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

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

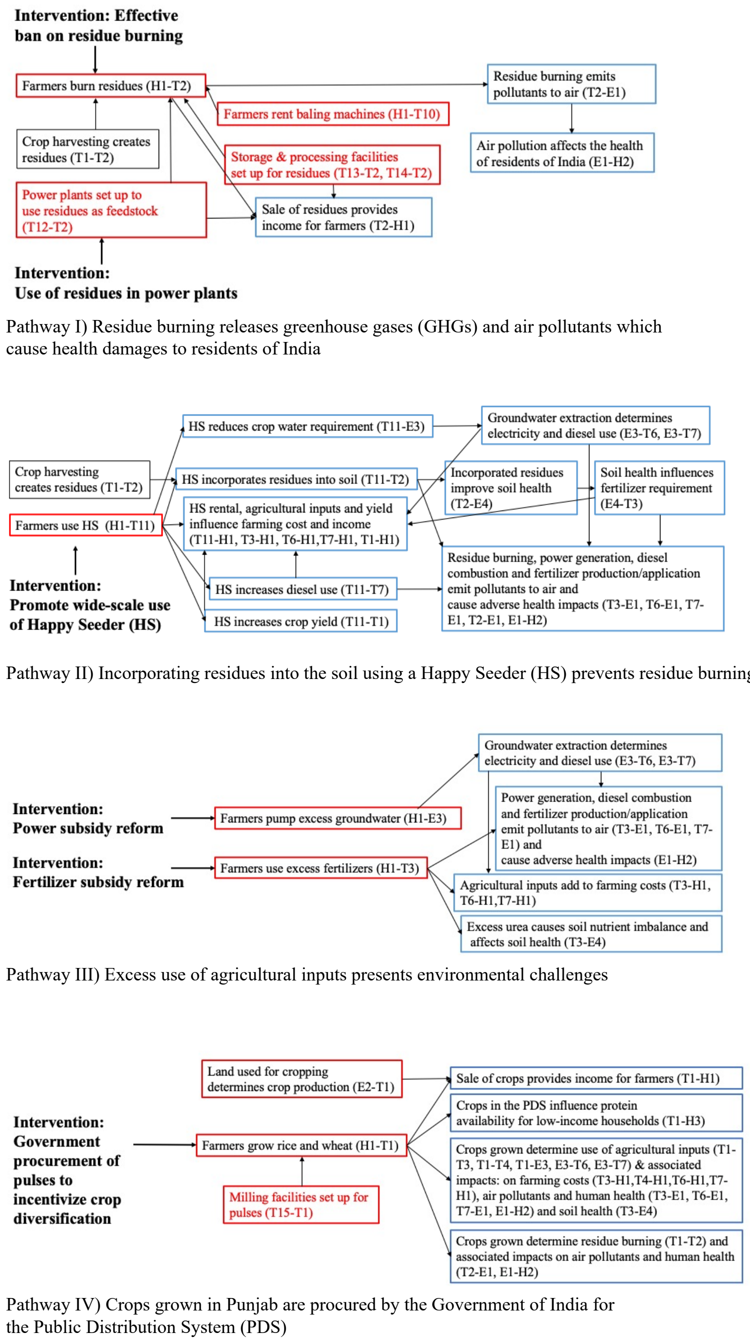


**Fig. 1** Pathways of interaction between system components *Note: Each box in the figure represents an interaction; arrows represent the direction of influence; H,T,E represent human, technical and environmental components respectively and numbers represent each component (see Table 1). Direct structural 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 $CO_2$eq | 152 Mt $CO_2$eq |
| 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.

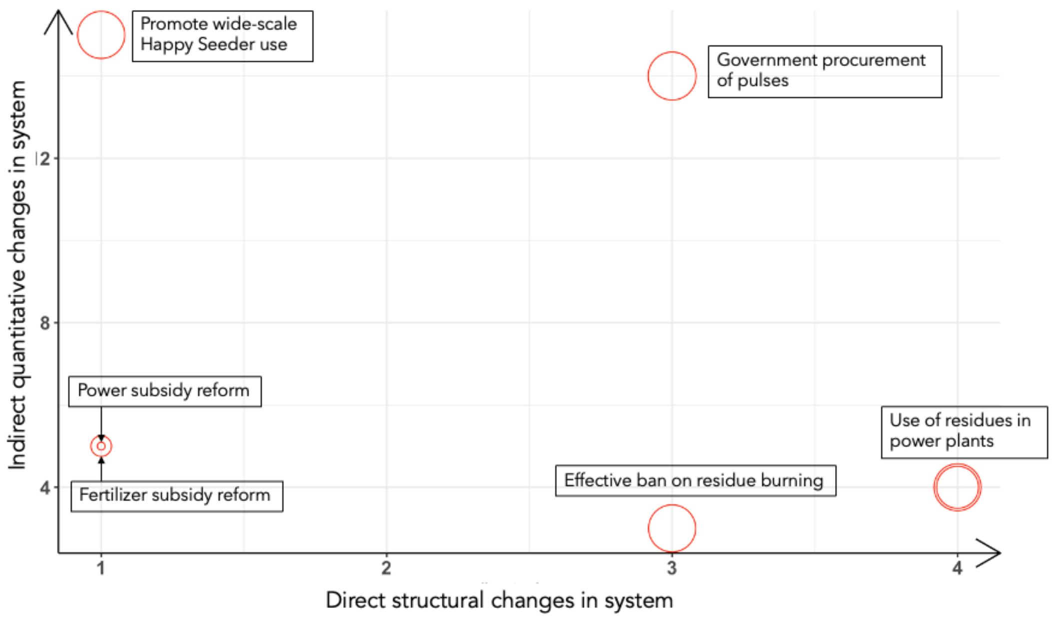


**Fig. 2**: Mapping the impacts of interventions on system structure and improvement in inclusive wealth relative to No New Policy scenario (2019-2029). *Note: Size of circle represents logarithm of change in inclusive wealth relative to a No New Policy scenario*

## 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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