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A Systems Analysis of Sustainability Impacts of Agricultural Policies in India

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Key Points:

- We apply a systems framework for analyzing policy interventions to the rice-wheat cropping system of Punjab (India)
- We quantify the sustainability impacts of interventions involving varying degrees of change in the system using an inclusive wealth-based approach
- We show how policy-induced changes can lead to substantial and wide-ranging sustainability benefits

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

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 quantify how varying degrees of change in interventions result in sustainability impacts using an inclusive wealth-based approach. We show that either improving the existing cropping system or inducing fundamental changes in 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

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 incremental and fundamental changes can lead to wide-ranging sustainability benefits.

1. Introduction

A large number of recent studies have focused on the importance of understanding linkages between multiple sectors relevant for sustainability. One example involves food, water, energy, and air pollution (Domingo et al., 2021; Qureshi et al., 2016). As a result of these linkages, efforts to mitigate damages in one sector 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).

A specific example of such a broader network of interconnected sustainability challenges involves agricultural residue burning in India. 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. This burning leads to 44,000–98,000 air pollution-related deaths annually (GBD MAPS Working Group, 2018; Lan et al., 2022). Previous studies have analyzed crop residue management options with a focus on reducing air pollution attributable to residue burning (Bhuvaneshwari et al., 2019; Shyamsundar et al., 2020; 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, for example, studies have evaluated the effect of electricity subsidies on groundwater use (Badiani-Magnusson & Jessoe, 2018; B. S. Sidhu et al., 2020), the effect of the nitrogen fertilizer subsidy (A. Gulati & Banerjee, 2015), impacts of crop residue burning on air quality (Jain et al., 2014; Jethva et al., 2019), 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. That is, solutions to the inter-connected sustainability challenges of agricultural residue burning have not been assessed within a common analytical framework that would enable comparing and contrasting expected impacts of interventions on a range of metrics.

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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 (Kumar et al., 2015; S. N. Sharma et al., 2010) 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 (Magrini et al., 2016; Meynard et al., 2013).

Evaluating systemic impacts of interventions toward sustainability is also 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 (Feola, 2015; Genus & Coles, 2008; Rotmans et al., 2001) and better quantitative metrics are needed to assess potential interventions and their sustainability-relevant outcomes. The degree of change toward 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; Folke et al., 2010; Frantzeskaki & Loorbach, 2010; Genus & Coles, 2008; Park et al., 2012; Rotmans et al., 2001; 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 (Correlje & Verbong, 2004; Rotmans et al., 2001). 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, evaluating them across a range of metrics. 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 (Arrow et al., 2012; Dasgupta et al., 2021; Managi & Kumar, 2018; Polasky et al., 2015)). We use the human-technical-environmental (HTE) framework (Selin & Selin, 2022)—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

The Human-Technical-Environmental (HTE) framework provides a system-oriented analytical framework based on an straightforward matrix approach, which we use to analyze the sustainability challenges and interventions

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in the agricultural system of Punjab. We follow the methodology outlined in the HTE framework (Selin & Selin, 2022) along four steps.

2.1.1. Itemize System Components

First, we itemize the components which form the building blocks of the system (Table 1)—human (H), technical (T), environmental (E), institutional (I), and knowledge (K) components are distinctly numbered within each category. We identified the relevant components in each category from previous studies on specific sustainability challenges in the agricultural system of Punjab on air pollution, groundwater exploitation, agricultural subsidies, and crop diversification (Badiani-Magnusson & Jessoe, 2018; A. Gulati & Banerjee, 2015; Jain et al., 2014; Jethva et al., 2019, B. S. Sidhu et al., 2020; Subramanian, 2016). See Data Table SD1 in Supporting Information S2 for a detailed list of components' attributes, that is, characteristics that represent the state of a component at any given time.

