerative agriculture. A number of publications usefully consider the long-term profitability and cost reductions associated with CRM (Shyamsundar et al., 2019; Keil et al., 2021; Singh et al., 2022) and how short-term monetary incentives might influence individual farmer behavior (Jack et al., 2023). Though this research provides valuable findings about the importance of financial incentives, it overlooks the role of social organizations in promoting no-burn CRM and the interactions among policy, practice, and technology that may act as barriers. Failing to account for interactions among social relationships, technology, and regulations can hide challenges that may emerge as systems move from one set of equilibrium conditions to another (Geels and Schot, 2007; Erbaugh et al., 2021). For example, in the context of Punjab, knowing that farmers can be incentivized to change their agricultural practices tells us little about the systemic changes required for no-burn CRM to grow in scale. Though focusing on how much money or in-kind incentives farmers require to stop burning crop residues can determine *how much* no-burn CRM might cost, it does not provide insights into *how* no-burn CRM innovations might diffuse across the landscape. We draw on sociotechnical systems thinking and the MLP theory to interpret qualitative data from farmers, professionals within the agriculture system, politicians, and civil servants. In so doing, we seek to better understand farmer and key informant perspectives on how the current sociotechnical regime reinforces crop residue burning and options for implementing and scaling no-burn CRM.

3. Methods

We collected data from farmers and key-informants using focus group discussions (FGDs) and semi-structured interviews to understand perspectives related to the practices and policies that reinforce crop residue burning and potential pathways to a no-burn CRM transition (Fig. 1). To collect this data, we worked in villages representing different levels of development, population, and crop residue burning. Within villages, we randomly selected small and medium/large farmers to participate in the FGDs, and we purposively selected key-informants that held critical positions within the agricultural system. We then coded FGD and interview transcripts according to major questions and themes to synthesize results from the several hundred pages of transcripts we collected.

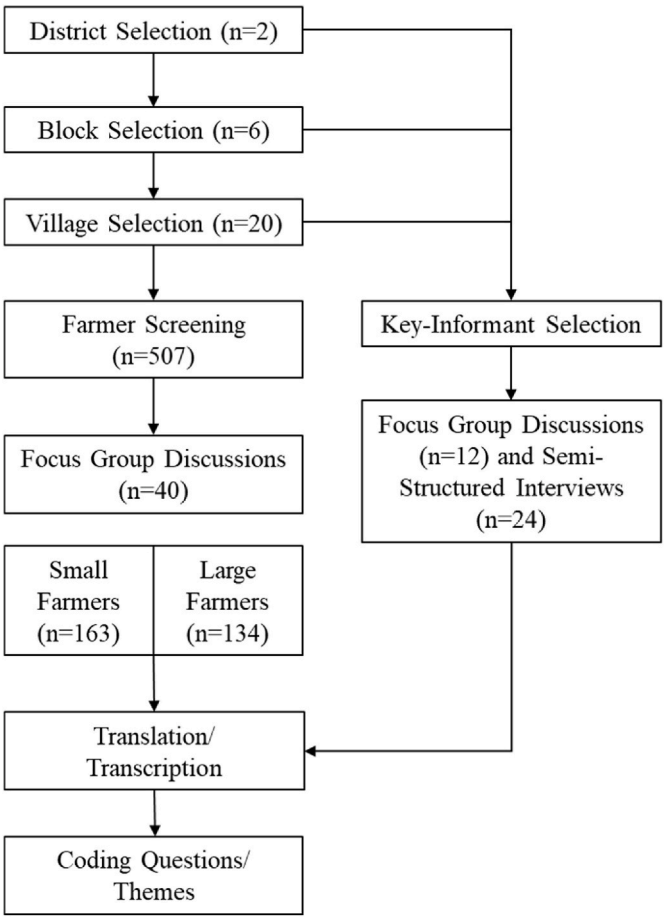

Fig. 1. Graphical summary of the research methods. We purposively selected districts, blocks, and villages to represent variation in of development, population, and fire occurrence. Within villages, we randomly selected farmers and conducted separate FGDs with small farmers (cultivate five acres or less) and medium/large farmers (cultivate more than five acres). Key informants represent agricultural service providers, members of agricultural organizations, politicians, and civil servants who influence the agricultural system in Punjab. All qualitative data was translated and transcribed from recordings and coded manually for important questions and response themes.

3.1. Study site and village selection

This research generated data on farmer and key-informant responses from Patiala and Moga districts in Punjab state (Fig. 2). We selected Patiala and Moga due to prevalence of burning, as well as differences in their population, size, agricultural coverage, and development. Patiala is a major rice cultivating district. It is in southeast Punjab, contains 1.9 M people, and covers 3430 km^2. Moga is in central Punjab and is smaller in area (2,242 km^2) as well as population (1 M people) than Patiala. However, compared to Patiala, Moga has greater market connectivity, a more extensive road network, and a greater proportion of land burned for crop.

residue management. Further information on the relevant differences between Moga and Patiala are detailed in Supplemental Information 1: Village and Sample Selection.

In Patiala and Moga, we selected blocks and villages purposively. We selected study blocks based on accessibility, prevalence of burning, and presence of agriculture. Within each block, we selected four villages in which to conduct focus group discussions and key informant interviews. We selected study villages based on population characteristics, infrastructure availability and fire incidence. Population and infrastructure related indicators include total village population, literacy, the number of agricultural laborers, the number of agricultural cultivators, the number of seed centers, and the number of fertilizer shops. For the population characteristics, we assigned individual scores to each village based on the proportion of population in a particular village (relative to the district). We calculated a composite index score from village population and infrastructure indicators, which we refer to as the DevPop index, as well as a fire index. Agricultural fire related indicators included both the number of paddy fire incidents as well as the probability of burning calculated from a cumulative density. We divided villages into four categories based on their DevPop and fire index scores. Within each block, we ordered villages according to their DevPop and fire index score, differentiating between the villages in the 50th percentile for both. We provide additional details in the Supplemental Information on the selection criteria for study villages (Supplemental Information 1: Village and Sample Selection) as well as methods developed to calculate the cumulative density function of village burning (Supplemental Information 2: Calculating Cumulative Fire Density).

3.2. Research design

3.2.1. Farmer FGD selection

To identify farmer participants for the focus group discussions, field staff first contacted the Sarpanch (village leader) to locate neighbourhoods, household locations, and obtain list of households for each village. Facilitators and project coordinators randomly selected household to complete a screener survey that elicited information to determine eligibility for participation in an FGD.

The screener survey identified a sample of farmers with agriculture as their main source of income, who cultivated non-Basmati paddy, were sole decision makers with respect to farming, and reported that they were knowledgeable about CRM. After determining eligibility, farmers were categorized as either small or medium/large farmers. Small farmers cultivated five acres (2.02 ha) of cropland or less, and medium/large farmers cultivated more. In each village, field staff facilitated two FGDs, one with small farmers and one with medium/large farmers.

As with previous research (Krishnapriya et al., 2024), we distinguish between small and medium/large farmers because of socioeconomic differences between them. In contrast to medium/large farmers who often own farm machinery and equipment individually, small farmers often rely on social networks, agricultural organizations, or service providers to access the equipment they require (Chahal et al., 2014). Though organizations that provide machinery rental are often owned or managed by medium/large farmers, small farmers are the primary users (Singh, 2017). Thus, to ensure our research collects diverse perspectives related to the system of agricultural production in Punjab, and to encourage open and free discussion about those organization among primary users and managers/owners, we sampled and held discussions with small and medium/large farmers separately.

