A systems framework for analyzing sustainability impacts of agricultural policies in India

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A systems framework for analyzing sustainability impacts of agricultural policies in India

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Key Points:

1. We apply a systems framework for analyzing policy interventions to the rice-wheat cropping system of Punjab (India).
2. We quantify the sustainability impacts using an inclusive weath-based approach and characterize varying degrees of change in the system.
3. We show that both small and large policy-induced changes can lead to substantial and wide-ranging sustainability benefits.

Abstract

Interventions to mitigate air pollution have impacts on multiple facets of human and environmental well-being. We apply a systems framework for analyzing the overall sustainability impacts of interventions to a case of the rice-wheat cropping system of Punjab (India), where agricultural practices lead to air pollution-related health impacts, over-exploitation of groundwater, over-use of fertilizers and reduced local crop diversity. We use this case to characterize varying degrees of change in interventions and quantify sustainability impacts using an inclusive wealth-based approach. We show that both small and large changes, in this case either improving the existing cropping system or fundamental changes to the cropping system, can lead to substantial and wide-ranging sustainability benefits. We also show that interventions that improve human health show the largest quantitative benefit due to the assumed high marginal value of human life. Accurate localized estimates of marginal values of stocks are needed for estimating overall sustainability impacts.

Plain Language Summary

Air pollution management policies have impacts on multiple aspects of human and environmental well-being. We use a systems-based approach for studying air pollution as a challenge embedded in a broader network of sustainability issues, and analyze the cross-sectoral impacts of policy interventions. We use the rice-wheat cropping system in Punjab, India, as a case study, since agricultural practices in this system are associated with a number of inter-linked sustainability challenges such as air pollution-related health impacts, over-exploitation of groundwater, over-use of fertilizers and reduced local crop diversity. We analyze the sustainability impacts of varying degrees of policy-induced change in this system and show that both small and large changes can lead to wide-ranging sustainability benefits.

1 Introduction

Air pollution is a major sustainability challenge, leading to millions of premature deaths every year worldwide. Recent studies have identified linkages between air pollution and climate change, energy production and food, largely focusing on how agriculture can affect atmospheric particulate matter (specifically $PM_{2.5}$, particulate matter with a diameter less than or equal to 2.5 um in size) (Domingo et al. 2021; Cusworth et al. 2018). As a result of these linkages, efforts to mitigate air pollution do not operate in isolation: they are interventions affecting a complex system, and these interventions have impacts and feedbacks across various sectors that in turn affect multiple facets of human and environmental well-being (N. E. Selin 2021). Addressing the sources of air pollution in ways that promote sustainability is thus a systems challenge.

A specific example of an air pollution-related challenge that is embedded in a broader network of interconnected sustainability challenges is agricultural residue burning in India, which leads to more than 66,000 air pollution-related deaths annually (GBD MAPS Working Group 2018). The state of Punjab in north India, where rice and wheat are most commonly grown, is the largest contributor to cereal crop residue burning in India (Jain et al. 2014), where farmers burn the stubble or residues left on fields after crop harvest. Previous studies have analyzed crop residue management options with a focus on reducing air pollution attributable to residue burning (Shyamsundar et al. 2020; Bhuvaneshwari et al. 2019; H. S. Sidhu et al. 2015). However, air pollution is also linked with over-exploitation of groundwater, over-use of fertilizers and reducing local crop diversity, associated with agricultural practices in Punjab. Most studies on the region have analyzed its sustainability challenges in isolation, e.g. studies have evaluated the effect of electricity subsidies on groundwater use (B. S. Sidhu et al. 2020; Badiani-Magnusson & Jessoe 2018), the effect of the nitrogen fertilizer subsidy (A. Gulati & Banerjee 2015), impacts of crop residue burning on air quality (Jethva et al. 2019; Jain et al. 2014), or incentivizing crop diversification to include pulses (Subramanian 2016).

Policy options that can contribute to overall sustainability in this region have been proposed, but their impacts on multiple, interacting sectors have not been comprehensively analyzed. Specifically, the multi-sectoral impacts of better residue management within the rice-wheat cropping system, relative to a fundamental shift in crops grown in Punjab, remain uncharacterized. Current policy focus has been on addressing air pollution through better residue management – the Government of India has implemented a ban on residue burning and subsidizes post-harvest machinery that enables easy removal or treatment of agricultural residues. However, some (S. N. Sharma et al. 2010; Parmod Kumar et al. 2015) have called for a change in Punjab's cropping pattern itself - air pollution and other sustainability challenges in the region have their roots in the structural aspects of the cropping system. Improvement in long-term sustainability-relevant outcomes can occur through diversification of crops in Punjab, particularly to include pulses (S. N. Sharma et al. 2010). Studies from France show that a fundamental shift from a cereal crop-based system to a diverse cropping system that includes pulses may provide multiple environmental benefits (Meynard et al. 2013; Magrini et al. 2016).

Evaluating systemic impacts of interventions towards sustainability is a methodological challenge. Much previous research does not fully distinguish between degrees of change in interventions and the magnitude of their effect on sustainability-relevant outcomes. Relatedly, multiple pathways may lead to sustainability within a system (Rotmans et al. 2001; Genus & Coles 2008; Feola 2015) and better quantitative metrics are needed to assess potential interventions and their sustainability-relevant outcomes. The degree of change towards sustainability in a system has been generally analyzed qualitatively (Loorbach et al. 2017) and categorized broadly into two types - incremental changes characterized as optimization through improvement of existing systems, and transformative changes characterized by implementation of new technologies, institutions and practices (Elzen & Wieczorek 2005; Genus & Coles 2008; Rotmans et al. 2001; Frantzeskaki & Loorbach 2010; Folke et al. 2010; Park et al. 2012; Smith et al. 2005). A widely cited example of transformative change in the energy sector is the transition from coal to natural gas-based system for cooking and heating in the Netherlands in 1960s, which led to a technological as well as a socio-cultural shift in the institutional framework of energy supply and public awareness about clean fuels (Rotmans et al. 2001; Correlje & Verbong 2004). Incremental interventions made at the margins of existing systems, such as efficiency improvements in coal power plants and internal combustion engines, are not expected to lead to drastic reductions in greenhouse gas emissions in electricity and transport sectors respectively (Elzen & Wieczorek 2005; Loorbach 2010; Markard et al. 2012). However, the features of systemic change that designate it as incremental or transformative are not well-defined (Feola 2015). Geels(2006) and Fischer-Kowalski and Rotmans (2009) highlight the principle of radical incrementalism, where incremental changes in existing systems lead to transformative changes in the long term (e.g. the gradual transformation of waste management from cesspools to sewer systems in Netherlands (Geels 2006)). Smith et al. (2005) argue that when resources for transition are available within the system, incremental systemic changes may lead to sustainability through cumulative improvements in the existing system. Thus, varying degrees of systemic interventions may lead to a range of sustainability-relevant outcomes.

Here, we formalize an analytical approach that can be used to quantify the sustainability impacts of interventions that involve varying degrees of change in a system. We develop and test this approach using the agricultural sector of Punjab (India) as a case study. We analyze interventions proposed in existing policy discussions and measure policy-induced changes in sustainability-relevant outcomes using metrics that align with the inclusive wealth methodology of measuring capital stocks (inclusive wealth has been used as a sustainability metric to represent comprehensive human well-being (Managi & Pushpam Kumar 2018; Polasky et al. 2015; Dasgupta et al. 2021; Arrow et al. 2012)). We use the human-technical-environmental (HTE) framework (H. Selin & N. E. Selin 2020) - a multi-dimensional generalizable systems framework that consists of human, technical, environmental, institutional and knowledge components - to represent sustainability challenges in the agricultural system of Punjab. This systems perspective allows us to: one, identify the leverage points within the system where interventions can be implemented; two, understand the pathways through which interventions change system structure and examine the degree of change; and three, quantitatively estimate the impacts of interventions on sustainability-relevant outcomes. Finally, we use our analysis to draw conclusions about the potential for selected interventions to address air pollution and related sustainability challenges in Punjab.

2 Methods

2.1 The Human-Technical-Environmental (HTE) systems framework

We follow the methodology outlined in the HTE framework (H. Selin & N. E. Selin 2020):

a) First, we itemize the components (human, technical, environmental, institutional and knowledge) which form part of the system (see Table 1 for a list of components and Supp. Data Table SD1 for a list of components' attributes, i.e. characteristics that represent the state of a component at any given time).
b) Second, we use the HTE matrix to specify the interactions between human, technical and environmental components qualitatively (see Table 2 for the interaction matrix and Supp. Data Table SD2 for a detailed interaction matrix)
c) Third, we use the completed HTE matrix to identify pathways of interaction between system components (see Fig. 1) that have impacts on sustainability-relevant outcomes in the system.
d) In the final step, we identify policy interventions (and the interveners) (see Table 3) that change the institutional and knowledge context within which human, technical and environmental components interact, and then examine how each intervention impacts the pathways of interactions outlined.

2.2 Implementing the HTE framework within a quantitative model

We implement the interaction matrix developed using the HTE framework in a quantitative system model that simulates the evolution of attributes through time (see Supp. Info. Text S1 for model details). We evaluated the model for the year 2019 with independent data (previous studies and government reports) for key attributes used in this work (details in Supp. Info. Text S2). We then use our quantitative model to evaluate changes in sustainability-relevant outcomes with time (2019-2029) by estimating change in capital stocks that comprise the foundations of human well-being (Polasky et al. 2015; Arrow et al. 2012; Dasgupta et al. 2021; Fenichel et al. 2016). Finally, we apply our model to examine five potential interventions to the system (see Supp. Info. Text S3 for details on interventions). For each of these interventions, we quantify the following: direct structural changes in the system (representing the ease of implementation and measured as the number of human-technical-environmental interactions structurally modified by an intervention), indirect quantitative changes in the system (representing the range of impacts and measured as the number of human-technical-environmental interactions in which attributes of system components are quantitatively altered downstream of direct changes), and the impacts on sustainability as measured by changes in capital stocks (see Supp. Info. Text S4 for measuring monetary impacts on stocks). We additionally estimate the public expenses associated with each intervention (including subsidies and investment in campaigns and infrastructure) as a partial measure of feasibility of policy implementation.

3 Results

3.1 Summary of results: Applying the HTE framework

3.1.1 System Components

Table 1 presents a list of human, technical, environmental, institutional and knowledge components that are included within the rice-wheat cropping system in Punjab, India.

Human (H)	Technical (T)	Environmental (E)
a) Farmers in Punjab (H1) b) Residents of India (H2) c) Low-income households (H3)	d) Crops grown in Punjab (T1) e) Crop residues (T2) f) Fertilizers (T3) g) Pesticides (T4) h) Irrigation pumps (T5) i) Electricity (T6) j) Diesel (T7) k) Combine harvesters (T8) l) Tractors (T9) m) Balers (T10) n) Happy Seeder (HS) (T11) o) Industrial capacity for residue use (T12) p) Residue storage centers (T13) q) Residue processing facilities (T14) r) Pulse milling facilities (T15)	s) Air (PM2.5 & GHG) (E1) t) Cropped land (E2) u) Groundwater (E3) v) Soil (E4)
Institutional (I)	Knowledge (K)	

a) Ban on residue burning (I1) b) Government subsidy for HS (I2) c) Cooperative societies (to enable HS rental) (I3) d) Market for agricultural residues (I4) e) Government power subsidy (I5) f) Government fertilizer subsidies (I6) g) Government crop procurement program (I7) h) Public distribution system (PDS) (I8)	i) Awareness about residue burning and its health impacts (K1) j) Awareness about Happy Seeder and its benefits and input requirements (K2) k) Knowledge about government procurement and guaranteed prices (K3) l) Knowledge about markets for residues and crops (K4) m) Knowledge at an institutional level about residue burning (K5)

Table 1: List of components in the system *(see Data Table SD1 for a list of components' attributes)*

3.1.2 System Interactions

The human, technical and environmental components identified above interact with each other within the institutional and knowledge landscape. Table 2 presents the interaction matrix where each row represents components that influences components in a column (see Supp. Data Table SD2 for a detailed matrix). Note that alpha-numeric codes used for interactions are linked to the system components – H, T, E represent human, technical and environmental components respectively and numbers represent different components. E.g., H1-T2 represents an interaction between farmers in Punjab (human component 1) and crop residues (technical component 2).

	Human (H)	Technical (T)	Environmental (E)
Human (H)	(H-H)	(H1-T1) Farmers decide on crops to grow; (H1-T2) Farmers burn residues; (H1-T3) Farmers use excess fertilizer; (H1-T5) Farmers install and use irrigation pumps; (H1-T11) Farmers use HS	(H1-E2) Farmers decide on land used for cropping; (H1-E3) Farmers pump excess groundwater
Technical (T)	(T1-H1) Farmers earn income from sale of crops; (T1-H3) Crops in PDS affect protein availability in low-income households; (T2-H1) Farmers earn income from sale of residues; (T3-H1,T4-H1,T6-H1,T7-H1) Agricultural inputs add to farming costs; (T11-H1) HS rental adds to farming cost	(T1-T2) Crop harvesting creates residues; (T1-T3,T1-T4) Crops need fertilizers and pesticides; (T11-T2) HS incorporates residues into soil & (T11-T1) increases crop yield; (T11-T7) HS uses diesel	(T1-E3) Crops require groundwater; (T3-E1, T6-E1, T7-E1) Fertilizers, diesel & electricity release GHGs & PM2.5; (T2-E1) Residue burning releases GHGs & PM2.5; (T11-E3) HS reduces water requirement; (T2-E4) Incorporated residues improve soil health; (T3-E4) Excess urea affects soil health
Environmental (E)	(E1-H2) Air pollution adversely affects the health of residents of India	(E2-T1) Land used for cropping determines production of crops; (E3-T6, E3-T7) Groundwater extraction determines electricity	(E1-E1)Ecosystem processes and dynamics determine air pollution concentrations

		and diesel use; (E4-T3) Soil health affects fertilizer requirement	

Table 2: Interaction matrix between system components (*HS = Happy Seeder; PDS = Public Distribution System)*
Note: Human, technical and environmental component categories are represented by H,T and E respectively, and numbers represent the components. E.g., interaction H1-T1 is an interaction between farmers (human component 1) and crops (technical component 1), where the human component (H1) influences the technical component(T1).

3.1.3 Pathways of interaction between system components

We outline four pathways through which interactions between human-technical-environmental components occur within the current institutional-knowledge context. Section 3.2 elaborates on each interaction pathway and associated interactions (see Fig. 1).We identify pathways by first selecting key interactions that are important for human and environmental well-being and then tracing the path of interactions that lead to the selected interaction or are influenced by it (H. Selin & N. E. Selin 2020). These pathways highlight the following interactions: I) residue burning releases greenhouse gases and air pollutants which cause health damages to residents of India; II) incorporating residues into the soil using a Happy Seeder prevents residue burning; III) excess use of agricultural inputs leads to environmental challenges; and IV) crops grown in Punjab are procured by the government for the Public Distribution System.