2.1.2. Constructing the Interaction Matrix

The human, technical, and environmental components identified above interact with each other within the institutional and knowledge landscape. We use previous studies on specific sustainability challenges to inform our construction of this interaction matrix that qualitatively represents how system components are connected and influence each other. Table 2 presents the interaction matrix where each row represents components that influences components in a column (see Data Table SD2 in Supporting Information S2 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. for example, H1-T2 represents an interaction between farmers in Punjab (human component 1) and crop residues (technical component 2).

2.1.3. Pathways of Interaction

We use the completed HTE matrix to identify key pathways of interaction between system components that have impacts on sustainability-relevant outcomes in the system (Figure 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 (Selin & Selin, 2022). 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.

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; Jethva et al., 2019; Kulkarni et al., 2020) (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 and 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; Ellis-Petersen, 2019; Slater, 2018; 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 (Bhatt, 2020; Bhuvaneshwari et al., 2019; 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, 2015). It reduces water and fertilizer input requirements, potentially

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Table 1
List of Components in the System (See Data Table SD1 in Supporting Information S2 for a List of Components' Attributes)

Human (H)	Technical (T)	Environmental (E)
(a) Farmers in Punjab (H1)	(d) Crops grown in Punjab (T1)	(s) Air (PM2.5 & GHG) (E1)
(b) Residents of India (H2)	(e) Crop residues (T2)	(t) Cropped land (E2)
(c) Low-income households (H3)	(f) Fertilizers (T3)	(u) Groundwater (E3)
	(g) Pesticides (T4)	(v) Soil (E4)
	(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)	

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

Table 2
Interaction Matrix Between System Components (HS = Happy Seeder; PDS = Public Distribution System)

	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 and diesel use; (E4-T3) Soil health affects fertilizer requirement	(E1-E1) Ecosystem processes and dynamics determine air pollution concentrations

Note. Human, technical, and environmental component categories are represented by H, T, and E respectively, and numbers represent the components. For example, 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).