A total of 507 farmers completed the screener survey, with 285 from Moga and 222 from Patiala. Approximately 60% of farmers who responded to the screener survey were between 39 and 58 years old, likely because these respondents felt most confident answering questions about agriculture practices as the "primary decisionmaker." A total of 113 (51%) small farmers and 107 medium/large farmers (49%) participated in the screener survey in Patiala district. In Moga district, 128 (45%) small farmers and 132 (55%) medium/large farmers participated in the survey. Though these proportions broadly represent the overall distribution of farmers in many districts of Punjab (Krishnapriya et al., 2024), we did not select roughly equal numbers of small and medium/large farmers based on representativeness. Rather, we engaged an approximately equal number of farmers cultivating small and medium/large tracts of land to understand differences and similarities in their perspectives across villages selected for historical burning probabilities and levels of development.

We conducted two FGDs in each study village, totaling 40 farmer FGDs (Table 1). In each village, one FGD included only small farmers and the other included only medium/large farmers. In each district, two

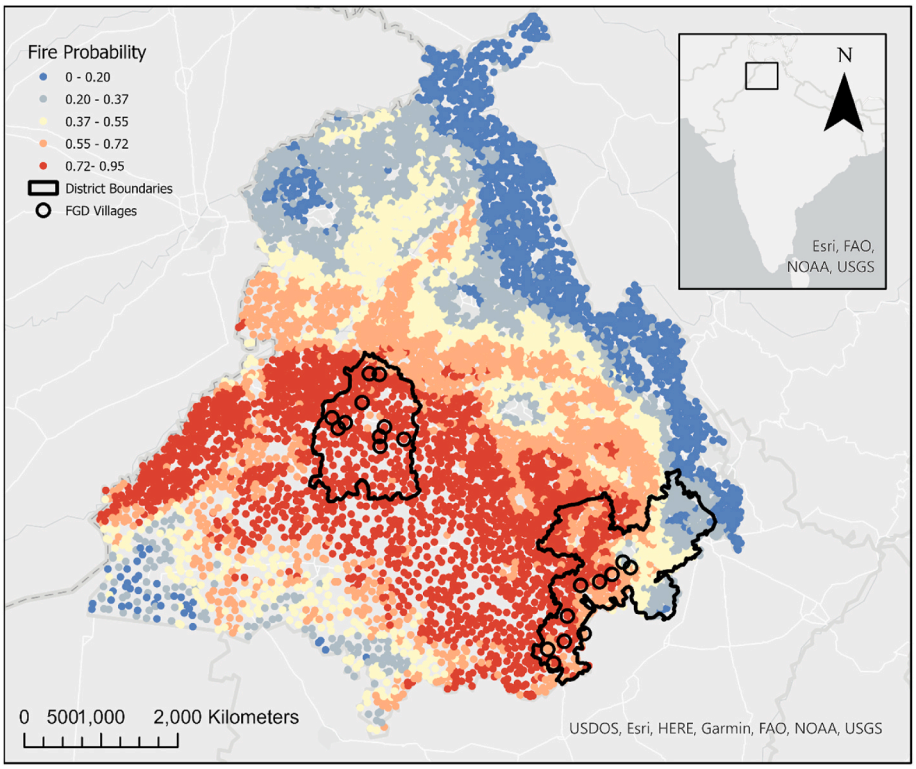

Fig. 2. Map of burn probabilities for villages in Punjab, with boundaries for Moga and Patiala Districts as well as villages where farmer FGDs were conducted.

Table 1
Research activities by district and block.

District	Block	Villages	Famer FGDs	APMC FGDs	CHC/Coop FGDs	Gram Panchayat Chairman	Dept. Agriculture Officers	Service Providers
Patiala	Sanaur	4	8	2	4	1	1	6
	Samran	3	6			1	1	
	Patran	3	6			1	1	
Moga	Moga I	4	8	2	4	1	1	6
	Moga II	3	6			1	1	
	Dharamkot	3	6			1	1	
Total		20	40	4	8	6	6	12

small farmer FGDs were comprised only of women. Of the 507 farmers from the screener survey, 297 participated in village-level FGDs. In Moga, 83 small farmers including 16 women and 69 medium/large farmers participated in FGD discussions. In Patiala, 80 small farmers including 11 women and 65 medium/large farmers participated. Farmer FGDs ranged from five to eight participants.

3.2.2. Key informant selection

In each district or block, field staff conducted interviews and a small set of additional FGDs to complement farmer FGD data. Following previous research that highlights important actors within the agricultural system of Punjab (e.g. Krishnapriya et al., 2024), we focused on local representatives and government officials, cooperative societies, custom hiring centers, agricultural produce marketing centers, and individual agricultural service providers at the village-level. Table 2 provides a list of the groups and positions represented by key informant discussions and interviews.

We conducted a total of 12 FGDs and 24 individual interviews with key informants (Table 1). In each district, we held two FGDs with Agricultural Produce Market Committee members and four with Custom Hiring Center or social cooperative members. Initially, we planned to conduct FGDs with agricultural service provider as well, but piloting revealed that they did not share information about machinery rental prices or where they operated with other service providers in the room. We therefore conducted six interviews with individual service providers in each district. At the block-level, we conducted interviews with Gram Panchayat Chairmen (locally elected officials) that represented constituents at either a village- or block-level, and we conducted interviews with representatives from the Department of Agriculture.

3.3. Data collection and analysis

To facilitate the systematic collection of data, we designed six research instruments that contain similar questions but have prompts and text tailored to the specific discussion or interview in question. FGDs with farmers, all-women farmer groups, and APMC/CHC/cooperative society members were each conducted with tailored research instruments. Gram Panchayat Chairmen, Agricultural Officers, and service providers were also interviewed with tailored questionnaires. We piloted all instruments in one village within each district to ensure the suitability and relevance of our questions and list of key-informants. After piloting, we made minor revisions to the discussion guides and confirmed the importance of intended key informants. Bilingual research staff translated all finalized research guides into Punjabi before their use. We provide additional information on the scripted questionnaires in the Supplemental Information (Supplemental Information 3: Questionnaire Design).

We used a manual coding system to analyze FGD and interview

Table 2
Group affiliations of key informants.

Group	Description	Administrative Level and Research Activity
Cooperative Societies (Coops)	Cooperatives provide agricultural inputs, rental machines for CRM, and education/training to members. Cooperatives also organize farmer education programs and provide training opportunities.	District-Level Interviews
Custom Hiring Centers (CHCs)	Units that provide farm machinery, implements and equipment meant for rent by farmers. The main objective of a CHC is to supply of farm implements to small, marginal, and poor farmers at subsidized rates.	District-Level Interviews
Agricultural Produce Marketing Centers (APMCs)	Marketing boards operating under the aegis of State Government. They regulate agricultural trading practices by limiting farmer exploitation by creditors or intermediaries, limiting sales where farmers are forced to sell produce at lower prices, and ensuring appropriate prices with timely payments	District-Level Discussions
Individual Service Providers	Service providers refer to the individuals who bought machines required for farming and CRM and provide them on rent to other farmers. Most service providers operate individually. Service providers typically farm their own land in addition to providing rental services.	District-Level Focus Group Discussions
Chairmen of Gram Panchayat	Gram Panchayats are responsible for overall development of the villages and for providing basic services for the health and well-being of people in the village including economic development and social justice based on state legislature.	Block-Level Interviews
Department of Agriculture Officers	Agricultural Officers are tasked with the marketization of agricultural commodities, checking crop output, assessing crop quality, handling complaints from farmers related to crop sales, creating awareness among farmers of new policies, introducing new techniques, and strengthening ties between farmers and universities.	Block-Level Interviews
Women-Only Farmer FGDs	Regional cultural norms determine that men are often household decisionmakers regarding agricultural, and women often make decisions regarding non-agricultural spending and activities, while supporting a limited number of agricultural activities. Due to these norms, farmer FGDs were exclusively male. To ensure the inclusion of women's voices and confirm findings from the farmer FGDs, women-only farmer FGDs included women from agricultural households with knowledge of agriculture and CRM	District-Level Discussions

Table 3
Summary of similarities and differences in Large and Small Farmer FGDs across questions of interest.