3.1.4 Interventions (and interveners) that affect one of more interaction pathways

We identify five interventions in the agricultural sector in Punjab that can be implemented by the Government of India and/or the State Government of Punjab (Table 3) and affect one or more interaction pathways. All interventions are policy options that are either currently partly in effect or discussed widely in policy, development and academic circles (B. S. Sidhu et al. 2020; H. S. Sidhu et al. 2015; Puri 2017; A. Gulati & Banerjee 2015; Ministry of Agriculture 2014; TERI 2006; M. Gulati & Pahuja 2015), and were selected on the basis of interviews conducted with researchers who specialize in different aspects of the agricultural sector of Punjab (see Supp. Info. Text S5). These interventions are: (1) an effective ban on residue burning, (2) use of residues in power plants, (3) promoting wide-scale Happy Seeder use, (4) input subsidy reform (power and fertilizer subsidies) and (5) government procurement of pulses to incentivize crop diversification. In the HTE framework, interventions involve changes in institutional and knowledge components and target one or more of the interaction pathways discussed above. As represented in Fig. 1, interventions lead to direct structural changes (including modifications (red boxes, black text) or additions (red boxes, red text)) in human-technical-environmental interactions, which lead to indirect quantitative changes (blue boxes, black text) in attributes of system components in other interactions. Section 3.3 elaborates on each intervention and associated impacts within this system.

	Human (H)	Technical (T)	Environmental (E)
Human (H)	(H-H)	(H-T) Government of India promotes wide-scale adoption of Happy Seeder ; Government of	(H-E)

		India and State Government of Punjab reform input subsidies	
Technical (T)	(T-H) Government of India expands procurement to include pulses	(T-T) Government of India, State Government of Punjab and National Thermal Power Corporation promote use of residues in industry	(T-E) State Government of Punjab effectively implements ban on residue burning
Environmental (E)	(E-H)	(E-T)	(E-E)
Interveners			
State Government of Punjab, Government of India, National Thermal Power Corporation			

Table 3: Interventions examined in this study

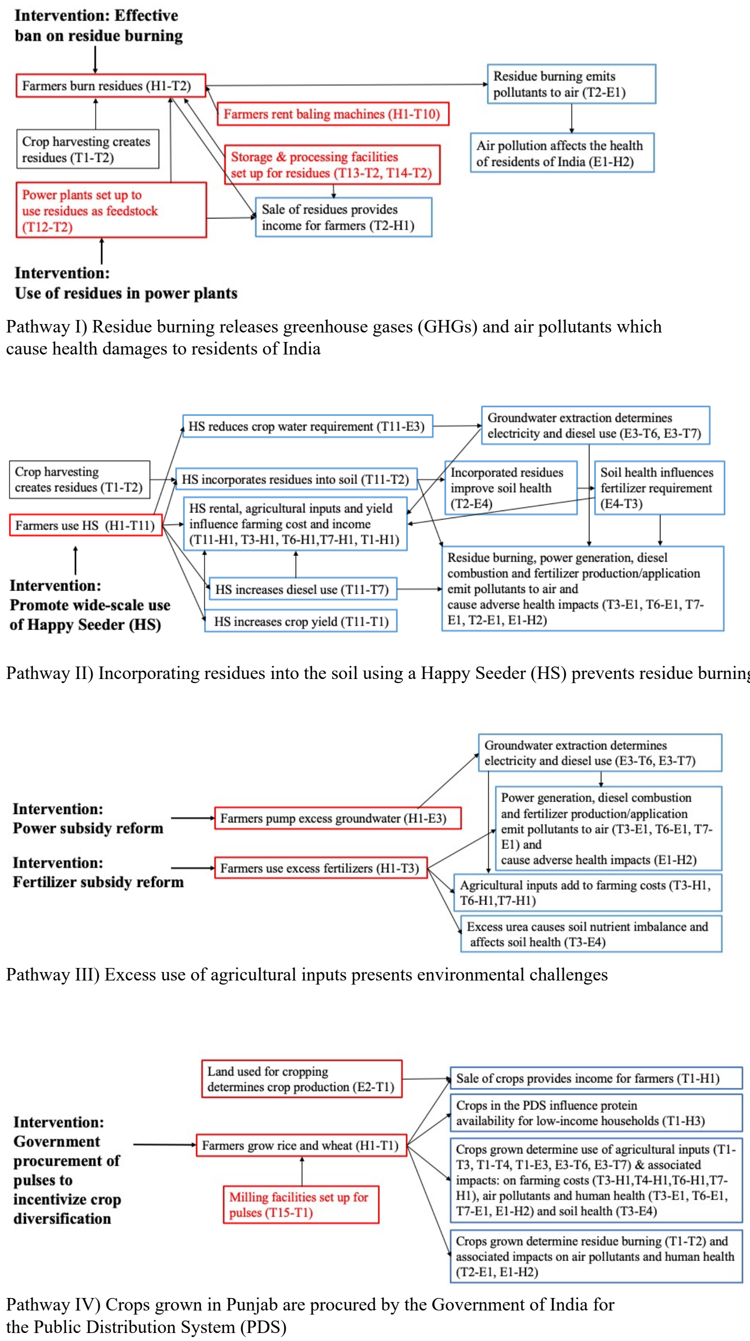

Fig. 1 Pathways of interaction between system components *Note: Each box in the figure represents an interaction; arrows represent the direction of influence; H,T,E represent human, technical and environmental components respectively and numbers represent each component (see Table 1). Direct structural changes are represented by red boxes/black text if they are modifications or red boxes/red text if they are additional human-technical-*

environmental interactions; Indirect quantitative changes are represented by blue boxes and black text (See Supp. Info Text S3 Table S3 for details on direct and indirect changes)

3.2 Interaction pathways within the rice-wheat cropping system and impacts on sustainability

Here we elaborate on four dominant pathways (illustrated in Fig. 1) through which system components interact with each other (all system components are italicized in this section).

In the first pathway (Pathway I), the key interactions identified are the impacts of agricultural *residue* burning, widely practiced in the rice-cropped areas of Punjab, on the emission of greenhouse gases (GHGs) and *air* pollutants like $PM_{2.5}$, which causes elevated levels of pollution in the densely populated Indo-Gangetic Plain including Delhi (Jain et al. 2014; Kulkarni et al. 2020; Jethva et al. 2019) (the key interactions in the associated pathway are represented as H1-T2, T2-E1 and E1-H2).

Residue burning is banned in India, and *farmers* may be fined between 2,500 – 15,000 INR (35-208 USD) depending on size of the landholding (Bhuvaneshwari et al. 2019; Dutta 2018). But farmers are often *unaware of the adverse impacts of residue burning,* and the *Punjab Government* has been reluctant to enforce compliance to the *ban* since farmers form more a third of the state's voting population (Dutta 2018; Slater 2018; Ellis-Petersen 2019; Yadav 2019). Farmers burn 80-90% of *rice* residues since there is a short time period (2-3 weeks) between harvesting rice and planting *wheat*. Labor and machinery costs associated with residue removal are high, and rice residue is not suitable as food for livestock, unlike other crop residue, due to its high silica content (Bhuvaneshwari et al. 2019; Bhatt 2020; Gupta 2011; Jitendra et al. 2017). An ex-situ alternative to burning is selling residues to *industry*. Currently, there is no large-scale industrial use of residues but residues can potentially be used for cofiring in coal power plants, as feedstock in biomass power plants, and in the pulp and paper industry (Ministry of Agriculture 2014; TERI 2018).

In the second pathway (Pathway II), the key interactions identified involve the use of in-situ residue management technologies like the Happy Seeder (interactions H1-T11 and T11-T2) which reduce air pollution due to residue burning (interactions T2-E1 and E1-H2) and provide a range of other economic and environmental benefits.

The *Happy Seeder* is a tractor-mounted device developed to avoid burning of *residues* by drilling seeds into residues left on the field (H. S. Sidhu et al. 2007; H. S. Sidhu et al. 2015). It reduces *water* and *fertilizer* input requirements and potentially leads to higher long term yields (after 3-5 years of use) (H. S. Sidhu et al. 2015; Shyamsundar et al. 2020), and is considered the most economical of alternative residue management options to burning (Shyamsundar et al. 2020; Government of India 2019). The *Government of India subsidizes* 50% of the cost of the machine for individual farmers and 80% of the cost for *cooperatives* where farmers can rent the machines. Although they have been commercially available for a decade, Happy Seeders were only used on about 20% of rice-cropped land in 2018 (Goyal 2019; Anon 2019) due to insufficient *awareness* about the technology, upfront cost being significantly higher than current practices, requirement of a heavy *tractor* and because potential yield-increasing benefits are not experienced immediately (H. S. Sidhu et al. 2015; Shyamsundar et al. 2020; Ailawadi & Bhattacharyya 2006; Gupta 2011; Jitendra et al. 2017; Tallis et al. 2018; Ashok 2017).

In the third pathway (Pathway III), the key interactions are the impacts of excess use of agricultural inputs in Punjab, driven by existing institutional structures, on air pollution and greenhouse gas emissions (arising from fertilizer manufacturing and application, power production and diesel combustion), as well as declining water table and soil health in the region (interactions H1-E3, H1-T3, T3-E1, T6-E1, T7-E1, E1-H2, T3-E4).

Farmers pump excess quantities of groundwater (primarily using electric *pumps* (B. S. Sidhu et al. 2020)) to irrigate rice due to a number of factors –the *Punjab Government* 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/day of electricity incentivizes over-pumping when electricity is available (with unreliable power supply adding to *diesel* costs through generator use as well) (B. S. Sidhu et al. 2020). This has led to much of Punjab's groundwater being overexploited with the water table declining at an annual rate of 0.2-0.6 m (Patle et al. 2016; Sukhwinder Singh 2020). A declining water table leads to rising electricity and diesel consumption to pump groundwater from increasingly greater depths.

While the price of nitrogen-based urea fertilizer (N) is determined by the Government of 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 (A. Gulati & Banerjee 2015). This has led to excessive use of urea - 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 leading to an imbalance in *soil* nutrient ratios (A. Gulati & Banerjee 2015; Jitendra 2020; Chaba 2019; Anand 2010).

In the fourth and final pathway (Pathway IV), the key interactions are the impacts of crops grown in Punjab (interaction H1-T1) on protein availability in the population (interaction T1-H3), as well as the use of agricultural inputs (interactions T1-T3, T1-T4, T1-E3) and post-harvest residue burning (interaction T1-T2), and associated human and environmental impacts.

Crops grown in Punjab are sold to low-income *households* across India at subsidized prices and constitute the majority of these households' caloric requirements (Rampal 2018). Rice and wheat are procured by the *Central Government* (through the Food Corporation of India), supplied to the *Public Distribution System* (PDS) and sold through 'low-price' shops regulated by *state governments*. More than 800 million people access the PDS (Puri 2017; World Bank 2019) and each beneficiary is entitled to receive 5 kg of rice per month according to the National Food Security Act (Press Information Bureau 2013). For those who rely on the PDS, this implies that higher protein alternatives like pulses (e.g. lentils) which are not supplied through the PDS are too expensive and excluded from their diets as reflected in low per capita protein availability estimates (Rampal 2018; M. Sharma et al. 2020). The high yielding varieties (HYV) of *rice and wheat* grown by *farmers in Punjab* (rice during June-October and wheat during October- May) are largely driven by *guaranteed prices* or Minimum Support Prices (MSP), meant to protect farmers against price fluctuations on the market. The Green Revolution (in 1960s and 1970s) targeted high agricultural productivity and promoted HYV varieties, along with expanding agricultural infrastructure such as irrigation facilities and electricity provision (Chand 2008;

Pingali 2012). Between 1960 and 2012, land under rice and wheat cultivation in Punjab increased from 5% to 36% of cropped area and 30% to 45% of cropped area respectively, while cultivation of all other crops (including pulses which constituted 19% of cropped area in 1960) declined (Parmod Kumar et al. 2015). *HYV rice and wheat* need higher *fertilizer* and *water* inputs than traditional varieties of rice and wheat (Manan et al. 2018) as well as other locally suitable *crops* such as pulses (Punjab Agricultural University 2019; Punjab Agricultural University 2020; Subramanian 2016). Additionally, the majority of residues from other crops, such as pulses, are not burnt but used as fodder or fuel (Bhuvaneshwari et al. 2019; Jain et al. 2014) .

We implement the interactions described in the pathways above in our quantitative model. Our model evaluation for the year 2019 (details in Supp. Info. Text S2) shows that model estimates of key attributes of components (residues burnt in Punjab, emission of GHG and $PM_{2.5}$, premature mortality attributable to $PM_{2.5}$ exposure, fertilizer, fuel and groundwater use, farmers' income and public expenses) are in close agreement with estimates from previous studies and reports. Table 4 presents the impact of continuing current practices of rice-wheat cropping in Punjab on sustainability metrics as estimated by our model for the period 2019-2029. For this baseline scenario (No New Policy), we assume that no new policy interventions are implemented during this period, and we estimate that agricultural subsidies (fertilizer and power) cost 860 billion INR (12 billion USD) in public expenses. The impact of the rice-wheat cropping system on sustainability is measured as change in inclusive wealth, which includes changes in human capital, natural capital and carbon damages. Change in human capital includes human health impacts and farmers' net income (used as a proxy for farmers' wealth), while change in natural capital is measured by estimating change in groundwater stock (Aly & Managi 2018; Fenichel et al. 2016). Carbon damages represent the cost of climate-related externalities produced by extraction of natural capital (Arrow et al. 2012). Impact on inclusive wealth is estimated by multiplying the change in capital stock over 2019-2029 by marginal values of capital stocks (details in Supp. Info. Text S4).

