The Agriculture-Air Pollution System in Punjab

Agricultural practices in the north Indian state of Punjab, where farmers typically grow rice and wheat, have led to multiple negative social and environmental impacts. The burning of crop residues in this region lead to some of the highest concentrations of air pollutants anywhere in the world, damaging human health. Other impacts include over-exploitation of groundwater, over-use of fertilizers and reduced local crop diversity [1]-[7]. *Current policies aim to address air pollution by improving the existing residue management system without fundamentally changing the cropping pattern in the region. For example, the Supreme Court of India has announced a ban on residue burning and the Government of India subsidizes post-harvest machinery that enables easy removal of residues from fields. However, some have called for a radical change in cropping patterns in Punjab to address these interconnected challenges. Air pollution in this region is part of a broader system of interconnected sustainability challenges which have their roots in the structural aspects of the cropping system, along with the policy incentives that drive these structures.*

System Components

Following the human-technical-environmental systems framework[1], human, technical, environmental, institutional, and knowledge components are identified by italics. A full table of system components is shown in Figure 1.

Farmers in Punjab produce foodgrains, which *low-income households* then purchase at subsidized prices. *Residents of India* in general are affected by the societal and environmental impacts of agricultural practices.

Crops grown in Punjab are primarily rice and wheat. Rice is grown from June-October, and wheat from October-May. Agricultural inputs necessary to support the high-yielding varieties (HYV) typically grown include *fertilizers* (nitrogen-based urea, phosphate and potash fertilizers) and irrigation pumps, which use *energy*. The majority of pumps are operated by electricity [2]. *Residues* comprise the material left behind after crops are harvested. Post-harvest machinery such as *Happy Seeders* can be used to incorporate residues into the soil instead of burning them, while at the same time sowing the next crop's seeds.

The agricultural system takes place in areas of *land* on *soil* with varying amounts of nutrients. *Groundwater* is necessary for irrigation. The health of surrounding communities is affected by the *air,* which often contains high levels of pollutants such as fine particulate matter or $PM_{2.5}$.

Policies and markets provide the macro-level landscape for human, technical and environmental components to interact. There is an existing *ban on residue burning*

[1] For more information on the framework, see: H. Selin and N. E. Selin, 2020. *Mercury Stories: Understanding Sustainability through a Volatile Element* (Cambridge, MA: MIT Press). http://mercurystories.org

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imposed by the Supreme Court of India and enforced by the State government of Punjab. *Markets* influence supply and demand for farming inputs including machinery post-harvest farm technology such as the Happy Seeder and other farm machinery, as well as for – market for farm machinery, technology subsidies provided by the Government of India, and cooperative societies that enable easy farm equipment rental; markets where farmers can sell agricultural residues instead of burning them; government subsidies for farming inputs such as electricity and fertilizers; Certain crops are purchased from farmers at guaranteed prices through the *government procurement program*, and low-income households can purchase staple foodgrains at subsidized prices through the *Public Distribution System (PDS).*

There is growing *awareness about residue burning and its impacts*, particularly the health impacts of air pollution caused by burning. *Awareness of the use and benefits of post-harvest farm technologies* [8]–[10] is also improving, including of technologies such as the Happy Seeder. *Knowledge of prevalence and location of residue burning* affects government capacity to regulate it [10].

Interactions

Interactions between the three sets of material components (human, technical, and environmental components) in the context of the non-material components (institutions and knowledge) are organized here into pathways focused on key interactions. See Figure 2 for a full interaction matrix. Figure 3 illustrates the pathway of interactions for each subsection.

a) Farming and Food Production

Farmers in Punjab grow crops (Figure 2, box 1-2a), primarily rice and wheat. Farmers sell these crops to earn income (Figure 2, box 2-1a), including through government procurement programs. Government procured rice and wheat enters the PDS, where crops are sold at subsidized prices to eligible beneficiaries through shops regulated by state governments. Institutional incentives such as guaranteed prices for crops are a result of the Green Revolution that promoted high-yielding varieties [11], [12]. As of 2019, more than 800 million people accessed the PDS for food [13], [14]. The fact that rice and wheat are the only crops available in the PDS influence protein availability for low-income households (Figure 2, box 2-1b). Higher protein alternatives such as pulses (for e.g. lentils), which are not supplied through the PDS, are expensive and thus not included in their diets [15], [16].