Question focus	Similarities	Medium/Large Farmer Differences	Small Farmer Differences
Current extent of burning	Large and small farmer FGDs demonstrated a similar willingness to discuss current burning practices in their villages.	Medium/large farmer FGDs estimated that more farmers burned overall (65%) and estimated a higher percentage of farmers burn partially (31%). However, fewer medium/large farmer FGDs discussed partial burning (n = 8).	Small farmer FGDs estimated lower levels of overall burning among farmers (55%) and lower levels of partial burning (12%). However, more small farmer FGDs discussed partial burning (n = 11).
Perceptions of machine subsidies and burning regulation	Large and small farmer FGDs discussed fines as well as subsidies at similar rates.	Medium/large farmer FGDs were more likely to mention fines were rarely implemented (n = 7). Also, they had greater awareness of machine subsidy programs (n = 18), more often contained individuals who had applied for a subsidy (n = 13), and reported positive perceptions of the subsidy program (n = 4).	Small farmer FGDs less often discussed whether fines were collected (n = 3). They also had less awareness of subsidy programs (n = 12), contained fewer individuals who applied for a machine subsidy (n = 6), and did not report positive perceptions of the subsidy program.
Preferred source for farming information	Large and small farmer FGDs consistently identified social media and other farmers as primary sources for farming information	Dominant source is other farmers (n = 13), followed by university professionals (n = 12), Youtube and Facebook (n = 9 for both)	Dominant source is Youtube (n = 12), followed by other farmers (n = 11), and Facebook (n = 9)
Key market barriers for no-burn CRM	Large and small farmer FGDs identified the importance of MSP for non-basmati rice as a key market barrier. Both FGD types identified the importance of cooperative societies for machinery rentals and discussed the challenge of accessing machinery in the short period for field preparation.	Medium/large farmer FGDs discussed fewer issues related to machinery rental markets, likely owing to greater rates of tractor and implement ownership.	A greater roportionn of small farmer FGDs discussed machinery rental markets (n = 16), the limited supply of no-burn CRM implements (n = 8), and the challenge of matching tractors with implements for no-burn CRM.

transcript data. Upon the completion of each research activity, bilingual research staff translated the transcripts from recordings into English (when necessary) for each FGD and interview. They also assigned each transcript an ID and added line numbers for reference. We identified seven variables to represent different research activities and demographic variables, and 44 questions of interest (Supplemental Information 4: Data Analysis). For each question of interest, we identified responses from the transcript and recorded the direct quotation along with the page and line number from the transcript. We divided these

questions into themes that focus on current practices of CRM, the perception of stubble burning, the role of penalties and rewards, sources of agriculture information, the impact of markets and barriers on CRM, and suggestions for improving the uptake of no-burn CRM.

4. Results

Farmers and key informants demonstrated a broad willingness to share insights and perspectives about CRM. Fig. 3 illustrates the extent of FGD engagement with key question topics. Below, we present results that focus on current CRM practices, perceptions of burning prevalence, the role of penalties and rewards, information about no-burn CRM, markets for no-burn CRM services, as well as suggestions for promoting no-burn CRM in Punjab. Within each of these subsections, we consider overall farmer responses, differences between medium/large and small farmer FGDs, and differences between farmer and key informant responses. We summarize the differences between small and medium/large farmer responses in Fig. 4 and Table 3.

4.1. Current CRM practices

Farmers and key informants agree that current practices related to CRM in Punjab are primarily determined by the short window of time between harvesting rice and sowing wheat. Respondents identified a set of major policy, production, and market drivers for the existence of this short window for crop management. First, to avoid extensive irrigation and the depletion of groundwater resources, the Punjab Preservation of Subsoil Water Act (2009) prohibits farmers from sowing seeds in paddy nurseries until the monsoons arrive. Previously, this Act established June 10th as the date when transplanting could begin. Now, however, transplanting dates are determined annually. In 2023, transplanting dates occurred in four phases, with different districts starting at different dates between June 10th and June 21st. Second, non-basmati long duration paddy varieties (e.g., PUSA 44, Peeli PUSA, Dogar PUSA) that produce greater yields but take longer to mature are popular among farmers. These varieties also produce larger quantities of crop residue as compared to some certain short duration varieties (e.g., PR-126). In addition, the minimum support price offered by the government for non-basmati rice encourages the production of long duration paddy varieties. Third, there is a broad lack of demand for crop residues produced when harvesting long duration non-basmati paddy crops. Some farmers noted the presence of *gujjars*, an agropastoral community, who pick baled residues from non-basmati rice. However, many FGDs and interviews identified a lack of demand for crop residues or a lack of labor available to gather and transport them. Recently, however, demand is growing in some districts as a result of state supported power plants that use crop residues for energy production (Government of Punjab, 2021).

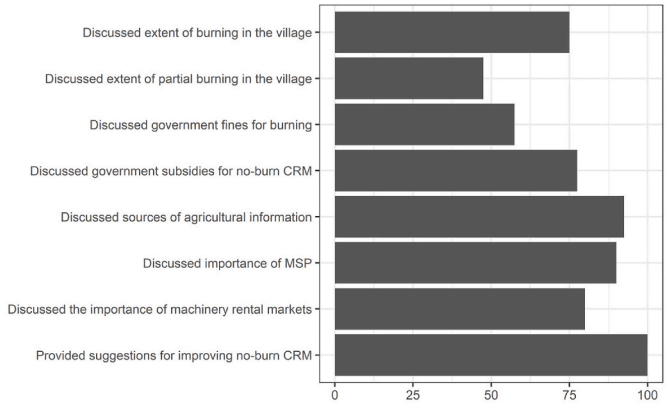

Fig. 3. Percentage of farmer FGDs (n = 40) that engaged with different question topics.

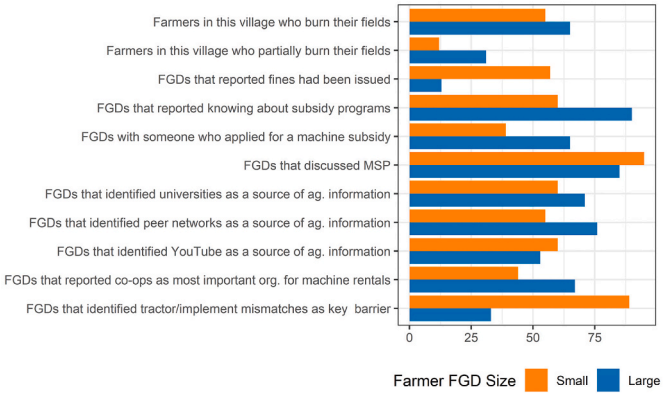

Fig. 4. Percentage of responding Farmer FGDs by question by Farmer FGD size.

The access and combination of different agricultural machines adds to the complexity of agricultural practices and determines CRM. Farmers and key informants discussed 12 different agricultural machines that are used to manage crop residues in some way. Table 4 lists these different agricultural machines and their usage, and Fig. 5 illustrates machine

Table 4
Agricultural machines and their usage.