Capital stock	Human capital			Natural capital	Carbon damages	
Sustainability metric	Premature mortality due to $PM_{2.5}$ emissions from residue burning and agricultural activities	Premature mortality due to low protein availability from crops grown in Punjab[1]	Farmers' income (excluding rent)	Groundwater extraction for irrigation	GHG emissions from residue burning and energy use[2]	GHG emissions from nitrogen fertilizer (urea) application[3]
Change in capital stock	760,000 lives[4]	-	762000 INR/ha (10600 USD/ha)	372 billion cubic metres	764 Mt CO_2eq	152 Mt CO_2eq
Change in monetary value of capital stock (billion USD)	- (596 – 967)	-	70	-5	- (27 – 75)	- (5.4 - 15)
Impact on inclusive wealth	Net decline of 563 – 992 billion USD					

Table 4: No New Policy: Estimated impacts of rice-wheat cropping in Punjab on sustainability (2019-2029) (range of values represents range of shadow prices of stocks). [1]*Protein constitutes 8.5% of total macronutrients by weight for rice and wheat grown in Punjab and supplied through the PDS. Given the relatively constant cropped area and yield of rice and wheat in Punjab between 2010-2016 [103], we assume that rice and wheat production remains constant in Punjab over 2019-2029.* [2]*Energy use includes electricity and diesel for irrigation and farm machinery, and fertilizer manufacturing.* [3]*Environmental impact of nitrogen fertilizer application is quantified in terms of carbon damages.* [4]*Loss of 690,000 lives attributed to primary* $PM_{2.5}$ *emissions from residue burning*

3.3 Interventions and impacts on sustainability

In this section, for each intervention, we present a brief summary of the intervention followed by outlining the direct and indirect changes in the system induced and the quantitative impacts on sustainability as measured by changes in capital stocks. Details on each intervention are provided in Supp. Info. Text S3, with detailed direct (structural) and indirect (quantitative) changes in

Table S3 and detailed quantitative impacts of interventions on sustainability metrics presented in Supp. Data Tables SD7-SD14.

In the first intervention (*Figure 1-Pathway I-Intervention 1)*, an effective ban on rice residue burning is implemented, with the Government of Punjab paying farmers 1000 INR/ton (14 USD/ton) of rice production (Mathur 2019), along with conducting an awareness campaign for farmers. Existing political constraints to implementing a ban include conflict of interest between local stakeholders, high administrative burden and lack of effective monitoring. (Dutta 2018; Slater 2018; Ellis-Petersen 2019; Yadav 2019). Paying farmers to prevent residue burning may increase public expenses by about 21% (an additional 267 million USD annually) relative to a No New Policy scenario.

This intervention involves two direct changes in system structure (farmers do not burn residues and storage facilities are established for residues), which lead to indirect quantitative changes in three interactions (between residues, air pollutants (GHG and $PM_{2.5}$) and human health). An effective ban on rice residue burning results in an estimated 47,000 lives saved annually (30-49 billion USD) due to lower $PM_{2.5}$ emissions, and reduction in GHG emissions by 46-47% (1.2-3 billion USD annually).

In the second intervention (*Figure 1-Pathway I-Intervention 2)*, rice residues are used as feedstock in coal or biomass power plants. The Government of India-owned National Thermal Power Corporation (NTPC) uses residues for cofiring (10%) in its coal power plants, paying farmers 5500 INR/ton (76 USD/ton) of residues (Special Correspondent 2017; Ghosal 2017). Alternately, the Punjab Government sets up 600MW of biomass power plants to utilize rice residues (TERI 2018). Cofiring with residues (10%) in coal power plants involves high capital costs (an estimated 412 million USD (Jaswinder Singh 2015; Griffin et al. 2014) equivalent to 34% of the government's current annual expenses on power and fertilizer subsidies), while setting up 600 MW of biomass power (80 biomass power plants each of size 7.5MW (Jaswinder Singh 2015)) is estimated to cost 375 million USD. This does not include costs of residue processing and storage - transport to and from storage facilities and storage and processing of residues adds about 42 USD/ton residue, adding to the cost of power production (Kurinji & Sankalp Kumar 2020).

This intervention involves four direct structural changes (farmers do not burn residues; farmers rent baling machines for residue removal; processing and storage facilities are established for residues; residues are used in power plants as feedstock) and indirectly leads to quantitative changes in four interactions (between residues, air pollutants (GHG and PM2.5) and human health; residues and farmers' incomes). If residues are used for cofiring (10% of NTPC's installed coal power capacity or 4 GW (NTPC n.d.)), this would utilize the rice residues previously burnt, preventing about 47000 premature deaths annually (30-49 billion USD). This would also reduce GHG emissions by 10% (0.7 billion USD annually) and increase farmers' income by 24% (1.4 billion USD annually). Utilizing rice residues in 600 MW of biomass plants would prevent 13,000 premature deaths annually (15 billion USD), reduce GHG emissions by 6% (0.26-0.4 billion USD annually) and increase farmers' income by 5% (318 million annually).

In the third intervention (*Figure 1-Pathway II-Intervention 3),* promoting wide-scale Happy Seeder use implies Happy Seeders are used on 90% of rice-cropped land and the machines are easily available to rent at 50% subsidy, along with government investment in farmer training camps (Government of India 2019). This would reduce annual government expenditure by 5% (96 million USD annually) despite additional subsidy costs for the Happy Seeder due to lower subsidies on fertilizer and electricity. Existing market infrastructure and public subsidies for the Happy Seeder and potential long-term financial benefits for the government implies that this intervention will not be politically challenging to implement.

This intervention directly changes the interaction between farmers and Happy Seeders and leads to indirect quantitative changes in components' attributes in 15 interactions, including interactions between Happy Seeders, agricultural inputs and farming costs, and those between agricultural inputs/residues, air pollutants and human health. Wide-scale Happy Seeder use would lead to 47000 fewer premature deaths annually (30-49 billion USD) due to lower $PM_{2.5}$ emissions, 55-56% lower GHG emissions (1.8-5 billion USD annually) and marginal reduction (2%) in groundwater consumption annually. It also leads to 15% reduction in urea use (by incorporating nutrients in rice residues into the soil) but we do not quantify the non-carbon benefit of reducing nitrogen pollution due to lack of available data on the localized impact of nitrogen pollution. Yield increases after 4 years of Happy Seeder use along with lower expenditure on agricultural inputs leads to higher incomes for farmers (384 million USD increase annually).

In the fourth intervention (*Figure 1-Pathway III-Intervention 4),*the Government of India and State Government of Punjab reform fertilizer and power subsidies, respectively, to disincentivize excess use of agricultural inputs. Farmers reduce groundwater use for irrigating rice by 33% (studies show that this would not adversely affect yield (Kaur et al. 2010; Dhillon et al. 2018; B. S. Sidhu et al. 2020)) and in an alternate scenario, farmers reduce urea usage by 29% to levels recommended by the Punjab Agricultural University (Punjab Agricultural University 2019; Punjab Agricultural University 2020). To incentivize lower power or fertilizer use, policy reform can include a Direct Benefit Transfer (DBT) scheme in which farmers have access to either metered power or rationed but guaranteed hours of power supply for irrigation, and the allotted power subsidy is transferred directly to farmers (M. Gulati & Pahuja 2015; Sally & S. Y. Sharma 2018). Similarly, a DBT scheme can be implemented for fertilizers where farmers buy all fertilizers at market prices and the subsidy is directly transferred to farmers, to reduce over-consumption of low-cost urea (Jitendra 2020; Chaba 2019; A. Gulati & Banerjee 2015). Rationed but guaranteed power may increase annual public expenses on subsidies by about 13-15% (165-185 million USD annually), while lower fertilizer usage would reduce expenses by about 11% (130 million USD annually). Input subsidy reform requires overcoming political challenges due to the long-standing existence of input subsidies for farmers, like unmetered power and low-cost urea (B. S. Sidhu et al. 2020; Monari 2002) and multiple stakeholders need to work together to develop a sustainable and equitable subsidy structure.

Power subsidy reform directly changes the interaction between farmers and groundwater, and leads to indirect quantitative changes in five interactions (groundwater and energy inputs; energy inputs, air pollutants (GHG/$PM_{2.5}$) and health; energy inputs and farming costs). Fertilizer subsidy reform directly changes the interactions between farmers and fertilizers, and leads to indirect quantitative changes in five interactions (fertilizers, air pollutants (GHG/$PM_{2.5}$) and human health; fertilizer and soil health; fertilizers and farming costs).

Reducing groundwater usage by 33% for rice leads to 22% lower annual groundwater extraction and would slow the decline in the water table in Punjab. If electricity is currently available for 60% of the required time for irrigation (Mukherji et al. 2009), guaranteed power leads to 16-18% higher farmer income (475 million USD increase annually) through lower diesel usage and marginally lower associated GHG and $PM_{2.5}$ emissions (2-5%). Reducing fertilizer usage by about 29% leads to marginally lower $PM_{2.5}$ emissions (2-3%) and 7% lower GHG emissions.

In the fifth and final intervention *(Figure 1-Pathway IV-Intervention 5)* the Government of India procures pulses (we select pigeon pea for our estimates), along with rice and wheat, at guaranteed Minimum Support Prices (announced annually for 19 foodgrains by the government). This intervention involves a fundamental shift in the dominant technology of the system, i.e. from rice-wheat cropping to a system including pulses. Farmers are generally in favor of shifting cultivation away from rice, largely driven by concerns about depleting groundwater in Punjab, but guaranteed procurement specifically of rice disincentivizes this shift (Bhatt 2020). The price volatility of pulses in the open market, rising imports and low water requirements make this an attractive option for both government and farmers (Puri 2017; Subramanian 2016). Public expenses on input subsidies would reduce by 22% (218 million USD annually) but this does not include the additional subsidy on pulses sold through the PDS, if consumers are to keep their monthly expenses on foodgrains constant (see Methods Section 4 for details).

This intervention involves three direct structural changes (farmers diversify crop production, land use shifts from rice to pulses, and milling facilities are established for pulses) which leads to quantitative changes in 14 interactions indirectly (those between crops and agricultural inputs, crops and residues, and associated human and environmental impacts). A shift of 50% of rice-cultivated land in Punjab to pulses (as incentivized through monetary benefits by the neighboring state government of Haryana (Sukhwinder Singh 2020)) would prevent almost 36,000 premature deaths annually due to lower $PM_{2.5}$ emissions, as well as prevent about 21,000 premature deaths annually by increasing the protein availability through crops grown in Punjab by an additional 1.2% (an estimated benefit of 38-61 billion USD annually in health capital relative to our base case). This shift from rice to pulses would also reduce GHG emissions by 40% (1.2-3 billion USD annually) and groundwater consumption by 21% (397 million USD). Urea consumption reduces by 20% but the monetary non-carbon benefits of lower nitrogen pollution are yet to be estimated. Farmers' incomes reduce by 10% (848 million USD annually) due to lower yield of pulses, in spite of pulses being procured at guaranteed prices.

Table 5 presents the results of our analysis of interventions (in order of increasing inclusive wealth relative to a No New Policy scenario) and highlights the degree of change in system structure and in sustainability metrics. Of the interventions considered, *government procurement of pulses* provides the largest increase in inclusive wealth, followed by *promoting wide-scale use of Happy Seeder*. These two interventions also lead to the widest range of impacts in the system (high number of indirect quantitative changes in system components). On the other hand, *input (fertilizer or power) subsidy reform* led to the smallest increase in inclusive wealth and provide a narrow range of benefits in primarily reducing GHG emissions and groundwater extraction respectively; however, these inclusive wealth estimates do not include the localized non-carbon benefits of reducing fertilizer use and further work is needed in estimating the regional marginal value of groundwater stock.

Degree of change in system structure			Change in human capital			Change in natural capital	Carbon damages		
Direct structural changes in system interactions	**Indirect quantitative changes in system components**	**Interventions**	**Premature deaths: PM2.5 emissions from residue burning/ agricultural activities**	**Premature deaths: Low protein availability from crops grown in Punjab**	**Farmers' income**	**Annual groundwater extraction**	**GHG emissions: residue burning/ direct and indirect energy use**	**GHG emissions: nitrogen fertilizer use**	**Change in Inclusive Wealth***
		Base case: No New Policy (2019-2029)	*760,000*	-	*10600 USD/ha*	*372 billion cubic metres*	*764 Mt CO2e*	*152 Mt CO2e*	*-563 to -992 billion USD*
1	**5**	Power subsidy reform: groundwater use for rice reduced by 33%		-	+7%	-22%	+1%	-	+0.01 to 0.5%
1	**5**	Fertilizer subsidy reform : Optimal use of urea		-	+0.7%	-	-3%	-29%	+1%
4	**4**	Residues for biomass power (600 MW)	-21%	-	+5%	-	-6%	-	+20-21%
4	**4**	Residues for cofiring 10% (4.4GW) of coal power	-69%	-	+20%	-	-10%	-	+61-66%
3	**3**	Effective ban on residue burning	-69%	-	-	-	-49%	-	+65-69%
1	**15**	Happy Seeder use tripled	-69%	-	+5%	-3%	-50%	-15%	+66-70%
3	**14**	Government procures pulses: 50% shift from rice to pulses	-53%	*-217000*	-11%	-21%	-42%	-20%	+80-85%

Table 5: Impacts of interventions on system structure and sustainability metrics (2019-2029)* *Range of inclusive wealth impact represents range of marginal values of stocks. Note: Interventions are organized in order of increasing inclusive wealth relative to No New Policy scenario*

In figure 2, we summarize our evaluation of policy interventions and show direct and indirect changes in the system (x and y-axes respectively) and corresponding impact on inclusive wealth (logarithm of increase in inclusive wealth represented as the size of circles) relative to a base case where no new policy is implemented. An ideal intervention can be expected to lie in the top left corner of the graph represented by a circle of large radius - easy to implement (few direct structural changes), with a wide range of impacts (large number of interactions in which system attributes are changed quantitatively) and substantial improvement in sustainability (large increase in inclusive wealth relative to the base case). Of the interventions considered, *promoting wide-scale Happy Seeder use* meets the said criteria – it involves few direct changes (high ease of implementation) given the existing market infrastructure, leads to the widest range of impacts (indirect changes) providing benefits for farmers' incomes, air quality, climate and soil, and large increase in inclusive wealth. Additionally, the intervention involves overall reduction in public expenses, implying that it is feasible to implement. Fig. 2 also shows an *effective ban on residue burning* and *use of residues in power plants* induce few indirect changes (narrow range of impacts), but at the same time provide a large sustainability benefit. These interventions primarily reduce air pollutants without benefits for soil and groundwater, but significantly reduce premature mortality attributable to $PM_{2.5}$ exposure which leads to a large increase in inclusive wealth.