b) Agricultural Inputs and the Environment

Growing rice and wheat requires both groundwater (Figure 2, box 2-3a) and fertilizers (Figure 2, box 2-2a). High yielding varieties of rice and wheat need higher fertilizer and water inputs than traditional varieties [18]. In tandem with promoting high-yielding varieties, the Green Revolution encouraged the development of infrastructure essential for higher productivity such as irrigation facilities and electricity provision [11], [12]. While the price of nitrogen-based urea fertilizer (N) is controlled by the Government of

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India and has remained stable over the last decade, the prices of phosphorus (P) and potash (K)-based fertilizers have increased significantly, as the subsidy on these remains fixed while the final market price is allowed to vary [19]. As a result, farmers use high amounts of fertilizers, especially urea (Figure 2, box 1-2b) – the recommended ratio of N:P:K application is 4:2:1 but reports suggest that fertilizer application in Punjab is in the ratio of 31:8:1 [19], [20], leading to an imbalance in soil nutrient ratios [21], [22]. The health of soil determines fertilizer requirements (Figure 2, box 3-2a).

Groundwater requirements for crop production affect energy use (Figure 2, box 3-2b). Farmers pump excess groundwater to irrigate rice-cropped land (Figure 2, box 1-3a) due to a number of factors. Rice has high water requirements, the State Government of Punjab charges farmers a flat power tariff which implies zero marginal cost of using excess electricity for pumping and poor quality of power supply where farmers have access to 6-10 hours of electricity during the day incentivizes over-pumping when electricity is available. This has led to much of Punjab's groundwater being overexploited with the water table declining at an annual rate of 0 – 2 metres [23].

Both energy use and fertilizer application lead to the emission of pollutants to air (Figure 2, box 2-3b).

c) Residue burning and health impacts

Crop harvesting creates residues (Figure 2, box 2-2b). Using farm machinery like combine harvesters leaves behind more residues than manual harvesting. Farmers burn 80-90% of rice residues since there a short time period (2-3 weeks) between harvesting rice and planting wheat, labour costs associated with residue removal are high and rice residue is not suitable as food for livestock due to its high silica content [7], [8], [17].

Residue burning emits pollutants to air (Figure 2, box 2-3c). These pollutants include greenhouse gases (GHGs). Air pollution from fine particulate matter ($PM_{2.5}$), resulting from residue burning, affects densely populated urban centres in the Indo-Gangetic Plain including Delhi [7], [18]. This air pollution affects the health of residents of India beyond the region (Figure 2, box 3-1a). Burning residues also leads to nutrient loss from the soil [19].

The sale of residues could provide income to farmers (Figure 2, box 2-1c). This would reduce emissions from burning as well as reduce nutrient loss from soil. Currently, there is no large-scale commercial or industrial use of residues; residues can potentially be used for cofiring in coal power plants, as feedstock in biomass power plants, and in pulp and paper industry, but this would require investment in technical and storage capabilities [10], [19].

d) Happy Seeder Use

Farmers can use post-harvest technologies such as the Happy Seeder (Figure 2, box 1-2c) – a tractor-mounted device developed specifically to avoid burning of residues by drilling seeds into rice residues left on the field [4], [20]. The Happy Seeder transforms crop residues (Figure 2, box 2-2c) by incorporating them into the soil. Use of the Happy

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Seeder reduces groundwater requirements (Figure 2, box 2-3d). It also improves the health of the soil (Figure 2, box 2-3e), which affects fertilizer input requirements (Figure 2, 3-2b). This currently occurs only for the winter wheat crop since it is used to sow wheat and not rice. This lowers costs for farmers and potentially leads to higher yields [4], [5]. However, yield increase in estimated to occur in the long term (after 3-5 years of use).

Few farmers currently use the Happy Seeder, however. This is because there is insufficient awareness about the technology and its benefits. In addition, potential benefits are not experienced immediately, while the upfront cost is significantly higher than current residue management practices [4], [9], [21].