Machine	Usage
Combine Harvester	Cuts, threshes, and cleans the grains. Used for harvesting, threshing, winnowing, and cleaning
Super Straw Management System (Super SMS)	Enables the harvester to chop, shred, and spread the straw in small pieces
Cultivator	Breaks the hard surface and clods, usually used after disc ploughs
Disc Plough	Cuts, lifts, and turns the soil
Super Seeder	Incorporates standing paddy stubble in soil and sows wheat seed in a single operation after harvesting the paddy with a combine harvester and Super-SMS attachment. Works on high powered tractor greater than 55 horsepower (hp)
Happy seeder	Cuts and lifts rice straw, sows wheat into the bare soil, and deposits the straw over the sown area as mulch after harvesting the paddy with a combine harvester and super SMS attachment. Works on a 45–50 hp tractor
Straw chopper/Mulcher	Cuts crop residue and spreads it evenly on the soil surface, often used after post surface seeding by broadcasting
Mould Board plough	Cuts, lifts, inverts, and pulverizes the soil and mixes it with straw after the use of a mulcher or straw chopper
Rotary slasher	Slashes pasture cover, shrubs, and growth up to 25 mm. Helps maintain grasslands, road verges, and lawns with finest shredding. Can be used in place of Super SMS
Zero Till Drill	Sows seeds using a seed and fertilizer boxes, often after total or partial burning
Rotavator	Ploughs by cutting, churning, breaking, and turning soil
Roto-drill	Combines a rotavator with a seed box to plough soil and sow wheat seeds.
Mulcher Seeder	Combines a mulcher with a seed box and sows seeds on surface of soil while leaving a thick mulch on the seeds as a cover
Baler	Compresses straw into cubes or cylinders for transport and storage
Smart Seeder	Strips tillage and drops seeds while mulching after. In contrast to Happy Seeder, it performs strip tillage or minimal tillage where the seed sowing is done. Works on 45–50 hp tractor
Combine Harvester Seeder Mount	Combines sow box with combine harvest to sow while harvesting. Sows seeds on surface of soil while leaving a thick mulch on seeds as a cover

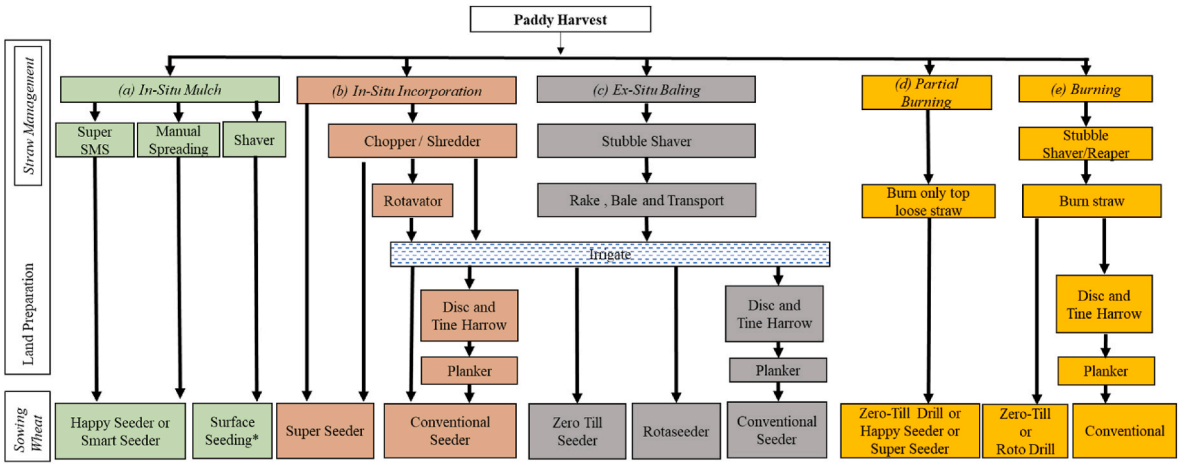

Fig. 5. Three distinct activities relate to rice-wheat production in Punjab: straw management, land preparation, and wheat sowing. Farmers have the option of using rice straw as mulch (a), incorporating it into the land (b), collecting and removing it (c), or burning it either in part (d) or in full (e). Following this choice, farmers use different machines to sow wheat seed using various agricultural implements (adapted from Lohan et al., 2018; Shyamsundar et al., 2019).

usage. In almost all cases, farmers report using more than one machine to harvest rice, manage crop residues, prepare their fields, and sow wheat. Though many proposals to increase no-burn CRM focus on providing better access to farming implements that assist with mulching or incorporating crop residues into the soil, these solutions must address the current distribution of implements and experience.

4.2. Perceptions regarding extent of stubble burning

In response to a broad question about the proportion of farmers who burn in the village where an FGD took place, 75.0% of all FGDs provided an answer. Of these, most FGDs (63.3%) differentiated between the proportion of farmers who burned crop residues partially and those who burned all crop residues from rice.

Large and small farmer FGDs demonstrated pronounced differences in their perceptions of burning. 83.3% of medium/large farmer FGDs responded to questions about the number of farmers who burn their fields, as compared to 68.1% of small farmer FGDs. Medium/large farmer FGDs reported an average of 64.7% of farmers burn in their villages, while small farmers report 55.3% of farmers in their villages burn crop residues. Small farmer FGDs were more likely to differentiate between complete and partial burning of crop residues (73.3%), as compared to medium/large farmer FGDs (53.3%).

When discussing the reasons for burning, medium/large farmer FGDs differed from small farmer FGDs. Medium/large farmers often discussed the expense of not burning, identifying the prohibitive role of no-burn CRM cost for small farmers. Though FGDs with small farmers also reported the importance of cost, they were more likely to cite a lack of access to other options for CRM. Alternatively, responses from key informants indicate the cost, both for diesel and machine rental, is most important to farmers deciding whether to practice crop residue burning ($n = 13$).

Differences in the reported time of burning were significant between farmer FGDs and key informant interviews. Half of all farmer FGDs indicated that farmers burn during the daytime, after checking the wind direction and when there is less moisture in the residue ($n = 20$). They also reported that they burn during the daytime to protect their neighbors' land. In contrast, four key-informants provided information on when farmers burn crop residues, and they all indicated that the farmers burned residues at night to evade government regulation ($n = 4$).

4.3. The role of penalties and rewards

The Government of Punjab, with support from the Indian National Government, provides different subsidy programs to promote no-burn agriculture (Ministry of Agriculture and Farmers Welfare, 2018). In addition, it has periodically relied on the use of fines for burning crop residues. FGDs reported awareness and criticisms of government policies related to the implementation of fines for burning and subsidies for no-burn CRM implements.

Though 42.5% of FGDs chose not to discuss government fines for burning ($n = 17$), those that did discuss them indicated that fines were collected infrequently and that bribing officials was often a cheaper and faster solution. In discussing fines, FGDs reported that although there is increasing government pressure to reduce burning crop residues, they have no choice but to keep burning. FGD responses to questions about subsidies for no-burn CRM implements demonstrate similar dissatisfaction.

Of the 77.5% of FGDs that chose to discuss government subsidies ($n = 31$), 96.7% were aware of government programs for different agricultural implements. Nearly two-thirds of these FGDs identified someone they knew who had applied to receive a machine subsidy ($n = 19$), either individually or as a group, but only 4 FGDs contained farmers that voiced satisfaction with the process and value of the subsidy. The 27 FGDs that discussed dissatisfaction with the current subsidy program identified the importance of money and power in receiving individual subsidies, the comparative low quality of machines available for subsidy, the length of time farmers wait to receive the subsidy, and the insufficiency of the subsidies to promote implement ownership for small farmers.