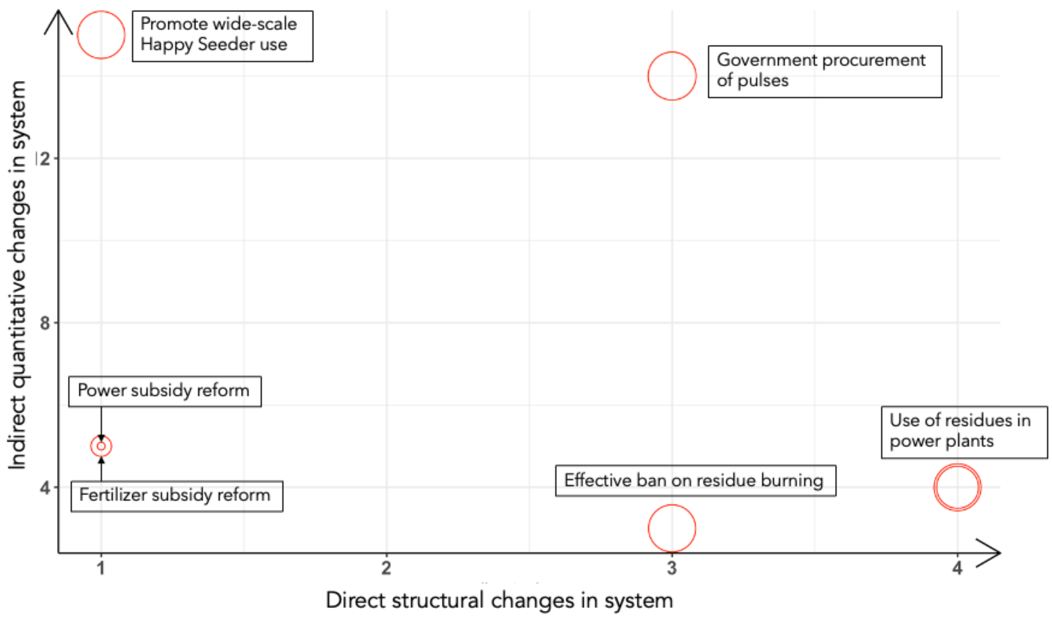

Fig. 2: Mapping the impacts of interventions on system structure and improvement in inclusive wealth relative to No New Policy scenario (2019-2029). *Note: Size of circle represents logarithm of change in inclusive wealth relative to a No New Policy scenario*

4 Conclusions & Discussion

In this paper we use a generalizable systems framework and a quantitative model to assess the sustainability impacts of policy interventions in the agricultural system of Punjab, India. We focused on *five* interventions - *effective ban on residue burning*, *use of residues in power plants, promoting wide-scale Happy Seeder use* and *input subsidy reform* aim to improve the existing cropping system through better agricultural practices; while *government procurement of pulses* aims to fundamentally shift cropping and consumption patterns. We examined three aspects of change associated with these five policy interventions – direct structural changes in system interactions, indirect quantitative changes in attributes of system components and quantitative impacts on sustainability metrics. For the interventions considered, these aspects represent ease of implementation, range of system impacts and magnitude of impact on sustainability respectively.

Of the interventions considered, *promoting wide-scale use of Happy Seeder* and *government procurement of pulses* provide the widest range and highest magnitude of sustainability benefits. Considering changes to health capital alone, tripling Happy Seeder use may reduce premature mortality attributable to air pollution to a greater extent (an estimated 30-48 billion USD saved annually) than a 50% shift in cultivation from rice to pulses (an estimated 24 – 40 billion USD saved annually). However, if the health impact of higher plant protein intake from pulses is taken into account (estimated benefit of 13-22 billion USD annually), subsidizing and incentivizing consumption of pulses in low-income households has a greater benefit for overall human health in India. Shifting cultivation from rice to pulses in Punjab also provides substantial benefits for groundwater levels (in contrast to marginal reduction in groundwater usage with wide-scale use of Happy Seeders) but may reduce farmers' incomes due to lower yield of pulses, even if pulses are procured at guaranteed prices.

We highlight some considerations needed in implementing these two interventions. Happy Seeder use raises concerns about longer term 'lock-in' of existing systems –incorporation of rice residues that currently have no alternate value may intensify the rice-wheat cropping system without addressing concerns about depleting groundwater resources in Punjab. Further modeling work could examine a longer time horizon to analyze the long-term impacts of rice-cropping on groundwater status in the region, accounting for non-linear relationships between groundwater availability and crop yield and tipping points within the system. Government procurement of pulses is associated with uncertainties unexamined in this work. First, the uncertainty in yield of pulses is higher than cereal crops due to sensitivity to rainfall (Subramanian 2016) and farmers need sufficient incentive to shift cropping patterns towards pulses. Second, diversion of particularly expensive grains such as pulses to the open market needs to be minimized. By our estimates, annual public expenses reduce by 389 million USD if leakage in the PDS system is reduced from 20% (Puri 2017) to zero (see Methods Section 3 for details). Third, availability of pulses does not ensure consumption (Chakrabarti et al. 2016) and PDS customers may need an impetus to shift consumption from rice towards pulses. A subsidy scheme that allows transfer of funds directly to beneficiaries could potentially reduce leakage in the system by eliminating illegal beneficiary cards and also allow beneficiaries to exercise choice over purchase of foodgrains (Puri 2017; George & McKay 2019).

We identify through our analysis that interventions that do not result in a fundamental change in the dominant technology of a system can nevertheless have wide-ranging social and environmental benefits. Wide-scale use of Happy Seeder improves residue management within the existing rice-wheat cropping system, and provides substantial benefits for farmer incomes, soil health, climate and air quality without requiring a fundamental shift in crops grown. Thus incremental structural changes in a system can lead to a broad range of impacts and large quantitative improvement in sustainability.

We also show that interventions that lead to a fundamental shift in dominant technologies may not involve a transformation in the configuration of human and institutional system elements. Previous studies have associated crop diversification with a transformative change in the agri-food system (Meynard et al. 2013; Magrini et al. 2016). We highlighted the institutional structures driving cropping patterns in Punjab to show that a shift in cultivation from rice to pulses, while providing the largest increase in inclusive wealth, does not require a radical overhauling of the existing socio-political landscape (relationships between farmers, consumers and markets and institutional frameworks and regulations) within which the system operates.

A transformative change - as defined by a shift in technologies, institutions and practices - in the agricultural system of Punjab may be brought about by agricultural market reform that expands farmers' access to agricultural markets and reduces dependence on government procurement. Increasing the venues available to farmers for selling crops may improve farmer livelihoods and incentivize crop diversification, leading to a shift away from the dominant rice-wheat cropping system of Punjab. Interventions that seek to expand farmers' access to agricultural markets may do so by promoting contract farming or open market transactions. Contract farming may not suitable for small farmers as companies often prefer farmers with large landholdings to reduce transaction costs (Sukhpal Singh 2012). Three agricultural acts in India (introduced in 2020 but repealed in 2021) aimed to liberalize the agricultural sector by removing the existing mandate of state-managed markets being the first point of sale for produce and foodgrains. They were controversial for a number of reasons – fear of reduced income security for farmers and corporate interests overriding farmers', and the potential loss of revenues (collected as fees at state-managed markets) that fund rural development in Punjab (Krishnamurthy & Chatterjee 2020; Hussain 2020; Sukhpal Singh 2020). Further work can examine the impacts of agricultural liberalization on the interactions between farmers, markets and institutions, crop diversification and sustainability.

The results of the assessment of sustainability outcomes show the greatest impact for those interventions that reduce air pollution, partially due to assumptions in the inclusive wealth methodology. In this work, interventions that incentivize residue removal instead of burning, either by directly paying farmers or establishing a market for residues, primarily improve air quality and human health without benefits for other human and environmental metrics, and yet lead to a large quantitative sustainability improvement due to the high shadow price associated with human life (known as the value of a statistical life). The high marginal value of human life implies that health capital often exceeds all other forms of capital (Agarwal & Sawhney 2021). Within this system, eliminating air pollution from agricultural activities would save lives equivalent to 47- 76.5 billion USD annually, with an additional 13-22 billion USD saved by an additional 1.2% protein intake from pulses procured only from Punjab. Compared to the health capital impact, the estimated environmental damage caused by carbon emissions (from direct fuel use in farm machinery and fertilizer manufacturing and application) is 3-8 billion USD annually. We highlight two caveats to representing sustainability impacts using monetary values. One, certain forms of capital may be critical and irreplaceable by other stocks, and representing change in inclusive wealth only in monetary values avoids the question of what forms of capital should constitute inclusive wealth and how it should be distributed (Polasky et al. 2015; Ekins et al. 2003; Neumayer 2010). As a result, interventions that benefit health capital to a large extent may be preferred to others that lead to lower but broader benefits for other forms of capital. Two, estimating changes in inclusive wealth involves knowing the monetary values that reflect the true contribution of capital stocks to well-being and while a number of studies focus on estimating the value of capital stocks in the US (Keeler et al. 2016; Fenichel et al. 2016; Shindell 2015), further work is needed in evaluating marginal values of stocks in Punjab and India. The cost of nitrogen pollution due to excess fertilizer application or the cost of excessive groundwater extraction are localized and there is no spatially generalizable monetary value of damages. An accurate estimation of marginal values of capital stocks can help in better evaluating the impact of interventions on overall sustainability.

Policies that involve localized trade-offs in benefits for improvement in sustainability elsewhere raise concerns about the equity impacts of interventions and their long-term support and effectiveness. We estimate that a 50% shift in cultivated area from rice to pulses in Punjab may save 37 billion USD annually in human health impacts across India, but simultaneously reduce Punjab farmers' income by 850 million USD. Similarly, power subsidy reform involving rationing of subsidized power may provide greater benefits to wealthier farmers by excluding landless farmers from its benefits or adversely affecting small-scale farmers who buy water from other farmers (Sukhpal Singh 2012; B. S. Sidhu et al. 2020). Future studies can use the analytical approach developed in this work to examine the distributional impacts of policy interventions.

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Open Research

All data used in this work are available in Supp. Info. Tables S1-S4 and Data Set S1 file uploaded separately (Data Tables SD1-SD14) with references to their sources. All equations used for model implementation are available in Supp. Info. Text S1-S4.

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Earth's Future

Supporting Information for

A systems framework for analyzing sustainability impacts of agricultural policies in India

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Contents of this file

Additional Supporting Information (Files uploaded separately)

Data Set S1: Data Tables SD1 to SD14

Introduction

This Supporting Information document provides additional details about the HTE framework applied to study sustainability challenges and interventions in the rice-wheat cropping system of Punjab, India. It includes:

- Text S1-S2 (Table S1-S2) on detailed quantitative model set-up and model evaluation results
- Text S3-S4 (Table S3-S4) on methods used to evaluate the impacts of interventions on interactions, specifying direct (structural) and indirect (quantitative) changes as well as sustainability benefits using the inclusive wealth approach.
- Text S5 on expert interviews conducted to inform choice of policy options analyzed in this work

Text S1. Quantitative model set-up

We develop a quantitative model (using R) based on the qualitative representation of system components and interactions outlined, and use it to estimate the impacts of the rice-wheat cropping system and policy interventions on sustainability metrics for the period 2019-2029. We first specify the values of attributes of institutional and knowledge components that form the landscape within which human, technical and environmental components interact in 2019. We also specify the initial values of attributes of human, technical and environmental components in 2019 (see Supp. Data Tables S3-S6).

Component	Attribute	No New Policy scenario	Intervention 1: Effective ban on residue burning	Intervention 2: Use of residues in power plants	Intervention 3: Promote wide-scale use of Happy Seeder	Intervention 4: Input (power or fertilizer) subsidy reform	Intervention 5: Government procurement of pulses
Institutional							
Ban on residue burning	Investment in awareness campaign (INR/landholding)	0	14 INR[1]	0	0	0	0
	Fine for burning (INR/ha)	6175[2]	6175	6175	6175	6175	6175
	Payment to farmers (INR/ha)	0	6500[3]	0	0	0	0
	Compliance level (%)	10%[3]	100%	10%	10%	10%	10%
Market for agricultural residues	Market price for residues (INR/ton)	0	0	5500[4]	0	0	0
	Cofiring share in coal power plants (% of installed GW)	0	0	10%[5]	0	0	0
	Biomass power plants (installed number of plants)	0	0	80 (7.5 MW each)[6]	0	0	0
Market for Happy Seeder	Market supply of HS (number of machines)	15,000[7]	15,000	15,000	45,000	15,000	15,000

Happy Seeder subsidy	Subsidy rate (%)	50%[7]	50%	50%	50%	50%	50%
	Investment in farmer training (INR)	0	0	0	150000000 INR[8]	0	0
Power subsidy	Rationed or unrationed power (categorical)	Unrationed	Unrationed	Unrationed	Unrationed	Rationed	Unrationed
	Availability of power (fraction of a day)	0.6[9]	0.6	0.6	0.6	1	0.6
Fertilizer subsidy	Subsidy reform to enable optimal use of urea (categorical)	False	False	False	False	True	False
Government crop procurement program	Crop types procured (categorical)	Rice, wheat	Rice, wheat	Rice, wheat	Rice, wheat	Rice, wheat	Rice, wheat, pulses (pigeon pea)
	Minimum Support Price for crops procured (INR/kg)	Rice = 19.25, Wheat = 20.25[10]	Rice = 19.25, Wheat = 20.25	Rice = 19.25, Wheat = 20.25	Rice = 19.25, Wheat = 20.25	Rice = 19.25, Wheat = 20.25	Rice = 19.25, Wheat = 20.25, Pigeon pea= 62.4[10]
Public distribution program (PDS)	Foodgrain availability quota per PDS beneficiary (kg/month)	Rice = 5 kg/month[11]	Rice = 5 kg/month	Rice = 5 kg/month	Rice = 5 kg/month	Rice = 5 kg/month	Rice = 3kg/month; Pulses= 1kg/month
	Leakage (% procured crops diverted illegally or wasted)	20%[12]	20%	20%	20%	20%	20% (0% tested as alternate value)
	PDS selling price of foodgrains (INR/kg)	Rice = 3; Wheat = 2[12]	Rice = 3; Wheat = 2	Rice = 3; Wheat = 2	Rice = 3; Wheat = 2	Rice = 3; Wheat = 2	Rice = 3; Wheat = 2; Pulses =10% of Minimum Support Price (MSP) paid to farmers
Knowledge							
Awareness about residue burning	Awareness amongst farmers about health impacts of	Low	High	Low	Low	Low	Low

	residue burning? (categorical)						
Monitoring data for residue burning	Data available to the government to monitor residue burning (categorical)	False	True	False	False	False	False
Awareness about Happy Seeder	Awareness amongst farmers about benefits of using Happy Seeder? (categorical)	Low	Low	Low	High	Low	Low

Table S1: Summary of institutional and knowledge attributes used in the model
[1](Thakur et al. 2016) [2](Bhuvaneshwari et al. 2019) [3](Jain et al. 2014; Bhatt 2020; Jitendra et al. 2017) [4] (Ghosal 2017; Special Correspondent 2017) [5](TERI 2018) [6](J. Singh 2015; TERI 2018) [7](Anon 2019; Goyal 2019) [8](Government of India 2019) [9](Sidhu et al. 2020) [10](Punjab Agricultural University 2020) [11](Puri 2017)

We follow the interaction pathways described in Fig.1 and quantify the human-technical-environmental interactions that occur within the institutional and knowledge landscape as follows.