Interventions

This section identifies ways in which different interveners can act to modify interactions in the system. Figure 4 provides a complete intervention matrix.

Potential interveners include the *Supreme Court of India*, *Government of India*, the *State Government of Punjab* and the *National Thermal Power Corporation of India*. This section presents five interventions in the agricultural sector in Punjab - all interventions are policy options that are either currently partly in effect or discussed widely in policy, development and academic circles [2], [4], [10], [13], [19], [22], [23].

a) Effective ban on residue burning:

The State Government of Punjab could effectively implement a ban on residue burning (Figure 3, box 2-3). Currently, armers may be fined between $35 and $210 depending on size of the landholding if they are caught setting fire to fields [24], [25], but weak ban enforcement by the State Government of Punjab means about 90% of rice residues are burnt on the field [3], [25]–[27]. One of the main barriers to ban compliance and enforcement is conflict of interest between stakeholders - the Supreme Court of India has directed the Punjab government to enforce the ban on residue burning, but farmers have no economically viable alternative to burning; the Punjab Government is reluctant to enforce the ban since farmers constitute more than 30% of the voting population in Punjab. Other barriers include inadequate monitoring capacity and lack of awareness amongst key stakeholders such as farmers and local government officials. The Punjab Government could pay farmers to remove residues and conduct an awareness campaign to ensure full compliance to the ban.

b) Wide-scale Happy Seeder adoption:

The Government of India could promote wide-scale adoption of Happy Seeders (Figure 3, box 1-2). Currently, it provides a 50% subsidy on purchase of Happy Seeders for individual farmers and 80% subsidy for farmers' cooperative societies. Although the Happy Seeder has been commercially available for a decade, adoption of Happy Seeders

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has been low (about 15,000 Happy Seeders are currently used in Punjab covering about 20% of rice-cropped land) and the majority of rice residues left on fields are still burnt [5], [8], [28]. The focus of government policy so far has been the subsidy on Happy Seeder, assuming that farmers will adopt the machine if costs are lowered. However, studies attribute low adoption of the Happy Seeder to a number of factors apart from high upfront costs – lack of knowledge among farmers about benefits, lack of awareness about the impacts of burning among farmers, and weak ban enforcement that disincentivizes investment in new machinery [5], [8], [28]. The Happy Seeder subsidy combined with long term public planning that includes investment in farmer awareness campaigns and farmer training can lead to wider adoption of the technology. The government would need to ensure that farmers who wish to rent the machine have access to cooperative societies and that adoption of the Happy Seeder is not constrained due to supply chain bottlenecks.

c) Use of rice residues in power plants:

The Government of India, the State Government of Punjab, and the National Thermal Power Corporation could promote the use of residues in industrial applications (Figure 3, box 2-2).

In 2017, the Government of India recommended that the state-owned National Thermal Power Corporation (NTPC) use residues for cofiring (5-10%) in its coal power plants, stating that farmers would be paid INR 5500/ton of residues [29], [30]. This recommendation is yet to be put into practice by the NTPC. The State Government of Punjab has plans for 150MW of power generation exclusively from rice residues [10] intended to utilize about 1 million tonnes of residues annually. Barriers to industrial use of residues as feedstock include seasonal availability of residues and high investment required in storage and technical capacity [5] and supply chain infrastructure such as pellet-making plants [30]. Industrial use of residues is also currently uneconomical due to prohibitive transport costs and the location of power plants will be crucial in creating a viable market for residues [31], [32].

d) Reforming subsidies for power and fertilizers

The Government of India and the State Government of Punjab could reform subsidies for farming inputs (Figure 3, box 1-2). Studies estimate that groundwater consumption for rice can potentially be reduced by about 33%, without adversely affecting yield [2], [33], [34]. Metering of electricity (used to pump groundwater) is difficult to implement politically since farmers have long had access to unmetered power and constitute a substantial portion of the voting population in Punjab. Policy reform in the form of a Minimum Energy Support (MES) scheme has been suggested where farmers have access to rationed but guaranteed hours of power supply and are allotted a fixed amount for electricity per landholding as deemed necessary for irrigation; farmers may get reimbursed or their water quota carried over if they use less, thus incentivizing conservative use of power [2], [22], [35].