When discussing penalties and rewards, the differences between small and medium/large farmer FGDs were pronounced. Though similar proportions of medium/large and small farmer FGDs were willing to discuss the issuance of fines for burning (35.0% and 40.0%, respectively), all of the medium/large FGDs that discussed fines indicated that they were rarely if ever implemented or collected. In contrast, 62.5% ($n = 5$) of small farmer FGDs that discussed fines for burning indicated they were implemented. Discussing subsidy benefits reflected further discrepancies between farmer FGD types. Medium/large farmer FGDs more often discussed no-burn CRM machine subsidies and were more knowledgeable about them. Medium/large farmer FGDs consisted of 68.4% ($n = 13$) of FGDs that reported knowing someone who applied for a subsidy and 100% of FGDs ($n = 4$) that reported satisfaction with the subsidy program.

In discussing the role of government with key informants, one interview and 3 FGDs identified that machine prices increased even as the subsidy program was launched ($n = 4$). Key informants across all types were aware that group applications receive greater machine

subsidies as compared to individual applications. Key informants reported that a group subsidy covers approximately 80% of machine costs and the individual subsidy approximately 50%.

4.4. Information about no-burn CRM

Farmers report receiving information about agricultural practices, including CRM, from a variety of sources and platforms. 92.5% of farmer FGDs provided responses about informational sources (n = 37), and they indicated that peer networks were the most common source of information (n = 27), followed by universities (n = 20), industry (n = 14), and government (n = 6). Media platforms that farmers referenced as most important for receiving information on agricultural practices include YouTube (n = 21), Facebook (n = 18), and TV (n = 10). However, FGDs across village and farmer types reported a lack of trust in social media information, and the importance of established in-person relationships with individuals who can provide support, guidance, and information on agricultural activities in the field. Few of the FGDs reported an awareness of government (n = 10 university n = 6), or industry (n = 4) visits to their village to provide information on agricultural practices. Farmers stressed the importance of trust related to information, with numerous FGDs reporting that online materials were often untrustworthy. Farmers identified repeated in-person contact with government officials or university experts as an important method for establishing trust. They also identified the usefulness of a trusted and comprehensive digital platform that could provide vetted information on climate, agricultural products/services, and local machine rentals. However, farmers did not provide information on how such a platform could improve its trustworthiness, or what organization might be able to provide such a platform.

Differences in FGD responses related to information on agricultural practices occurred primarily between small and medium/large farmer FGDs, rather than between FGDs in villages with historically high or low burning. FGDs conducted with medium/large farmers reported a greater dependence on university actors as a source of information (n = 12) as compared to FGDs with small farmers (n = 8). Medium/large farmers similarly stated that they trusted university actors most, with one respondent stating, “Farmers can trust only university experts, [who] should visit the field and explain new schemes provided by the government” (FGD 20, Ln. 496–500). FGDs with small farmers more often reported the importance of YouTube, TV, Industry actors, and Government actors (rather than university sources), focusing on the importance of field demonstrations, receiving information from government officials, and the need for better information about government programs and subsidies. Despite these differences, FGDs from large as well as small farmer groups both indicate a desire to work with individuals who visit their villages and are available to troubleshoot problems and provide expert opinions on farming practices.

When asked about no-burn CRM, key informants emphasized the type of information they provide to farmers. In all interviews with Gram Panchayat Chairmen, they referenced their role in guiding farmers and delivering information about governmental policies and programs (n = 6). Agriculture Officers reported on the importance of providing new information and technology to help inform farmer decisions (n = 4), providing information on governmental policy (n = 3), arranging camps (n = 3) and arranging to provide demos to farmers (n = 1).

4.5. Markets for no-burn CRM services

Farmers across village contexts identify the importance of market drivers for the current agricultural system. 90% of all farmer FGDs mentioned the importance of the minimum support price in their decision to grow non-basmati rice (n = 36). According to farmers, the minimum support price generates a viable market for non-basmati rice that reduces risks related to the sale of rice harvest. In addition to receiving a minimum price for non-basmati rice, farmers indicated that non-basmati varieties of rice produce between one third to one half more in yield relative to basmati varieties and require less labor. However, basmati is also grown by some farmers as a third crop due to its faster time to harvest, need for less water, and household taste prefernces. In addition to higher yields and taste contributing to preferences for of long-duration paddy varieties (PUSA-44 Peeli Pusa, Dogar Pusa), farmers also indicate the importance of machinery markets in influencing CRM strategies.

Rental markets for tractors and farming implements are a key market driver of current CRM practices. 80% of farmer FGDs discussed the importance of rental markets for agriculture in their villages (n = 32), and among those farmer FGDs that discussed specific rental options and prices (n = 28), cooperative societies were most often the most important source of rental options (n = 15), as compared to borrowing equipment or renting it from a private source. However, farmers identified the cost, tractor/implement mismatches, and availability of machines as critical challenges. For all machinery (n = 10) as well as for machinery specific to no-burn CRM (n = 11), farmer FGDs most often identified tractor/implement mismatches as a key challenge. Happy Seeder was popular for CRM among farmers but farmers report that current preferences have shifted to using Super Seeders. Farmers report that Super Seeders require tractors with higher horsepower (>55 HP); however, many farmers do not own such a tractor, and so must rent it and pay for the higher diesel costs it entails.

Farmer FGDs more often identified cost as a challenge for renting and operating no-burn CRM implements (n = 8) than for overall machinery rentals (n = 4). The limited availability of machinery—both overall and no-burn CRM machinery—was discussed as the second most important challenge for rental markets. In order of descending frequency, farmers discussed challenges to overall machine availability in terms of limited time for using rented equipment (n = 8), limited supply of rental machines (n = 6), and coordination/delivery issues (n = 2). For no-burn CRM implements, farmers identified the limited supply (n = 15) and the limited amount of time for their use (n = 12), without referencing coordination/delivery issues. Other challenges that farmers identified for no-burn CRM implements include limited knowledge of how-to best use implements (n = 2) as well as functionality issues with rented machines, such as insufficient energy resources or inappropriate fit with drier soil conditions (n = 6). For example, operating a Super Seeder requires knowledge of soil moisture and its impact on seeding depth. Without this background knowledge, farmers may experience low rates of germination following Super Seeder use.

In discussing crop insurance, farmer FGDs reported awareness and skepticism. 65% of farmer FGDs (n = 26) reported awareness of what crop insurance is. However, only two farmer FGDs reported that farmers knew someone with experience in purchasing a crop insurance premium. Related to crop insurance markets, farmers were skeptical, having received information online or having heard that most advertisements did not provide timely or sufficient coverage. Although awareness of crop insurance was equal across small and medium/large farmer FGDs, only participants in medium/large farmer FGDs indicated that they knew someone who had purchased it.

Medium/large farmer FGDs more often identified issues with rental coordination, whereas small farmer FGDs discussed a wider range of market challenges. For example, small farmer FGDs identified cost as a barrier to overall machine rental (n = 3) as well as no-burn CRM machine rental (n = 5) more often than medium/large farmer FGDs. Further, small farmer FGDs cited mismatches between tractor power and no-burn CRM machines as a major barrier (n = 8). In contrast, only medium/large farmer FGDs identified issues with rental coordination and machine delivery as a barrier (n = 2).