1. **Pathway I): Residue burning releases greenhouse gases (GHGs) and $PM_{2.5}$ which cause health damages to residents of India**

i) Quantifying interaction T1-T2 Crop harvesting creates residues:

Residues generated by crop type:

$$\sum_{crop} Residues_{generated,crop} = P_{crop} * RPR_{crop} \quad \text{...... Equation 1}$$

Where,
P_{crop} = Production of crops (tons)
RPR_{crop} = Residue to product ratio of each crop
See Supp. Data Table SD3 for above attributes of crops

ii) Quantifying interaction H1-T2 Farmers burn residues:

Residues burnt:

$$Residues_{burnt} = \left(\sum_{crop} Residues_{generated,crop} * R_{frac_{unused,\ crop}} * (1 - Ban)\right) - (P_{rice\ on\ HS\ land} * RPR_{rice}) - Residues_{industry}$$

…… Equation 2

Where
$Residues_{generated,\ crop}$ = see Equation 1
$R\_frac_{unused,\ crop}$ = Fraction of unused residues of each crop type available for burning
$P_{rice\ on\ HS\ land}$ = Production of rice on HS used land = Yield of rice x Land on which HS is used
See Supp. Data Table SD3 for above attributes of crops
$Residues_{industry}$ = Residues used in industry, currently at 0 tons
Ban = Level of ban compliance (%), currently at 10% (see Table 3 for attributes of institutional components)

iii) Quantifying interaction T2-E1 Residue burning emits GHGs to air

GHG emissions from residue burning:

$$GHG_{residue\ burning} = \sum_{species} (emf_{species,residue\ burning} * Residues_{burnt}) * GWP_{species}$$

…… Equation 3

where,
$GWP_{species}$ = Global warming potential of GHGs
$emf_{species,residues,burning}$ = emissions (CO_2, CH_4, N_2O) per kg residues burnt
$Residues_{burnt}$ = total residues burnt (see Equation 2)
(see Supp. Data Table SD5 for emission factors and GWP)

iv) Quantifying interaction T2-E1 Residue burning emits fine particulate matter ($PM_{2.5}$) to air

$$PM2.5_{residue\ burning} = emf_{PM2.5,residue\ burning} * Residues_{burnt}$$ …… Equation 4

where,
$emf_{residue\ burning}$ = primary $PM_{2.5}$ emissions per kg residue burnt (see Supp. Data Table SD5 for attributes of residues)
$Residues_{burnt}$ = total residues burnt (see Equation 2)

v) Quantifying interaction E1-H2 Air pollution affects the health of residents of India

Mean annual per capita $PM_{2.5}$ exposure level z (ug/m^3) due to agricultural residue burning (or other agricultural activities) in Punjab is estimated from the following relation:

$$z = Sensitivity * Emissions/Population \quad \text{...... Equation 5}$$

where,
Sensitivity = sensitivity of exposure to emissions (27,300 ppl-ug/m^3 per kg of emissions (Lan 2021)). This is the change in total exposure across India due to 1 kg of $PM_{2.5}$ emissions in Punjab.
Emissions = $PM_{2.5}$ emissions in Punjab from residue burning (see Equation 4) (or other agricultural activities, assuming $PM_{2.5}$ emissions due to activities other than residue burning such as power production, diesel use and fertilizer production, occur within Punjab)
Population = exposed population > 25 years of age in India (675,000,000 using World Bank population estimate for 2019 and age group proportions from Census 2011)

We estimate $PM_{2.5}$ exposure level z (ug/m^3) due to agricultural residue burning in Punjab was 9.7 ug/m^3 in 2019.

To estimate premature mortality attributable to agricultural residue burning (or other agricultural activities) in Punjab, we use:

$$\Delta M = P \quad * \frac{Y_{baseline}}{RR_{baseline}} * \left(RR_{obs} - RR_{obs\ minus\ z}\right) \quad \text{....... Equation 6}$$

where,
P = population exposed to observed mean annual $PM_{2.5}$ concentration in 2019

$Y_{baseline}$ = baseline mortality rate of 685 per 100,000 people available for the year 2010 from WHO.

$RR_{baseline}$ = Relative risk of non-communicable diseases and lower respiratory infections (NCD + LRI) when $PM_{2.5}$ exposure level changes from theoretical minimum risk z_0 to the exposure level in the baseline year of 2010

RR_{obs} = Relative risk of non-communicable diseases and lower respiratory infections (NCD + LRI), when $PM_{2.5}$ exposure level changes from theoretical minimum risk z_0 to observed exposure level in 2019

$RR_{obs\ minus\ z}$ = Relative risk associated with observed concentration minus the concentration z attributable to the agricultural system in 2019

RR_{obs}, $RR_{obs\ minus\ z}$ and $RR_{baseline}$ are estimated using the Global Exposure Mortality Model (GEMM) equation (Burnett et al. 2018):

$$RR = \exp\left(\theta * \log\left(1 + \frac{x}{\alpha}\right) * \frac{1}{1+\exp\left(-\frac{x-\mu}{\nu}\right)}\right. \quad \text{...... Equation 6a}$$

where

$\theta = 0.143$ for age > 25 , $\alpha = 1.6$, $\mu = 15.5$, $\nu = 36.8$ (parameter estimates for NCD + LRI in GEMM (Burnett et al. 2018)) and x = mean annual $PM_{2.5}$ exposure per capita in ug/m^3 . We use 3 values for x = baseline value in 2010 (per capita exposure level for 2010 in India = 76.7 ug/m^3(Health Effects Institute 2019)) , observed value in 2019 (per capita exposure level for 2019 in India = 83 ug/m^3 (Health Effects Institute 2019)), and observed minus concentration attributable to agricultural activities in Punjab in 2019 (estimated as 73.3 ug/m^3 using Equation 5 and per capita exposure level for 2019 in India (Health Effects Institute 2019)).

2. **Pathway II): Incorporating residues into the soil using a Happy Seeder (HS) prevents residue burning and provides social and environmental benefits**

i) Quantifying interactions H1-T11, T11-T2 (Farmers use HS to incorporate residues into soil); T2-E4, E4-T3 (Incorporated residues improve soil health and reduce fertilizer requirement); T11-E3 HS reduces crop water requirement; T11-T1 HS increases crop (wheat) yield:

See Supp. Data Tables SD3 and SD4 for attributes of wheat sown using HS (cropped land area, water and fertilizer requirements, yield)
See Equations 9 and 10 for calculations of total fertilizer quantity used and total groundwater extracted respectively

ii) Quantifying interaction T11-H1 HS rental increases farming cost

Cost associated with Happy Seeder (HS) rental:

$$HS_{cost\ per\ ha} = \left(HS\ rental * \frac{Area_{HS}}{Total\ wheat\ sown\ area}\right) + Manual\ spreading$$

…… Equation 7

where,
HS rental = subsidy*unsubsidized rental cost of HS per hectare= 0.5*3300 INR/ha (Shyamsundar et al. 2020)
$Area_{HS}$, Total wheat sown area = Supp. Data Table SD3 for attributes of crops
Manual spreading = Cost of manually spreading residues before using Happy Seeder to incorporating them into soil= 550 INR/ha (Shyamsundar et al. 2020)

iii) Quantifying interaction T11-T7 HS (and other farm machinery) increase diesel use:

Diesel used in a HS:

$$Diesel_{HS}(litres) = Diesel_{HS\ per\ ha} * Area_{HS}$$ …… Equation 8a

where,

$Diesel_{HS\ per\ ha}$ = diesel required by a Happy Seeder mounted tractor per hectare (14 litres (Shyamsundar et al. 2020))
$Area_{HS}$ = area over which Happy Seeder is used (hectares) (Supp. Data Table SD3 for attributes of crops)

Diesel required for mechanized residue management:

$$Diesel_{residue\ management}(litres) = Diesel_{conventional} * \sum_{crops}(Area_{crop} - Area_{HS})$$

…… Equation 8b

where
$Diesel_{conventional}$ = Diesel required per hectare for residue management (using stubble shaver, disc, tine , planker, seeder) (40 litres/ha (Shyamsundar et al. 2020))

iv) Quantifying interaction E3-T6, E3-T7 Groundwater extraction determines energy used (electricity and diesel) for irrigation: see Equations 11-13 for calculating energy used for irrigation

v) Quantifying interactions T3-E1, T6-E1, T7-E1 Power generation, diesel combustion and fertilizer production emit pollutants to air: see Equations 14-15 for calculating emissions of GHG and PM2.5 from direct and indirect energy use

vi) Quantifying interactions T2-E1 Residue burning emits pollutants to air: see Equation 4

vii) Quantifying interactions E1-H2 Air pollution causes adverse human health impacts: See Equations 5-6

viii) Quantifying interactions T3-H1, T6-H1, T7-H1 Agricultural inputs affect farming costs: see Equation 16

3. Pathway III): Excess use of agricultural inputs presents environmental challenges

i) Quantifying interaction H1-T3 Farmers use excess fertilizer

Total quantity of fertilizer used by type is given by:

$$Fertilizer_{type} = \sum_{crops} Area_{crop} * \ Fert\ per\ ha_{type,crop} * \ Excess$$

......Equation 9

where

$Area_{crop}$ = Cropped area by crop type (hectares)
$Fert\ per\ ha_{type,\ crop}$ = Fertilizer type (urea, DAP, MOP) required by crop type as recommended by Punjab Agricultural University (tons/hectare)
Excess = fraction in excess of recommended/required usage
See Supp. Data Tables SD3 and SD4 for above attributes of crops

ii) Quantifying interaction H1-E3 Farmers pump excess groundwater

Total groundwater extracted in cubic metres:

$$Water \ = Tubewell_{share} * \sum_{crops} Area_{crop} * \ CWR_{crop} * \ Excess$$
…... Equation 10

where
$Tubewell_{share}$ = Share of irrigation requirement met by groundwater extraction using tubewell (73% and the rest is canal irrigation (Grover et al. 2017))
$Area_{crop}$ = Cropped area by crop type (hectares)
CWR_{crop} = water required by crop type per hectare (metres)
Excess = fraction in excess of recommended/required usage
See Supp. Data Tables SD3 and SD4 for above attributes of crops

Depth of groundwater table in metres:

$$Water\ table\ (t+1) = Water\ table\ (t) + \left[(1 - Recharge) * \frac{Water}{\sum Area_{cropped}}\right]$$
…… Equation 10a

where,
t = 1…10 years
Water table(t) = depth of water table at time t (metres) (25m in 2019 (Grover et al. 2017)
Recharge = annual recharge of water table as a fraction of groundwater withdrawal (60% (Central Ground Water Board 2018))
Water = Annual groundwater extraction (m3) (see Equation 10)
$Area_{cropped}$= Cropped area by crop type (hectares) (see Supp. Data Table SD3 for attributes of crops)

iii) Quantifying interactions E3-T6, E3-T7 Groundwater extraction determines energy used (electricity and diesel) for irrigation:

Annual electricity usage in irrigation pumps:

$$kWh = \ Water * \ Share_{electric} * \ Avail * \ H * \ 99 * \frac{9.8}{(3.6\ x\ 10^6) * \ (Eff_{electric} * \ Eff_{T\&D})}$$
…… Equation 11

where
Water = annual groundwater extraction (cubic metres) (Equation 10)
$Share_{electric}$ = share of groundwater requirement met by electric pumps (85% (Sidhu et al. 2020))
Avail = Power availability expressed as share of required power that is available (0.6) (Sidhu et al. 2020)
H= dynamic head (metres) , see Equation 11a
$Eff_{electric}$ = efficiency of electric irrigation pumps (30% (Dhillon et al. 2018; Patle et al. 2016)
$Eff_{T\&D}$ = efficiency of power transmission and distribution system (75% (Dhillon et al. 2018; Buckley 2015))
997 = density of water (kg/m^3)
9.8 = g (m/s^2)
3.6 x 10^6 = conversion factor between Joule to kWh

Dynamic head (total height water needs to be pumped through) (Dhillon et al. 2018; Patle et al. 2016):

$$H = Water\ table\ (t) + Drawdown + Friction$$ …… Equation 11a

where,
Water table(t) = depth of water table at time t (metres) (25m in 2019 (Grover et al. 2017); see Equation 10a)
Drawdown = lowering of water table near pump (metres) (3m (Dhillon et al. 2018; Patle et al. 2016))
Friction = accounting for frictional losses in pipe (about 20% of water table depth and drawdown (Dhillon et al. 2018; Patle et al. 2016))

Annual diesel use in irrigation pumps in litres:

$$Diesel_{pumps} = Water * (1 - Share_{electric}) * Avail * H * 997 * \frac{9.8}{(E * 10^6) * Eff_{diesel}}$$ ...... Equation 12

where,
Eff_{diesel} = efficiency of diesel irrigation pumps (12%(Dhillon et al. 2018; Patle et al. 2016))
E = energy density of diesel =38 MJ/litre
10^6 = conversion factor between Joule and Megajoule
Other variables as specified above

Diesel requirement in generators to compensate for unavailable electricity that is required for electric pumps:

$$Diesel_{gen}(litres) = (1 - Avail) * \left(\frac{kWh}{Avail}\right) * \frac{3.6 * (Eff_{electric} * Eff_{T\&D})}{E * Eff_{diesel}}$$
…… Equation 13

See Equations 11-12 for explanations of variables.

iv) Quantifying interactions T3-E1, T6-E1, T7-E1 Power generation, diesel combustion and fertilizer production emit pollutants to air

GHG emissions from energy use:

$$GHG_{energy\ use} = \sum_{species}\{(emf_{species,power} * kWh) + (emf_{species,diesel,use} * Diesel_{uses}) + (emf_{species,fertilizer,type} * Fertilizer_{type})\} * GWP_{species}$$
…… Equation 14

where,
$GWP_{species}$ = Global warming potential of GHGs
$emf_{species,\ power}$ = emissions (CO_2, CH_4, N_20) per kWh
$emf_{species,\ diesel,\ use}$ = emissions (CO_2, CH_4, N_20) per litre diesel for used in pumping, generator sets for pumps, residue management and Happy Seeder
$emf_{species,\ fertilizer,\ type}$ = emissions (CO_2, CH_4, N_20) per kg fertilizer manufactured (urea, DAP, MOP)
(see Supp. Data Table SD5 for all emission factors and GWP)
kWh, $Diesel_{uses}$, $Fertilizer_{type}$ and $Residues_{burnt}$ from equations above