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Farmers use urea in excess of more than a third of quantities recommended by the Punjab Agricultural University. Suggested policy reform includes eliminating the price-control of urea and implementing a Direct Benefit Transfer scheme where farmers buy all fertilizers at market prices and the subsidy is directly transferred to farmers [36], [37].

***e) Expand government procurement to include pulses to in order to incentivize a shift away from growing rice*:**

The Government of India could expand procurement to include pulses (Figure 3, box 2-10. Currently, only rice and wheat are procured at guaranteed prices (known as minimum support prices (MSP)) by the Government of India; this incentivizes farmers in Punjab to primarily grow grow these crops [13] as there is no limit to the quantities of produce farmers can sell to the government [38]. Government procurement of rice and wheat is meant to protect farmers against price fluctuations on the market as well as supply foodgrains for the PDS. However, guaranteed procurement of these crops has led to a loss of crop diversity in the region. The Government of India could include pulses, suitable for Punjab's soil and climactic conditions and a high protein crop, in the procurement program – MSPs for pulses are announced annually but not enforced on a national basis. The challenges in designing this intervention include ensuring farmers have sufficient economic incentive to shift cropping patterns towards pulses and creating a strong enough impetus for PDS consumers to shift consumption from rice towards pulses. Pulses are more expensive to grow than rice or wheat and the subsidized price provided through the PDS, would need to be sufficiently low to encourage consumption.

Promoting a sustainability transition in agriculture requires considering multi-dimensional impacts - environmental elements such as pollutant emissions, groundwater consumption and soil health, as well as socio-economic aspects such as health and income. Current policy focuses on preventing agricultural residue burning, addressing elevated levels of air pollutants in urban regions. However, this air pollution challenges are part of a larger set of connected sustainability challenges associated with institutions, cropping patterns and technology options in Punjab. Effective solutions need to address this entire interacting system.

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Components, Interactions, and Interventions

Human components	Technical components	Environmental components
Farmers in Punjab Low-income households Residents of India	Crops Residues Fertilizer Energy Farm machinery Happy Seeder (HS)	Air Land Groundwater Soil

Institutional components	Knowledge components
Ban on residue burning Subsidies for farming inputs Markets for farming inputs and agricultural residues Government crop procurement program Public distribution system (PDS)	Awareness about residue burning and its impacts Awareness of the use and benefits of post-harvest farm technologies Knowledge of prevalence and location of residue burning

Figure 1. Components in the agriculture and air pollution system in Punjab.

Knowledge

Institutions

	1. Human	2. Technical	3. Environmental
1. Human	(1-1)	(1-2) Farmers grow crops (a); Farmers use excess fertilizers (b); Farmers use Happy Seeder (c)	(1-3) Farmers pump excess groundwater (a);
2. Technical	(2-1) Sale of crops provides income for farmers (a); Crops in the PDS influence protein availability for low-income households (b); Sale of residues provides income for farmers (c)	(2-2) Crops require fertilizers (a); Crop harvesting creates residues (b); Happy Seeder transforms crop residues (c)	(2-3) Crops require groundwater (a); Energy use and fertilizer application emit pollutants to air (b); Residue burning emits pollutants to air (c); Residues affect groundwater requirements (d); Residues affect soil health (e)
3. Environmental	(3-1) Air pollution affects the health of residents of India (a)	(3-2) Soil health determines fertilizer requirements (a) Groundwater requirements affect energy use (b)	(3-3) Ecosystem processes and dynamics

Figure 2. Interaction matrix for the agriculture and air pollution system in Punjab.