CHC and Cooperative FGDs reported that they take a leading role in providing machinery rental services to farmers (n = 8). Individual service providers also play a key role in rental market because they represent peer-to-peer borrowing. 75% of individual service providers reported that they only provide services to nearby villages, citing

barriers such as costs, travel time, and limited machine resources that prevent service provision to more distant farmers. 50% of service providers reported entering the rental market in recent years after the government started fining the burning activities (n = 4). In addition, they indicated that profits from rental business had decreased because of increasing diesel costs (n = 2).

According to Agriculture Officers, the relationship between small and medium/large farmers in rental markets is complicated. One Agriculture Officer reported that some medium/large farmers cannot lend machines to small farmers because they have their own land to manage. Another reported that some small farmers work on medium/large farmer lands in exchange for access to machines.

4.6. Suggestions to promote no-burn CRM

Farmer FGDs provided numerous suggestions for promoting no-burn CRM in Patiala and Moga. We identify 13 unique suggestions, 10 of which focus specifically on government action. The.

suggestions that did not specify government action include "provide more demonstrations," "improve university communication," and "direct payments to farmers."

Suggestions with the greatest number of mentions (Fig. 6) focus on reducing costs associated with no-burn CRM. These suggestions include "change MSP (minimum support price)," "improve machine subsidies," and "implement diesel subsidies." Over half of all FGDs identified the importance of providing minimum support prices for crops other than non-Basmati rice to improve crop diversity (n = 22), reduce burning, and reduce water requirements. However, an almost equal number of farmers mentioned the importance of improving machine subsidies (n = 21). Most of these responses identify the fairness of sharing costs between government and farmers, with governments fully subsidizing machine costs and farmers paying for diesel. Subsidizing diesel was the third most common suggestion for promoting no-burn CRM (n = 14). Farmer FGDs that identified this suggestion pointed to the comparatively high diesel requirements for some no-burn CRM machines.

The next category of suggestions focus on structural changes. Many farmer FGDs suggested government investment in providing balers and supporting the use of crop residue as an energy source for electricity or to power local manufacturing (n = 14). FGDs that identified this suggestion also mentioned that it can contribute to improved electricity provision, especially during harvest and sowing periods. The fifth most common suggestion identifies the importance of improved government communication (n = 11), especially around partial versus complete burning. Farmer FGDs differentiated burning the top layers, in contrast to burning all crop residue, and reported that improved government communication around the different types of burning would be helpful. Farmer FGDs also identified the possibility of removing restrictions on sowing dates for rice, so that farmers had more time to manage crop residues (n = 9).

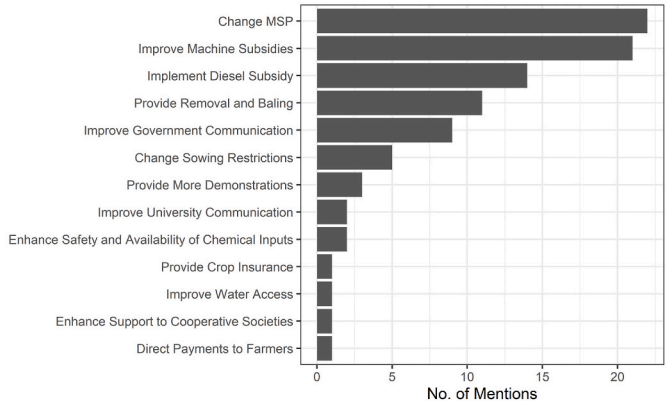

Fig. 6. Number of Farmer FGDs that make mention of a suggestion for promoting no-burn CRM.

The CRM suggestions from key informants parallel those obtained from farmer FGDs. However, two Agriculture Officers, two service providers and one Gram Panchayat Chairman suggested that the government should restrict or stop providing subsidies to farmers who burn (n = 5). One service provider and one CHC FGD suggested the government deduct the subsidy from price at the time of purchase so that farmers don't have to pay the full amount in advance. At present, farmers pay full price for agricultural machines and may receive subsidy payments later. Cooperative FGDs also recommended a ban on some paddy varieties (*Peeli* PUSA and PUSA 44) because of their high consumption of water (n = 2). One APMC FGD, one Agriculture Officer and one service provider also mentioned direct payment to farmers who implement no-burn CRM (n = 3).

5. Discussion

Burning remains the dominant method of CRM in Moga and Patiala. Farmer FGDs report that approximately 60% of farmers burn their crop residues. Previous research finds similar proportions of burning in Punjab. For example, Keil et al. (2021) find that 59% of farmers burned their crop residues, using a survey of farmers across four districts (n = 1021); Jack et al. (2023) find that 68% of farmers burned, using a survey of farmers across two districts (n = 1576); and Singh et al. (2020), found that 57% of farmers burned in a survey within the village of Biro KeKalan (n = 100). Though there is some evidence that crop residue burning has decreased slightly over the past decade (Lan et al., 2022), farmer responses about the prevalence of burning are corroborated, broadly, by survey research. Despite formal efforts to penalize burning and promote no-burn CRM, farmers continue to burn and discuss its prevalence in their village openly. This may be due to the prevalence and normalization of crop residue burning.

Farmers in our research emphasize the importance of understanding differences between full and partial burning. They highlight that though full burning lasts longer and generates more emissions, partial burning is a comparatively low-impact treatment that provides benefits to fields and generates fewer negative externalities. At present, there is a lack of literature that considers differences in full and partial burning on emissions, water use, and soil health. Indeed, literature on CRM in northwest India rarely distinguishes between full and partial burning at all. One notable exception is Krishnapriya et al., (2024), who evaluate behavior changes related to CRM and consider full as well as partial burning. This is an important field of study for future research. However, because current research, policy, and agricultural interventions focus on no-burn CRM, we continue our discussion by considering differences in any burning of crop residues (full or partial) as compared to no burning.

5.1. Exogenous factors and the policy landscape

Several policies reinforce current CRM practices in Punjab. Across all FGDs, farmers indicated that they plant non-basmati, long duration rice varieties because of the minimum support price they are guaranteed to receive. The minimum support price, and the state-level agricultural markets (*Mandis*), have their foundation in the Essential Commodities Act (1955) and the Punjab Agricultural Produce Markets Act (1961), which seek to improve food security and agricultural self-sufficiency. One outcome has been the implementation of minimum support prices for non-basmati rice and wheat, to ensure grain reserves and provide transparent prices to farmers across India (Kozicka, 2014). The security that the minimum support price provides for non-basmati rice, the comparative economic benefits long duration, higher-yield rice varieties provide, and water management policies that restrict when farmers can sow their paddy crops combine to produce the short window of time for managing rice crop residues (Downing et al., 2022).

Farmers discussed the usefulness of flexible sowing dates across

districts, which allow them to transplant their crop earlier, providing more time to manage crop residues. In addition, a number of farmer FGDs suggested that minimum support prices could be expanded to cover basmati, which may reduce water use, in addition to incentivizing alternative and more diverse cropping strategies (Davis et al., 2018), with potential benefits for climate adaptation and resilience (Singh et al., 2018). A new short-duration paddy variety, PR 126, is gaining traction among farmers because it produces yields like those of long-duration crops and it generates less residue making it amenable to Super Seeder or Happy Seeder adoption. However, the diffusion of PR 126 will depend on seed availability, farmer acceptance, and demand.