$PM_{2.5}$ emissions from energy use:

$$PM\ 2.5_{energy\ use} = (emf_{power} * kWh) + \sum_{use}(emf_{diesel,use} * Diesel_{uses}) + \sum_{type}(emf_{fertilizer,type} * Fertilizer_{type})$$
…… Equation 15

where
emf_{power} = primary $PM_{2.5}$ emissions per kWh
$emf_{diesel,\ use}$ = primary $PM_{2.5}$ emissions per litre diesel for used in pumping, generator sets for pumps, residue management and Happy Seeder
$emf_{fertilizer,\ type}$ = primary $PM_{2.5}$ emissions per kg fertilizer (urea, DAP, MOP)
(see Supp. Data Table SD5 for all emission factors)
kWh, $Diesel_{uses}$, and $Fertilizer_{type}$ from equations above

v) Quantifying interaction E1-H2 Air pollution causes adverse human health impacts: See Equations 5-6

vi) Quantifying interaction T3-H1,T6-H1,T7-H1 Agricultural inputs affect farming costs: see Equation 16

4. **Pathway IV) Crops grown in Punjab are procured by the Government of India for the Public Distribution System (PDS)**

i) Quantifying interactions T1-T3, T1-T4, T1-E3 (crops grown determine use of agricultural inputs) and T1-T2 (crops grown determine residue burning)

See Supp. Data Tables SD3 and SD4 for attributes of crops grown in Punjab (yield, production, proportion of residues generated and burnt, water, fertilizer and pesticide requirements)
See Equations 1 and 2 for calculations of residues burnt, Equations 9 and 10 for fertilizer and groundwater used for irrigation and Equations 11-13 for energy used for irrigation

ii) Quantifying interactions T2-E1, T3-E1, T6-E1, and T7-E1 Residue burning, fertilizer production , power generation and diesel combustion emit pollutants to air

See Equations 3 and 4 for emission of air pollutants from residue burning and Equations 14 and 15 for emission of air pollutants from power generation, diesel combustion and fertilizer production.

iii) Quantifying interaction E1-H2 Air pollution causes adverse human health impacts: See Equations 5-6

iv) Quantifying interaction T1-H1 (Sale of crops provides income to farmers), T3-H1, T4-H1, T6-H1, T7-H1 (agricultural inputs determine farming costs) and T11-H1 (HS rental adds to farming cost)

Farmer income (per hectare of cropped land) is estimated as the difference between income from sale of crops (through public procurement) and expenses on farming inputs and residue management

$$\begin{aligned}
&Income\ per\ ha \\
&= \left(\sum_{crop} Yield_{crop} * MSP_{crop}\right) \\
&- \left(\sum_{fert\ type} Fertilizer_{type} * \frac{Cost_{fert\ type}}{\sum_{crop} Area_{crop}}\right) \\
&- \left(\sum_{crop} Pesticide\ cost_{crop,per\ ha} * \frac{Area_{crop}}{\sum_{crop} Area_{crop}}\right) \\
&- \sum_{uses} Diesel_{uses} * \frac{Cost_{diesel}}{\sum_{crop} Area_{crop}} - Other_{inputs} \\
&- HS_{rental\ per\ ha} - Residue\ management
\end{aligned}$$

…… Equation 16

where,
$Yield_{crop}$ = yield per hectare
$Area_{crop}$ = Area cropped by crop type
$Pesticide\ cost_{crop}$ = Pesticide expenditure by crop type
See Supp. Data Tables SD3-SD4 for above attributes of crops
$Fertilizer_{type}$ = total fertilizer use by fertilizer type (urea, DAP, MOP) (see Equation 9)
$Diesel_{uses}$ = Diesel used in pumping, generator sets for pumps, residue removal and Happy Seeder (litres) (Equation 12-13)
$HS_{rental\ per\ ha}$ =see Equation 7

MSP_{crop} = minimum support price (MSP) for crops procured by the government
$Cost_{fert\ type}$ = Subsidized cost of fertilizer by fertilizer type
See Table S1 for above attributes of institutional components

$Cost_{diesel}$ = Cost of diesel (55 INR/litre (Shyamsundar et al. 2020))
$Other_{inputs}$ = Costs of harvesting operations (13,000 INR/ha) and seeds (3000 INR/ha) (Government of India n.d.)
Residue management = Rental, labour and diesel costs associated with conventional residue management before burning residues (stubble shaver, disc, tine, plank, seeder – 6550 INR/ha (Shyamsundar et al. 2020))

v) Quantifying interaction T1-H3 Crops in the PDS influence protein availability in low-income households:

Protein available through crops grown in Punjab and supplied through Public Distribution System,

$$P = \frac{(\sum_{crop} Protein_{crop} * P_{crop}) * (1 - Leakage)}{(\sum_{crop} P_{crop}) * (1 - Leakage)} \qquad \text{…… Equation 17}$$

where,
$Protein_{crop}$ = protein content (grams per ton) (Supp. Data Table SD3 for attributes of crops)
Leakage = diversion of grains supplied through the PDS illegally or wastage (20% (Puri 2017))

Using Equation 17, we estimate that protein constitutes 8.5% of the macro-nutrient content of Punjab's foodgrains supplied through PDS.

In addition to quantifying the interactions in the system, we quantify the public expenses associated with the rice-wheat cropping system in Punjab. This includes expenses on agricultural subsidies (fertilizer, electricity, machinery) and the consumer subsidies on foodgrains through the Public Distribution System.

Public expenses on crop production and residue management are calculated as the sum of the agricultural subsidies provided for Happy Seeders, fertilizers and power in addition to expenses on interventions:

$$Public\ expenses_{subsidies} = (HS_{count} * HS_{subsidy\ rate}) + (\sum_{type} Fertilizer_{type} * Fert\ subsidy_{type}) + (kWh * Cost_{per\ kWh}) + Intervention$$

…… Equation 18a

where
HS_{count} = Happy Seeders on the market
$HS_{subsidy\ rate}$ = subsidy on each Happy Seeder (subsidy calculated for year = 1)
$Fert\ subsidy_{type}$ = subsidy on urea, DAP, MOP
(See Table S1 for above attributes of institutional components)
$Cost_{per\ kWh}$= cost of power production in Punjab (4.2 INR/kWh (Commission 2020; Grover et al. 2020))
$Fertilizer_{type}$ = see Equation 9
kWh = see Equation 11
Intervention = additional public expenses on interventions 1-5 (Equations 19 – 24) outlined below (0 INR for the current institutional and knowledge landscape)

Annual consumer subsidy on foodgrains sold through the Public Distribution System and guaranteed to low-income households is estimated as:

$$Public\ expenses_{per\ cap\ PDS} = \sum_{crop} Consumption_{\ crop} * (MSP_{crop} - (PDS\ price_{crop} * (1 - leakage)))$$

…… Equation 18b

where,
$Consumption_{crop}$ = annual per capita consumption of foodgrains through the PDS
MSP_{crop} and PDS $price_{crop}$ = procurement and PDS selling prices of foodgrains respectively
Leakage = diversion of foodgrains procured by the government intended for PDS
(See Table S1 for above attributes of institutional components)

Text S2: Quantitative model evaluation

We use data available from other studies and government reports for previous years to evaluate our estimates of system components' key attributes (summarized in Table S2).

We evaluate our quantitative model estimates for the year 2019 since the model dynamics for 2019-2029 are based on attributes in the base year of 2019.

a) Residues burnt: Using Equations 1 and 2, we estimate 14.9 million tonnes of rice residue was burnt in 2019. Estimates for rice residues burnt in 2018 range from 13 million tonnes (Davis et al. 2018) to 17 million tonnes (TERI 2018). Our estimate of total residues burnt in Punjab in 2019 is 21.6 millon tonnes compared to official estimates of 19.7 million tonnes in 2010 (Ministry of Agriculture 2014).

b) Emission of GHGs: We estimate (using Equation 3) that burning 21.6 million tonnes of residues in Punjab in 2019 emitted 29.6 million tonnes of CO2. Jain et al. (2014) estimate that burning 98.4 Mt of residue across India in 2009 emitted 141.15 Mt of CO2 (equivalent to emissions of 31 Mt of CO2 on burning 21.6 Mt of residues).
We estimate (using Equation 14) that the whole rice-wheat cropping system in Punjab was responsible for 76 Mt of GHGs (CO2e) but could not find equivalent estimates from other studies for validation.

c) Emissions of PM2.5: We estimate (using Equation 4) about 177.5 Gg of primary PM2.5 was released in 2019 due to residue burning in Punjab which is in close agreement with the estimate of 137 Gg PM2.5 released in 2018 (T. Singh et al. 2020), given the uncertainty range of emission factor of PM2.5 from residue burning (+/- 34%) (Pandey et al. 2014).

d) Premature mortality due to PM2.5 exposure attributable to agricultural residue burning in Punjab: We estimate (using Equation 5 and 6) that PM2.5 emissions from residue burning in Punjab was responsible for 68,000 premature deaths in 2019. This is comparable to the Global Burden of Diseases estimate of 66,000 premature deaths in 2015 from all-India residue burning and within the 95% confidence interval of 65,000 – 78,000 premature deaths in 2015 (GBD MAPS Working Group 2018) .

e) Total nitrogen fertilizer used : Our estimate (using Equation 9) of 2.2 million tonnes of annual urea usage in the rice-wheat cropped land in Punjab, is lower than official estimates of 3.0 million tonnes used in Punjab in 2015 (Grover et al. 2018). This may be due to a few reasons: we consider lower fertilizer application on wheat-cropped land sown with Happy Seeder (Government of India 2019), but this may not be the case in practice; the estimates of per hectare application of fertilizers used in our analysis may be conservative; and we only consider rice-wheat cropped land and not all crops grown in Punjab.

f) Annual groundwater extracted and impact on water table: Our estimate of 37 billion cubic metres of groundwater extracted in 2019 (using Equation 10) is 5% higher than annual groundwater extraction of 35 billion cubic metres for 2012-2016 by the Central Ground Water Board (Central Ground Water Board 2018). We estimate an average annual water table decline of 0.22m (using Equation S10a), while estimates from other studies are 0.2m - 0.6m annually (Patle et al. 2016; S. Singh 2020), depending on the ‘block’ studied in Punjab (blocks are local administrative units within the state).

g) Electricity used for irrigation: Our estimate (using Equation 11) of 11.3 TWh electricity used in 2019 for irrigation of rice-wheat system in Punjab is 2% less than estimates for 2015 and 2016 from other studies (Dhillon et al. 2018; India 2016) and 6% higher than estimates for 2014 (Grover et al. 2020).

h) Diesel used for irrigation and other agricultural activities: We estimate (using Equations 12 and 13) about 327 litres of diesel is used annually per hectare of rice-wheat cropped land in Punjab in 2019. This is higher than estimates of 300 litres of diesel used per hectare (156 litres/ha for rice and 144 litres/ha for wheat) for 2012 by Punjab Agricultural University (Grover et al. 2015), and this may be because we account for diesel use in Happy Seeders in 2019.

i) Farmers' income: By our estimates (using Equation 16), farmers earn about 75,000 INR/ha annually (not accounting for fixed costs of cultivation such as rent for land). This is in agreement with other estimates of 80,000-82,000 INR/ha for rice and 60-65000/ha for wheat (Grover et al. 2015) and 60,000-70,000 INR/ha using conventional residue management or Happy Seeder use (Shyamsundar et al. 2020). Including fixed costs related to rent is expected to drive down income by about 40000 INR/ha (Shyamsundar et al. 2020; Government of India n.d.), with net income equal to about 35,000 INR/ha.

j) Public expenses on crop production and residue management in Punjab: By our estimates (using Equation 18a), power subsidy to farmers cost the government about 44 billion INR in 2019 (compared to other estimates of 61-71 billion INR (Bajwa 2019; Rambani 2020) and 45 billion INR in 2015 (Grover et al. 2020)) and fertilizer subsidy to farmers costs about 41 billion INR (compared to estimates of 35-46 billion INR for the period 2010-2015 (Gulati & Banerjee 2015)) .
Public expenses on the Public Distribution System: We estimate (using Equation 18b) that the government spends about 1050 INR per beneficiary annually, only accounting for subsidies on rice, while other estimates are about 1400 INR per capita annually for the Public Distribution program (World Bank 2019).

Attribute evaluated	**Our model estimate for 2019**	**Estimate from other studies and reports**
Rice residues burnt in Punjab	14.9 million tonnes	13 million tonnes (Davis et al. 2018) to 17 million tonnes (TERI 2018) in 2018
Total residues burnt in Punjab	21.6 million tonnes	19.7 million tonnes in 2010 (Ministry of Agriculture 2014)
Emission of CO_2 due to residue burning in Punjab	29.6 million tonnes of CO_2 emitted due to burning 21.6 million tonnes of residues	Burning 98.4 Mt of residue across India in 2009 emitted 141.15 Mt of CO2 (equivalent to emissions of

		31 Mt of CO_2 on burning 21.6 Mt of residues) (Jain et al. 2014)
Emission of primary PM2.5 due to residue burning in Punjab	177.5 Gg of primary PM2.5	137 Gg PM2.5 released in 2018 (T. Singh et al. 2020) (uncertainty range of emission factor of PM2.5 from residue burning is +/-34% (Pandey et al. 2014))
Premature mortality due to PM2.5 exposure attributable to agricultural residue burning in Punjab	68,000 premature deaths	66,000 premature deaths in 2015 from all-India residue burning (95% confidence interval of 65,000 – 78,000) (GBD MAPS, 2018)
Total nitrogen fertilizer (urea) used in Punjab	2.2 million tonnes on rice-wheat cropped land in Punjab	3.0 million tonnes used in Punjab in 2015 (Grover et al. 2018).
Annual groundwater extracted and impact on water table	37 billion cubic metres of groundwater; average annual water table decline of 0.22m	35 billion cubic metres annually for 2012-2016(Central Ground Water Board 2018); average annual water table decline of 0.2m - 0.6m annually (Patle et al. 2016; S. Singh 2020)
Electricity used for irrigation in Punjab	11.3 TWh	11 TWh for 2015 and 2016 from other studies (Dhillon et al. 2018; India 2016) and 10.6 TWh for 2014 (Grover et al. 2020).
Diesel used for irrigation and other agricultural activities	About 327 litres of diesel used per hectare of rice-wheat cropped land in Punjab in 2019.	300 litres of diesel used per hectare (156 litres/ha for rice and 144 litres/ha for wheat) for 2012 (Grover et al. 2015)
Farmers' income	About 75,000 INR/ha annually (not accounting for fixed costs such as rent).	80,000-82,000 INR/ha for rice and 60-65000/ha for wheat (Grover et al. 2015); 60,000-70,000 INR/ha for rice-wheat cropping using conventional residue

		management or Happy Seeder use (Shyamsundar et al. 2020).
Public expenses on crop production and residue management in Punjab	Power and fertilizer subsidies for farmers cost the government about 44 billion INR and 41 billion INR respectively in 2019.	Power subsidy: 61-71 billion INR in 2015(Bajwa 2019; Rambani 2020) and 45 billion INR in 2015 (Grover et al. 2020) Fertilizer subsidy: 35-46 billion INR annually for the period 2010-2015 (Gulati & Banerjee 2015)
Public expenses on the Public Distribution System	1050 INR per beneficiary annually, only accounting for subsidies on rice	About 1400 INR per beneficiary annually for the Public Distribution program (World Bank 2019).