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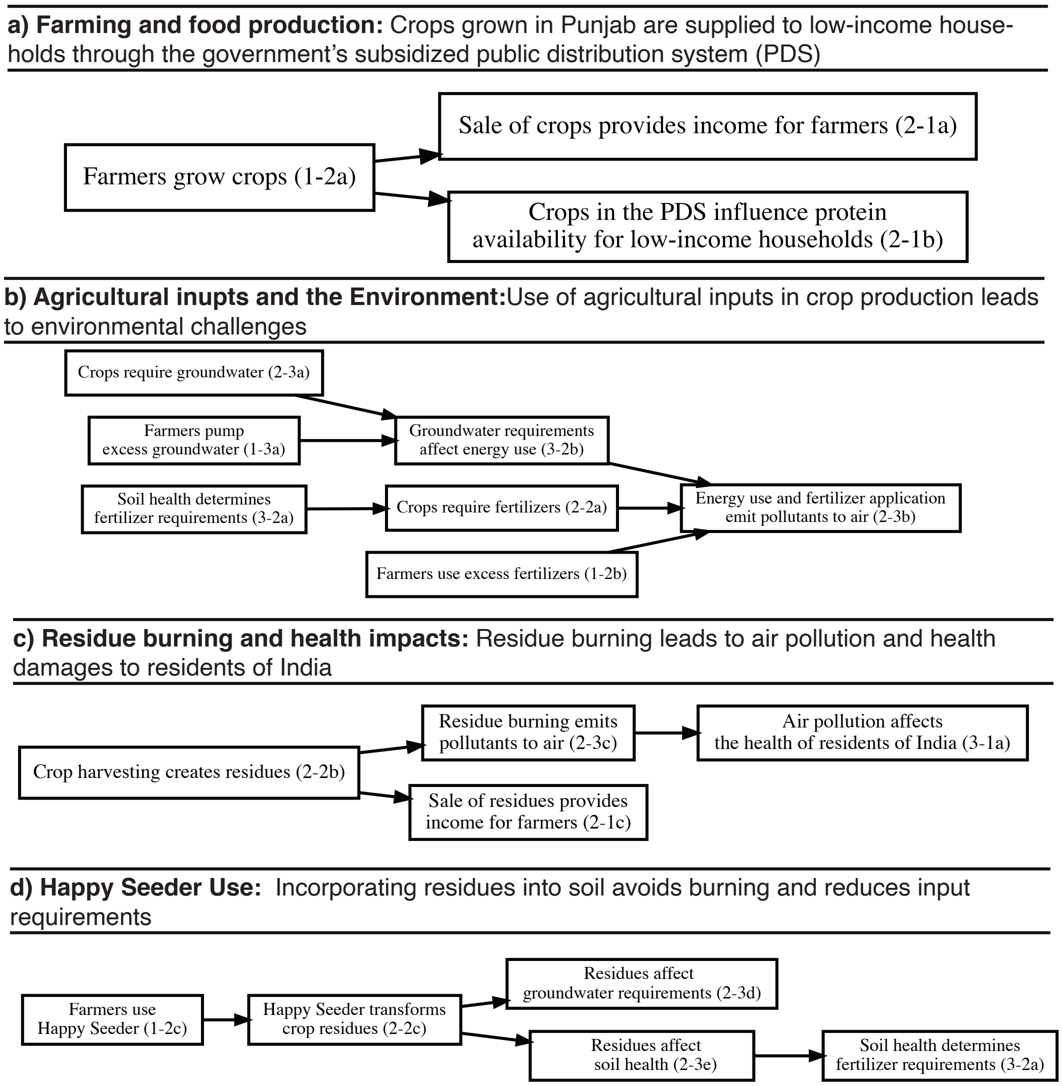

Figure 3. Pathways of interactions in the agriculture and air pollution system in Punjab.

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Knowledge

Institutions

	1. Human	2. Technical	3. Environmental
1. Human	(1-1)	(1-2) Government of India promotes wide-scale adoption of HS; Government of India and State Government of Punjab reform input subsidies	(1-3)
2. Technical	(2-1) Government of India expands procurement to include pulses	(2-2) Government of India, State Government of Punjab, and National Thermal Power Corporation promote use of residues in industry;	(2-3) State government of Punjab effectively implements residue burning ban
3. Environmental	(3-1)	(3-2)	(3-3)
Interveners			
State government of Punjab; Government of India; National Thermal Power Corporation			

Figure 4. Intervention matrix for the agriculture and air pollution system in Punjab.

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