Though all farmers FGDs were interested in discussing the potential shifts in state and national policy that could promote no-burn CRM, none of the farmer FGDs provided information about the political uses of burning as an "everyday form of resistance" (Scott, 1985). Preceding this research, farmers staged largescale protests of three farm acts passed in September 2020, resulting in the Farm Laws Repeal Bill and further demands for increased minimum support prices. Actions related to protest included marches as well as blockades and may have included increased residue burning (Sharma, 2022). In our FGDs, farmers reflected on cost trade-offs related to no-burn CRM, but they did not provide information on any political strategies that may drive burning (Schmall, 2020; Sharma, 2022). This could indicate farmers responded strategically to FGD questions, showing that discussion of burning as a political tactic may be sensitive. Future research may want to investigate the use of crop residue burning as a form of individual or group protest, especially as an act of resistance.

5.2. The current sociotechnical regime and the role of crop residue burning

The current sociotechnical regime for rice-wheat agriculture in Punjab supports burning crop residue, though practices, perceptions, and reasons for burning vary. Farmers and key-informants are aware of the negative impacts from burning crop residues but report the need for assistance to stop. Farmer FGDs commonly referred to negative health impacts from burning crop residues, a trend that was particularly evident in the female farmer FGDs. This awareness is reflected in recent research on the health impacts from crop residue burning. Punjab and Haryana states, together, are responsible for more premature mortalities from particulate matter exposure than the rest of India combined (Lan et al., 2022).

As with previous research, farmers in our study identify the importance of timing on the impact of emissions from crop residue burning (Cusworth et al., 2018; Lan et al., 2022). Though farmers provide reasons for burning during the day, key-informants suggest that some burning occurs at night to avoid enforcement and monitoring by satellite, as it may not pass the region during evening hours. However, farmer FGDs broadly agree that fines are rarely imposed or collected. Thus, farmers may not bear some of the most consequential negative impacts from crop residue burning, such as health impacts caused by air pollution (Lan et al., 2022) and sanctioning. Instead, farmers are concerned with agricultural production that, they note, feeds their families and the country. They also point to the financial risk they face as food producers due to small profit margins, weather uncertainty, variable input costs, and sale price fluctuations.

The low cost and ease of burning, as well as the high cost and difficulty of no-burn CRM, are the primary reasons farmers and key-informants identified for the persistence of crop residue burning. The technological evolution and path dependency of agricultural implements and tractor ownership represent an important driver of current cost and difficulty related to no-burn CRM. Farmers who burn are reliant on a number of agricultural implements (e.g. disc harrows, cultivators, and drills) that are often owned and require tractors with lower horsepower (Parihar et al., 2023) as compared to implements for no-burn CRM. Currently prices for no-burn implements are high. Happy Seeders cost approximately $2100 (USD), Smart Seeders, $2,800, and Super Seeders, $3,500. Additionally, owning these machines requires using tractors to operate them. For example, the Super Seeder requires a tractor bigger than 55 horsepower, and such tractors are less common in the region. The most economically viable option for small farmers to pursue no-burn CRM using these implements is to pay for CRM rentals. Rental prices typically range between $20–30 per acre.

Thus, farmers report that the lower prices and greater interoperability of implements often paired with burning saves money and offers greater flexibility in the current system. In addition, farmers state that implements required for no-burn CRM use more fuel. Recently, however, a low-cost method called "surface seeding", which does not require heavy machinery or big tractors, is emerging with endorsement from Punjab Agriculture University. Despite the promise of this technique, much remains unknown about its efficacy across diverse soil types in Punjab.

Our FGDs suggest that incentives for machinery purchases have led to a sense of dissatisfaction among farmers. Farmers report that the subsidy is thus far ineffective because of complications in receiving it, unequal access, and higher prices for machines on offer through the subsidy. This reflects the case of drip irrigation technology (Rathore and Mark Giordano, 2020), where the subsidy system acts as a deterrent to the advancement of the technology. Complex technical prerequisites, excessively bureaucratic processes, and rent seeking behavior of retailers and manufacturers led to substantial price escalations of 40% or more in drip irrigation (Rathore and Mark Giordano, 2020). It will remain important to assess how and if machine subsidies assist in the availability and use of agricultural implements for no-burn CRM.

The combination of policies, social-practices, and technologies that have evolved over time to generate the rice-wheat agriculture in Punjab represent the current sociotechnical regime. Our research finds that the current system requires farmers to bear high individual costs for residue management, dispersed benefits for no-burn CRM, and a variety of penalty and reward processes that continue to normalize residue burning as a simple, low-cost CRM activity (Downing et al., 2022). Niche innovations that promote no-burn CRM, however, are available and promise to reduce the negative externalities that crop residue burning generate.

5.3. No burn CRM as niche innovation

Farmer FGDs and previous literature align on the multiple paths available to reduce or eliminate crop residue burning in Punjab. In-situ methods of incorporation and mulching rely on agricultural implements that are already in some use among farmers in our FGDs. Farmers report the practice of ex-situ CRM, such as baling and removing crop residue, are also in practice across the broader region, though farmers in our FGDs do not report first-hand accounts. Different methods of no-burn CRM are spreading, but they are also in competition (Shyamsundar et al., 2019; Krishnapriya et al., 2024).

Happy Seeder and Super Seeder implements use in-situ methods to use crop residue. In our study context, the Happy Seeder uses crop residue as a mulch as it sows wheat, whereas the Super Seeder incorporates crop residue into the soil as it sows wheat. Though Happy Seeder was once seen as the primary implement for promoting no-burn agriculture in Punjab, farmers in our FGDs report greater interest in the Super Seeder. According to farmers, mulching crop residue from Happy Seeder can lead to pest infestations and reduced crop yield. Happy Seeder has been well studied in Punjab, with studies reporting no yield penalties (Shyamsundar et al., 2019; Keil et al., 2021). However, the perception of yield trade-offs persists among farmers in our research, potentially explaining its limited use. Farmers indicate that both implements are often used in combination with partial burning of crop residues. They explain that farmers may burn a top layer of crop residue (loose fallen straw) to complement in-situ methods of crop residue management. Thus, different machines—even for in-situ methods—and

different burning strategies represent the full account of no-burn CRM.

Farmers report interest in ex-situ CRM, but they have little experience with it. Some crop residues in Punjab are used as bioenergy, powering local electricity plants. Introducing a lifecycle approach to the rice-wheat agricultural system in Punjab can, indeed, promote a reduction in burning. This CRM strategy may be especially appealing to farmers if residue is removed through third party services, or if their residues provide additional income. Indeed, ex-situ management and the use of crop residues, should it be scaled, may be the most promising method for reducing crop residue burning, based on the market drivers that determine cropping patterns and current CRM. Substituting crop residues for coal in thermal power plants across northern India holds promise to support large-scale ex-situ management (Sokhansanj et al., 2023). Despite the promise of ex-situ management for energy production, infrastructure and transaction costs remain high (Kurinji and Kumar, 2021). At present, ex-situ management seems highly clustered and uses only six percent of total residue (Government of Punjab, 2022). Future assessments related to scaling ex-situ management will need to account for trade-offs related to reduced soil amendment and downstream emissions from burning crop residues.

To influence the continued growth of no-burn CRM within the dominant system, farmers echo the need for coordinated actions (Hellin et al., 2021; Porichha et al., 2021) that promote cost reduction strategies and more durable markets for tractors and implements. Connecteing sociotechnical niches to external processes is essential for promoting system level change (Schot and Geels, 2008). Many FGDs suggested supplementing the cost of machine rental or purchases and cited the usefulness of cooperative societies for facilitation. Farmers indicated that although they already work with a cooperative society to rent or partner purchase machines, they experience long wait times and coordination issues with machine rental. Strengthening the capacity of these organizations and reducing the number of villages per cooperative society could help to coordinate machine rentals, cost sharing, and knowledge production.