Table S2: Evaluation of quantitative model estimates for key attributes for the year 2019

Text S3: Evaluation of impacts of interventions

We use our quantitative model to examine the impact of five interventions on sustainability metrics. (see Table S3 for attributes of institutional and knowledge components for interventions). For each intervention: we characterize direct structural changes and indirect quantitative changes in the system (see Table S3); and we calculate Equations 1 – Equation 18 for a period of 10 years (2019-2029) and estimate quantitative impacts on capital stocks (see Text S4 for details on estimating monetary impacts on capital stocks and Supp. Data Tables SD7-SD14 for detailed estimates of quantitative impacts on sustainability).

a) Intervention 1: Effective ban on residue burning (Interaction Pathway I)

Complete ban compliance requires awareness amongst farmers regarding the impacts of residue burning and alternate residue management options, and monetary compensation to farmers for residue removal (Dutta 2018; Slater 2018; Ellis-Petersen 2019; Yadav 2019).

We estimate the annual public cost of ensuring 100% ban compliance:

$$Ban_{public\ cost} = \left(Payment * Area_{crop}\right) + (Landholdings * Campaign)$$

…… Equation 19

where,
Payment = annual payment (INR/ha) to farmers to not burn residues at the end of summer cropping season
Campaign = expenses incurred for conducting a door-to-door awareness campaign in Punjab, only included in the year(s) of conducting awareness campaign
(see Table 3 for attributes of institutional and knowledge components)
$Area_{crop}$ = summer cropped land area (hectares) (see Supp. Data Table S3 for attributes of crops)
Landholdings = total landholdings in Punjab (1,100,000 in 2019 from Ministry of Agriculture, Government of India)

We estimate system impacts due to complete compliance to ban on residue burning (0% residues burnt) using Equations 1-5 (where Ban=1 and $Residues_{burnt}$=0 in Equation 2) and account for direct payment to farmers in estimating farmer income using Equation 16.

b) Intervention 2: Use of rice residues in the power sector (cofiring in coal power plants and in biomass power plants) (Interaction Pathway I)

Residues are used for cofiring in coal power plants if the Government of India mandates a cofiring share (5-10%) for agricultural residues to be used in state-owned (National Thermal Power Corporation) coal power plants (TERI 2018) and farmers are paid 5500 INR per ton of residues (Ghosal 2017; Special Correspondent 2017).

Residues used in cofiring:

$$Residues_{cofiring} = Share_{cofiring} * \ Installed\ Capacity_{coal} * \ Hours * \frac{3600}{Eff_{coal} * LHV}$$

…… Equation 20

Where, $Share_{cofiring}$ = cofiring share in coal power plants (% of installed coal power capacity; see Table 3)
$Installed\ Capacity_{coal}$ = installed coal power capacity (44GW all-India from NTPC)
Hours = annual operating hours of coal power plants (6500 hours) (J. Singh 2015)
3600 = conversion factor from MWh to MJ
Eff_{coal} = coal power plant thermal efficiency (33 %(CEA 2013))
LHV = Lower heating value of agricultural residues (15540 MJ/ton (J. Singh 2015))

Capital cost of residues utilization in coal power plant for cofiring is estimated using:

$$Cofiring_{cap\ cost} = (Cap\ cost_{cofiring} * Share_{cofiring} * Installed\ capacity_{coal})$$

…… Equation 21

where

Cap cost$_{cofiring}$ = Cost of retrofitting a coal power plant for cofiring (6750000 INR/MW (J. Singh 2015; Griffin et al. 2014))
See above for other variables

Alternately, residues are used to generate power in biomass power plants if there is sufficient installed capacity for utilization of residues (planned 600 MW of biomass power in Punjab (TERI 2018)) and farmers are paid 5500 INR per ton of residues (Ghosal 2017; Special Correspondent 2017).

Residues used in biomass power generation:

$$Residues_{bio\ power} = Installed\ Capacity\ _{biomass} *\ Hours * \frac{3600}{Eff_{biomass} * LHV}$$

…... Equation 22

Installed capacity$_{biomass}$ = biomass power capacity (=number of plants x average size of power plant; see Table 3)
Hours = annual operating hours of biomass power plants (6500 hours (J. Singh 2015))
3600 = conversion factor from MWh to MJ
Eff$_{biomass}$ = biomass power plant thermal efficiency (20 % (J. Singh 2015))
LHV = Lower heating value of agricultural residues (15540 MJ/ton (J. Singh 2015))

Capital cost of biomass power plant that utilizes residues:

$$Biomass_{cap\ cost} = \left(Cap\ cost_{biomass} * Size_{biomass\ power} * N\right)$$ …... Equation 23

where
Cap cost = capital cost of biomass power plant (45000000 INR/MW (J. Singh 2015; J. Singh 2016))
Size$_{biomass\ power}$ = Size (in MW) of average biomass power plant
N = number of biomass power plants set up (see Table 3)

We estimate the impacts of residue use in industry on residue burning (and associated effects) using Equations 1-5 (where $\text{Residues}_{\text{industry}}$= $\text{Residues}_{\text{cofiring}}$ or $\text{Residues}_{\text{bio power}}$ in Equation 2).

We modify Equation 8b ($\text{Diesel}_{\text{residue management}}$) to include additional diesel use in balers for residue removal in $\text{Diesel}_{\text{residue management}}$ as follows:

$$Diesel_{baling,total}(litres) = Diesel_{baling} * \sum_{crops} Area_{crop} * \left(\frac{Residues_{industry,crop}}{Residues_{generated,crop}}\right)$$

…… Equation 8b (addition)

where
$\text{Diesel}_{\text{baling}}$= Diesel required per hectare for baling (6 litres/ha (Verma et al. 2019))
$Residues_{generated,crop}$ = Residues generated minus residues on Happy Seeder used land (these residues are not removed but incorporated into the soil) (see Equation 1)

$Residues_{industry,crop}$ = Residues used in industry (see Equation 20 and Equation 22)

We modify Equations 14 and 15 to include GHG and PM2.5 emissions respectively from residue use in industry as follows:

$$GHG_{residue,industry} = \sum_{species} \{(emf_{residues,power} * Residues_{cofiring}) + (emf_{residues,power} * Residues_{biomass\ power})\} * GWP_{species}$$
…… Equation 14 (addition)

where,
$GWP_{species}$ = Global warming potential of GHGs
$emf_{species,\ residues,\ power}$ = emissions (CO_2, CH_4, N_2O) per kg residues used in power plants *(see Supp. Data Table SD5 for all emission factors and GWP)*
$Residues_{cofiring}$ *and* $Residues_{biomass\ power}$ = Residues used in industry for cofiring in coal power plants and in biomass power plants respectively (see Equations 20 and 22)

$$PM2.5_{residues,industry} = (emf_{residues,power} * Residues_{cofiring}) + (emf_{residues,power} * Residues_{biomass\ power})$$
…… Equation 15 (addition)

where,
$emf_{residues,\ power}$ = primary $PM_{2.5}$ emissions per kg residues used in power plants *(see Supp. Data Table SD5 for all emission factors)*
$Residues_{cofiring}$ *and* $Residues_{biomass\ power}$ = Residues used in industry for cofiring in coal power plants and in biomass power plants respectively (see Equations 20 and 22)

We modify Equation S16 to include additional income earned through sale of residues and baling costs in calculating net farmer income as follows:

$$Additional\ net\ income\ per\ ha = (Residues_{ind,per\ ha} * Price_{residue}) - Baling$$
…… Equation 16 (addition)

where,
$Residues_{ind,\ per\ ha}$ = residues used in industry per hectare of cropped land (see Equations 20 and 22)
$Price_{residue}$ = Market price of residues
Baling = Costs of renting baling machines (including diesel and labour) per hectare for residues used in industry = $Baler_{rental}$*$Residues_{industry}$/$Residues_{generated}$ where, $Baler_{rental}$= 3700 INR/ha (Jaidka et al. 2020; Shyamsundar et al. 2020; Kurinji & S. Kumar 2020). See Equation 1 for $Residues_{generated}$, and Equations 20 and 22 for $Residues_{industry}$

c) Intervention 3: Widespread Happy Seeder (HS) use (Interaction Pathway II)

As of 2019, about 15,000 Happy Seeders were sold either to individual farmers or to farmer cooperatives. We assume that farmers have access to 45000 Happy Seeders in this intervention, through farmers' cooperative societies for machinery rentals, to cover about 80% of rice-cropped land in Punjab (each machine covers 61 hectares (Shyamsundar et al. 2020)). Farmers need to be aware of the benefits of using a Happy Seeder, the associated subsidy, as well as have adequate knowledge on changes in farming inputs when using the machine (lower water requirement as the incorporated residues add moisture to the soil and lower fertilizer requirements (Tallis et al. 2018; Gupta 2011; TERI 2018)).

Public cost of incentivizing widespread use of Happy Seeder by farmers:

$$HS_{public\ cost} = (Subsidy * Market\ price\ of\ HS) + Farmer\ training$$

…… Equation 24

where
Subsidy = Government subsidy (% of total market price) provided to farmers' cooperative societies
Farmer training = Government of India budget for farmer training camps
(see Table 3 for attributes of institutional and knowledge components)

Wheat-cropped area on which Happy Seeder is used,

$$Area_{HS} = N\ x\ Land$$

..…. Equation 25

N = No. of Happy Seeder machines in the market (45,000 in this scenario)
Land = Land covered by each machine in the 25-day period between cropping seasons (61 hectares (Shyamsundar et al. 2020))

We estimate the impact of widespread Happy Seeder use on residue burning and associated effects on air pollutants and human health using Equations 1-6 (where in Equation 2 land on which Happy Seeder is used = $Area_{HS}$) and impacts of HS use on agricultural inputs and associated effects using Equations 7-16.

d) Intervention 4: Reform of subsidy schemes for power and fertilizers (Interaction Pathway III)

We use Equations 9-13 to estimate fertilizer use (optimal levels as prescribed by Punjab Agricultural University) and irrigation energy use (33% less groundwater use for rice relative to current levels) in this intervention, Equations 14-16 to estimate associated impacts on emission of air pollutants and income, and Equation 5-6 to estimate human health impacts. We estimate public expenses on fertilizer and power subsidies using Equation 18a and our revised estimates of fertilizer and power consumption.

e) **Intervention 5: Government procurement of pulses from Punjab at Minimum Support Prices (MSPs) (Interaction Pathway IV)**

Farmers' shift cultivation from rice to pulses if they are procured at guaranteed Minimum Support Price (MSP) by Government of India (announced MSP for pigeon pea, a locally grown pulse, for 2019 = 62.4 INR/kg (Punjab Agricultural University 2020)). We test a 50% shift from rice to pulses in this intervention scenario (S. Singh 2020).

We use Equations 1-17 to estimate the impacts of shifting 50% rice cultivation to pulses on residue burning and associated effects, use of agricultural inputs and associated effects and farmers' income. We estimate public expenses on fertilizer and power subsidies using Equation 18a and per capita consumer subsidy on foodgrains using Equations 18b. By our estimates using Equation 18b, annual public expenses reduces by INR 35 per beneficiary (or 28 billion INR given an estimated 800 million Indians access the PDS (Puri 2017; World Bank 2019)) if leakage in the PDS system (either through diversion of food or through wastage of grain due to poor quality storage) is reduced from 20% to zero.

In our quantitative model, pulses are sold through the PDS at 10% of MSP (as is the case with rice and wheat), and each PDS beneficiary buys 3kg rice and 1kg pulses each month (as opposed to 5kg of rice as each beneficiary is entitled to receive (Press Information Bureau 2013)). This would keep consumer expenses constant and public expenses on PDS would increase by 25% (from 1010 INR to 1260 INR/capita).

Table S3 presents the direct and indirect changes in system interactions due to each intervention.

Intervention	**Direct structural changes**	**Indirect quantitative changes**
Intervention 1 : Effective ban on burning	Farmers do not burn rice residues (H1-T2)	Rice residues are not burnt and emit fewer GHGs (T2-E1)
	Storage facilities established for residues (T13-T2)	Rice residues are not burnt and emit fewer air pollutants (PM2.5) (T2-E1)
		Lower emission of PM2.5 leads to lower adverse health impacts (E1-H2)
Intervention 2: Residues used in power plants	Farmers do not burn rice residues (H1-T2)	Rice residues are not burnt and emit fewer GHGs (T2-E1)

	Farmers rent baling machines (H1-T10)	Rice residues are not burnt and emit fewer air pollutants (T2-E1)
	Storage & processing facilities established for residues (T13-T2, T14-T2)	Lower emission of air pollutants leads to lower adverse health impacts (E1-H2)
	Power plants set up to use residues (T12-T2)	Farmers earn income from sale of residues (T2-H1)
Intervention 3: Wide-scale Happy Seeder use	Farmers use Happy Seeders (H1-T11)	HS incorporates rice residues into the soil (T11-T2)
		Happy Seeder use increases crop yield (T11-T1) and income (T1-H1)
		Incorporated residues improve soil health and reduces fertilizer use (T2-E4; E4-T3)
		Happy Seeder use reduces groundwater extraction (T11-E3) and lowers irrigation fuel (electricity/diesel) consumption (E3-T6, E3-T7);
		Happy Seeder use increases tractor diesel consumption (T11-T7)
		Residue burning and agricultural inputs determine emission of air pollutants (PM2.5 and GHG) (T2-E1, T3-E1, T6-E1, T7-E1).
		Lower emission of PM2.5 leads to lower adverse health impacts (E1-H2)
		Agricultural inputs and Happy Seeder rental affect

		farming costs (T3-H1, T6-H1, T7-H1, T11-H1)
Intervention 4: Input subsidy reform	Farmers extract less groundwater (H1-E3)	Lower groundwater extraction reduces electricity/diesel consumption (E3-T6, E3-T7)
		Lower diesel use reduces farming costs (T7-H1)
		Agricultural inputs (electricity, diesel) determine emission of air pollutants (PM2.5 and GHG) (T6-E1, T7-E1)
		Lower emission of PM2.5 leads to lower adverse health impacts (E1-H2)
	Farmers use less fertilizers (H1-T3)	Lower fertilizer use reduces emission of GHG and PM2.5 (T3-E1)
		Lower emission of PM2.5 leads to lower adverse health impacts (E1-H2)
		Lower nitrogen fertilizer use improves soil health (T3-E4)
Intervention 5: Procurement of pulses	Farmers shift 50% of cultivation from rice to pulses (H1-T1)	Crop yield influences farmers' income (T1-H1)
	Milling facilities are established for pulses (T15-T1)	Crops grown determine protein availability in low-income households who access the PDS (T1-H3)
		Crops grown determine use of agricultural inputs (groundwater, fertilizer, electricity, diesel, pesticides) (T1-E3, T1-T3, T1-T4, T1-T6, T1-T7) and

		farming costs (T3-H1, T4-H1, T6-H1, T7-H1)
		Farmers do not burn all residues (H1-T2)
		Fewer residues are burnt and emit fewer GHGs/PM2.5 (T2-E1)
		Agricultural inputs (fertilizer, electricity, diesel) determine emission of air pollutants (PM2.5 and GHG) (T3, T6-E1, T7-E1)
		Lower emission of PM2.5 leads to lower adverse health impacts (E1-H2)

Table S3: Direct and indirect changes in the system due to interventions
Human, technical and environmental component categories are represented by H,T and E respectively, and numbers represent the components (see Table 1 in manuscript for component numbers). E.g., interaction H1-T1 is an interaction between farmers (human component 1) and crops (technical component 1), where the human component (H1) influences the technical component (T1).