5.4. Synthesizing farmer and key informant perspectives for policy

While studies point to positive returns from the use of no-burn machinery (Shyamsundar et al., 2019; Keil et al., 2021), our research demonstrates that farmers are often reluctant to begin practicing no-burn CRM within the current sociotechnical regime. Farmers burn for many reasons, including the costs of alternate strategies, lack of timely access to machinery, weak rental markets, and inevitable lags in the ability to learning new technologies (Kurinji and Prakash, 2021; Parihar et al., 2023; Krishnapriya et al., 2024). Advancing no-burn CRM through policy adjustments will require a holistic approach that considers incentives, learning, and markets.

Shifting current incentives for crop residue burning may focus on rice and wheat production or on other livelihood options. Farmers in our research report that penalties for burning are broadly ineffective. This emphasizes the importance of carefully considering positive incentives for agricultural production and how they relate to burning crop residues. Farmers and key informants reported strong support for expanding minimum support prices to include the procurement of other crops. Such a policy can support the transition from water intensive paddy crops and diversify agriculture beyond the rice-wheat system, but it would have significant implications for government budgets. In addition, incentives that seek to diversify livelihoods beyond agricultural production may also reduce burning. For example, grid connected solar pumps (an emerging development) may lead farmers to sell their electricity and shift away from rice production. Additionally, developing carbon markets can incentivize farmers to diversify into agroforestry, meeting agricultural, tree-product, and carbon sequestration needs (Rizvi et al., 2020; Singh et al., 2024). For such incentives to be accepted and effective, however, learning and extension services will be essential.

Learning and extension services that focus on farmers' needs promise to advance no-burn CRM and promote alternative livelihood options. Our research finds that farmers trust and rely on peer networks most for learning about new agricultural technology and practices. A comparative lack of trust in social media platforms among farmers and a preference for in-person learning reflects broader patterns of communication preferences in environmental governance (Erbaugh et al., 2024). Other research finds that while medium/large farmers in Punjab are willing to learn from their peers, small farmers are more likely to experiment independently before adopting new agricultural practices (Krishnapriya et al., 2024). Extension and experiential learning opportunities that demonstrate and teach skills thus hold promise for advancing no-burn CRM beyond a set of niche innovations. Very few farmer FGDs reported that individuals from universities or government had visited their village. We find that farmers prefer face-to-face opportunities to learn about agricultural practices, highlighting the opportunity for expanded extension services and village demonstrations.

Finally, strengthening rental markets and service provision will remain important for scaling no-burn CRM. Costs related to searching for services, negotiating prices, and enforcing contracts pose challenges to the use of implements used in no-burn CRM (Daum et al., 2021). Digital tools have proven effective in reducing some of these costs (Deichmann et al., 2016; Van Campenhout, Spielman and Lecoutere, 2021). However, very few farmers currently use digital platforms for rental markets and service provision and instead prefer to work through social networks to find and rent machines (Daum et al., 2021). Our research reinforces this finding by showing that farmers find digital sources to be less trustworthy than their peers, university employees, or government officials. Policy efforts should focus on fostering an environment that supports the increased adoption of digital solutions by combining them with traditional methods. The approach could entail creating an annual directory of local CRM service providers available for rent and distributing this information through local government and organizations, while also enhancing digital literacy among farmers. An additional policy measure could involve enhancing the skills of rental drivers in the use of advanced machinery like Smart and Super Seeders. This is crucial because poor operation can lead to reduced yields and diminish farmers' trust in the technology.

6. Conclusion

Drawing on farmer perspectives and sociotechnical systems theory, our research finds several leverage points that may have systemic impacts. First, farmers and key informants point to the importance of agricultural policy in shaping decisions about cropping as well as the time available for managing crop residues. Farmers mention the central role that the minimum support price for non-basmati rice plays in their cropping decisions, and how water conservation policies reduce the time they have for managing rice crop residues. Addressing either of these policy mechanisms may alter the sociotechnical landscape and promote change. Second, farmers and key informants report the critical nature of market drivers in the current sociotechnical system. Newer agricultural implements that assist farmers with no-burn CRM, such as the Super Seeder, require higher horsepower tractors to which small scale farmers and some larger scale farmers do not have access. Using these machines thus requires additional time for arranging rental or purchase, financial burdens associated with the additional diesel and rental/purchase requirements, and they introduce greater uncertainty due to being a niche innovation. Farmers report a desire to stop burning crop residue, but they highlight the importance of resolving these financial and market barriers to promote no-burn CRM that focuses on mulching or incorporation. Third, farmers highlight the potential and appeal of ex-situ CRM. Though ex-situ management also requires additional and expensive implements to bail crop residue, farmers note that it is often provided as a full service and is sometimes offered for free. Finally, farmers and key informants emphasize the importance of considering full burn

and partial burn CRM as different interventions. Though most literature on this system conceptualizes crop residue burning as binary, farmers point to the reduced emissions and health burden, and potential soil benefits, from burning only a top layer of rice stubble.

Our research collects and analyzes qualitative data on farmer and key informant perspectives, and in doing so is subject to certain limitations. We purposively selected districts, blocks, and villages to represent variation in population, development, and historical burning. In addition, we conducted FGDs with approximately equal numbers of small and medium/large farmers. These methods capture important variation in farmer and key informant perspective across key analytical variables, but they do not necessarily represent the broader population distribution. Though we carefully considered how to select study sites and participants, it is important to recognize that our findings are less representative than a study that randomly selects participants from across Punjab. In addition, the rich qualitative data we analyze reduced the number of participants we could include. Translating and coding this data further abstracts our findings from the words farmers and key informants used. Our study contains perspectives from hundreds of farmers and dozens of key informants, but it is important to keep in mind the limitations of our results. Future research based on a larger sample of farmers, perhaps through survey methods, would do well to assess one or multiple of the numerous questions and discussion topics we introduce here. Building on the perspectives of the farmers and key informants that generously gave their time to our research promises to advance knowledge about this unique sociotechnical system and potential transitions to no-burn CRM.

In contrast to literature that employs survey methods or randomized control trials to measure farmer behaviors related burning and CRM, we use a sociotechnical systems approach to interpret and analyze interview data from 40 farmer FGDs, 12 key informant FGDs, and 24 key informant interviews. We highlight the social, economic, and political factors that farmers discussed as challenges to no-burn CRM. Our research makes it clear that farmers' CRM decisions are not made in isolation. Scaling behavioral change for no-burn CRM in Punjab demands attention to the sociotechnical system in which farmers cultivate and harvest their crops. The dominant system of rice-wheat cropping and the prevalence of burning crop residues exists because of an array of policy, market, and social drivers. Though no-burn CRM innovations exist in the form of mulching, incorporation, or baling and removing residues, farmers now inherit much of the cost and risk these niche innovations entail. Programs that emphasize the environmental and public health benefits may result in progress toward no-burn CRM, but farmers in our FGDs already reported an interest in no-burn CRM and identified the negative health impacts burning can have. Farmer perspectives thus indicate that addressing policy constraints, improving machinery and service markets, reducing transaction costs, and promoting technical training through consistent and trusted information may speed progress toward reduced burning.

CRediT authorship contribution statement

James Erbaugh: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gurpreet Singh:** Writing – original draft, Conceptualization. **Zhixian Luo:** Writing – original draft, Investigation, Formal analysis. **Gurulingappa Koppa:** Validation, Funding acquisition, Conceptualization. **Jeffrey Evans:** Writing – original draft, Methodology, Data curation. **Priya Shyamsundar:** Writing – original draft, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

none.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jrurstud.2024.103387.

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