Text S4: Using inclusive wealth as a measure of sustainability

We estimate the changes in inclusive wealth as the sum of changes in capital stocks (human and natural capital and carbon damages) over the period 2019-2029. We calculate this by multiplying the change in stock as estimated by our model with marginal values of stocks. We use marginal values of carbon emissions and human and natural capital from previous studies to provide high-level estimates of the agricultural system's impacts on capital stocks, recognizing the significant uncertainty associated with the shadow prices of stocks (see Supp. Data Tables SD7-SD14 for detailed estimates for 2019-2029).

Human capital: We estimate the change in human capital by accounting for the value of health impacts and farmers' income (Aly & Managi 2018). Health impacts include lives lost due to air pollution exposure from residue burning and other agricultural activities in Punjab and lives saved by increasing protein consumption through subsidizing pulses for low-income households. Farmers' income is estimated as net income earned by farmers through sale of crops and residues, accounting for the cost of agricultural inputs.

$$\Delta Human\ capital = Health_{air\ pollution} + Health_{protein\ availability} + Income$$

…… Equation 26

Health impacts: The value of a statistical life (VSL) can be defined as the monetary worth of a human life or the amount individuals are willing to pay collectively to save a human life. VSL has been estimated and used in practice extensively in developed countries with little focus on estimating it specifically for developing countries (Majumder & Madheswaran 2018). Majumder and Madheswaran (2018) estimate VSL in India as INR 44.69 million (0.62 million USD) (based on Indian labour market data for 2010 – 2017), while Viscusi and Masterman (2017) estimate the VSL for India as 1.009 million USD, based on VSL for US and an income elasticity of 1. We use an income elasticity of 1 (Viscusi & Masterman 2017; Masterman & Viscusi 2018) and expected GDP growth rate of 5%(Bank 2020) to estimate VSL for India for the 10-year period of model run (2019-2029).

We estimate the health capital impact of air pollution due to air pollution exposure from residue burning and other agricultural activities (diesel use in farm machinery, power production and fertilizer manufacturing) in Punjab as:

$$Health_{air\ pollution} = Premature\ mortality\ estimate\ x\ VSL$$ …… Equation 27

The impact of increasing protein intake depends on a number of factors such as the kind of protein and whether protein is over consumed, among others (Naghshi et al. 2020). Naghshi et al. (2020) conducted a systematic review and meta-analysis of cohort studies from different countries (this list of countries excludes India) between 2000 and 2019 to show that, based on a linear dose-response analysis, an additional 3% increase in daily energy from plant protein reduces all-cause mortality risk by 5%. In our analysis, a 50% shift in cultivation area from rice to pulses in Punjab can increase protein intake by an additional 1.2% for about 142 million people (assuming individuals buy 1kg of pulses a month and 3kg rice a month, as opposed to 5kg of rice as entitled by the National Food Security Act (Puri 2017), to keep consumer expenses on foodgrains constant. We also assume that low-income individuals rely on the Public Distribution System for most of their caloric and protein requirement).

We estimate the health capital impact of increasing protein consumption as :

$$Health_{protein\ availability} = Protein\ impact * \ Premature\ mortality\ rate * \ Population * \ VSL$$
..…. Equation 28

Where
Protein impact = 2% reduction in mortality due to 1.2% additional daily energy from plant protein (estimated from linear dose-response relationship in (Naghshi et al. 2020))
Premature mortality rate = 691 per 100,000 people (estimated from the relation: $Y_z/RR_z = Y_{baseline}/RR_{baseline}$ where $Y_{baseline}$= 685 per 100,000 in 2010 (WHO 2011), and relative risk estimated for annual mean exposure to $PM_{2.5}$ in 2010 and 2019 using Equation 21)

Population = 142 million people who are enabled to buy pulses at a subsidized cost through the PDS (see above)
VSL = 0.62 (Majumder & Madheswaran 2018) – 1.009 million USD (Viscusi & Masterman 2017)

Our estimate of the health capital impact of increasing protein consumption is based on a few assumptions: individuals will increase consumption of pulses if it is made available through the PDS; low-income households derive most of the calorific and protein requirement through subsidized foodgrains (Rampal 2018); and Naghshi et al.'s (2020) linear dose-response relationship, between protein consumption and premature mortality, is applicable to the Indian population.

Farmers' income: Income underpins the ability to gain skills and education that constitute human capital (Managi & P. Kumar 2018), however the decadal time scale of our analysis makes it challenging to estimate long-term impacts on farmer's skills and education with each intervention. We include changes in farmers' net income from sale of crops and residues in our estimate for changes in human capital (Aly & Managi 2018). We do not consider changes in support prices provided by the government to farmers over the 10-year period of model run (2019-2029) and assume that support prices do not rise in real terms.

We estimate total farmer income from the rice-wheat cropping system in Punjab as

$$Income = Income_{per\ ha} * \ Area \qquad \text{…… Equation 29}$$

where,
$Income_{per\ ha}$ = annual farmer income per hectare of land cropped (see Materials & Methods Section 2 and Equation 16)
$Area$ = total area cropped annually (see Supp. Data Table S3)

Natural capital: Natural capital includes natural resources such as oil, timber, land, water etc. We estimate changes in natural capital as changes in groundwater stock due to the agricultural system of Punjab, assuming total cropped area remains constant with each intervention. The value of groundwater can be estimated by calculating the value of foregone production due to groundwater extraction but needs careful application of discount rate (discount rates for natural capital are controversial) and marginal human impact on groundwater stock (e.g., how human action such as varying rates of pumping affect groundwater stock) (Fenichel & Abbott 2014; Fenichel et al. 2016). We estimate of the value groundwater stock as the value of foregone rice and wheat production due to groundwater extracted:

$$\Delta Natural\ capital = (\textstyle\sum_{rice,wheat} MPP * \ MP * \ Ratio\ of\ water\ usage) * Groundwater \qquad \text{…… Equation 30}$$

Where,
MPP = marginal physical production of rice and wheat estimated by Srivastava et al. (2015) as 195 kg/ha-m and 1056 kg/ha-m respectively (using a log-linear regression

model for Punjab with yield of rice or wheat as the dependent variable). This represents the additional output of rice or wheat for an incremental unit of groundwater (1 ha-m).
MP = marginal price of rice and wheat. We assume the minimum support prices (19.25 INR/kg for rice and 20.24 INR/kg for wheat (Punjab Agricultural University 2019; Punjab Agricultural University 2020)) at which rice and wheat were procured in 2019 as the marginal prices
Ratio of water usage = By our model estimates, irrigation of rice accounts for about 66% of annual groundwater extraction in Punjab's rice-wheat cropped area and wheat accounts for remaining 34%
Groundwater = groundwater extracted for irrigating rice and wheat in 2019

We estimate the value of foregone future production of rice and wheat due to pumping an additional hectare-metre of groundwater at present at 135 USD (compared to 57 USD and 138 USD estimated by Fenichel (2016) using a 7% and 3% discount rate respectively for Kansas, USA). We do not discount the value of future crop production to emphasize on inter-generational equity in the long-term sustainability of the agricultural sector of Punjab. We also assume that groundwater is available as required in the future (there is no discontinuity in the availability of groundwater) and the future foregone production is due to incremental unavailability of groundwater.

Carbon damages: Climate change is a global externality and the available estimates of social cost of carbon (SCC) provide a measure of the marginal cost of global damages caused by CO_2 (Greenstone et al. 2013). Estimates for SCC vary widely due to uncertainties in economic harm expected from CO_2 (damage function) and in the sensitivity of the climate system's response to CO_2, among other factors (Ricke et al. 2018; Stern & Stiglitz 2021). Studies provide a range of SCC estimates (in 2019 terms): 32.5 USD/t CO_2 in 2020 growing at 1.9% per year (Greenstone et al. 2013); 42 USD/tCO_2 in 2020 growing at 3% per year (EPA 2016); US administration's latest announced value at 51 USD/tCO_2 (Chemnick 2021); a range of 32.5 – 95 USD/tCO_2 in 2025 depending on emissions reduction target (Kaufman et al. 2020); and as high as 409 USD/tCO2 in 2020 (Ricke et al. 2018). Ricke et al. (2018) specify country-level SCCs or the marginal damage caused in each country due to an additional unit of CO_2 emitted – India has the highest country-level SCC at 86 USD/tCO_2 (range of 49-157 USD/tCO_2) in 2020.

We use a conservative value of 32.5 USD/tCO_2 (Greenstone et al. 2013) and the country-level SCC of 86 USD/tCO_2 (Ricke et al. 2018) to highlight the uncertainty in damages caused by GHG emissions. We estimate the damage caused by GHG emissions using the following relation:

$$\Delta Carbon\ damages \quad = GHG\ x\ SCC \qquad \text{….. Equation 31}$$

where,
GHG = Total GHG emissions in CO_2 equivalent

SCC = Social cost of carbon estimated at 32.5 USD/tCO_2 in 2020 or 86 USD/tCO_2 (see above)

The social and environmental costs of nitrogen pollution from fertilizer application are site-specific and challenging to estimate; they include the warming impacts of N_2O emitted into the atmosphere, nitrate pollution in groundwater and soil, and emissions of ammonia which lead to acid rain, soil acidification, and other effects (Good & Beatty 2011; Keeler et al. 2016). We estimate only the damages caused by N_2O as a GHG emitted through fertilizer application since the social cost of carbon is spatially generalizable, accounting for the higher global warming potential of N_2O (GWP = 296(Venkataraman et al. 2016)) using Equation 31.

1% of nitrogen in fertilizers applied is emitted as N_2O (1 tonne of nitrogen fertilizer releases = 0.01*44/28=15.7 kg N_2O; ratio of mol. Weights of N_2O and N = 44/28) and each tonne of nitrogen fertilizer releases 7.22 kg of N_2O through atmospheric ammonia oxidation (Good & Beatty 2011). This results in a total of 23 kg N_2O released with the application of 1 tonne of nitrogen fertilizer.

Table S4 presents the estimated changes in inclusive wealth (monetary values of capital stocks) due to interventions over the period 2019-2029, relative to a No New Policy scenario (see Table 4 for estimated changes in inclusive wealth in the No New Policy scenario). See Supp. Data Tables SD7-SD14 for detailed estimates of quantitative impacts of interventions on sustainability metrics (changes in physical and monetary values of stocks) for the period 2019-2029.

Interventions	**Change in human capital**	**Change in natural capital**	**Carbon damages**
Effective ban on residue burning : by paying farmers and raising awareness	376 - 613	-	13 - 36
Use of residues in power plants: 600 MW biomass power plants	118 - 190	-	2 -5
Use of residues in power plants: Cofiring 10% (or 4.4GW) of state-owned coal power plants	372 - 596	-	3 - 8
Fertilizer subsidy reform : Optimal use of urea	2 - 3	-	2 - 8

Power subsidy reform: guaranteed but rationed power to reduce groundwater extraction for rice by 33%	-0.3 to 1.7	1.1	-0.2 to -0.7
Promote wide-scale use of Happy Seeder (HS): HS use tripled	379 – 614	0.1	14 - 40
Government procurement of pulses: 50% shift from rice to pulses	466 - 762	1.1	13 - 35

Table S4: Cumulative changes in capital stocks relative to base case (No New Policy) 2019 -2029 *(all values in billion USD; range of values depicts range of marginal values of capital stocks)*

Text S5: Details on expert interviews

We conducted four semi-structured interviews with researchers who specialize in different aspects of the agricultural sector of Punjab, India. The policy interventions considered in this work are widely discussed in policy, academic and development circles but have not been implemented on a large scale yet. Our interview questions were aimed at understanding existing institutional barriers to effective policy implementation and helped inform our selection of policy options in this work.

We conducted interviews with the following experts:

Researcher at University of British Columbia's Institute for Resources, Environment & Sustainability, who conducted extensive interviews with farmers in Punjab to understand their perspectives on agricultural residue management. (Interview date: December 14, 2020).

Researcher at University of British Columbia's Institute for Resources, Environment & Sustainability, whose research focuses on irrigation policies that can reduce the adverse environmental impact of the cropping system in India, particularly in Punjab. (Interview date: February 12, 2021)

Researcher at the Council on Energy, Environment & Water (India), working on air pollution and crop residue burning in north India, with a particular focus on technological alternatives to residue burning such as use of residues in power plants. (Interview date: February 24, 2020) .

Researcher at Pennsylvania State University whose work focuses on agricultural markets in India, and particularly on policy issues related to the economics of crop diversification in Punjab. (Interview date: December 1, 2020).

Data Set S1. Data Tables SD1-SD14

Data Set S1 includes the following tables:
Data Table SD1: List of system components and their attributes
Data Table SD2: Detailed interaction matrix between system components
Data Table SD3: Attributes of crops and residues: crop production, protein content and residue generation
Data Table SD4: Attributes of crops: use of agricultural inputs for crop production
Data Table SD5: Attributes of technical components: Emission factors and GWP
Data Table SD6: Values of system components' attributes at t=1 (year=2019)
Data Tables SD7-SD14: Detailed quantitative impacts of interventions on sustainability metrics