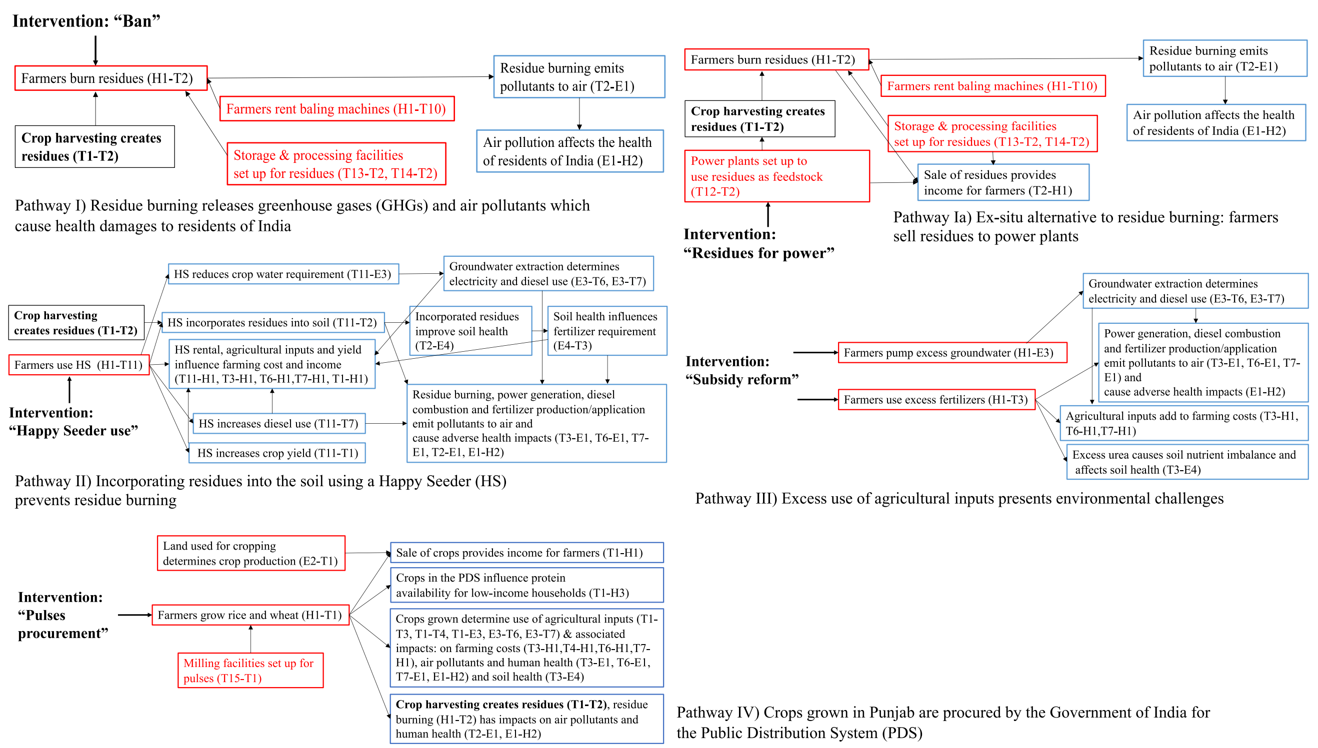

Figure 1. Pathways of interaction between system components. Note: Each box in the figure represents an interaction; arrows represent the direction of influence; H, T, E represent human, technical and environmental components respectively and numbers represent each component (e.g., H1 = farmers in Punjab as specified in 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 Text S3 and Table S3 in Supporting Information S1 for details on direct and indirect changes). Common interaction across pathways I, II, and IV highlighted in bold = "Crop harvesting creates resides (T1-T2)".

leads to higher long term yields (after 3–5 years of use) (Shyamsundar et al., 2020; H. S. Sidhu et al., 2015), and is considered the most economical of alternative residue management options to burning (Government of India, 2019; Shyamsundar et al., 2020). 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 (Anon, 2019; Goyal, 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 (Ailawadi & Bhattacharyya, 2006; Ashok, 2017; Gupta, 2011; Jitendra et al., 2017; Shyamsundar et al., 2020; H. S. Sidhu et al., 2015; Tallis et al., 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 hr/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; Singh, 2020b) and consequently rising energy consumption to pump groundwater from increasingly greater depths. Similarly, fertilizer subsidy structures have led to excessive use of urea—nitrogen-based urea fertilizer (N) is price-controlled by the Government of India while the market prices of phosphorus (P) and potash (K)-based fertilizers have increased significantly, as only the subsidy on these remains fixed (A. Gulati & Banerjee, 2015). 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 (Anand, 2010; Chaba, 2019; A. Gulati & Banerjee, 2015; Jitendra, 2020).

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%–45% of cropped area respectively, while cultivation of all other crops (including pulses which constituted 19% of cropped area in 1960) declined (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, 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).

2.1.4. Identifying Interventions to Change System Interactions

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 (Figure 1) 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 (A. Gulati & Banerjee, 2015; M. Gulati & Pahuja, 2015; Ministry of Agriculture, 2014; Puri, 2017; H. S. Sidhu et al., 2015; B. S. Sidhu et al., 2020; TERI, 2006), and were selected on the basis of interviews conducted with researchers who specialize in different aspects of the agricultural sector of Punjab (see Text S5 in Supporting Information S1). These interventions are: (a) an effective ban on residue burning ("Ban"), (b) use of residues in power plants ("Residues for power"), (c) promoting wide-scale Happy Seeder use ("Happy Seeder use"), (d) power and fertilizer subsidy reform ("Subsidy reform") and (e) government procurement of pulses to incentivize crop diversification ("Pulses procurement"). 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 Figure 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 3.2 elaborates on each intervention and associated impacts within this system.

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 over a period of 10 years (2019–2029) for the state of Punjab (India) (see Text S1 in Supporting Information S1 for model details). We used 2019 as the baseline year and validated the model for the year 2019 with independent data (previous studies and government reports) for key attributes used in this work, including a sensitivity analysis of key sustainability outcomes to input parameters (details in Text S2 of the Supporting Information S1). We then use our quantitative model to evaluate changes in sustainability-relevant outcomes over a period of 10 years (2019–2029) by estimating cumulative change in capital stocks that comprise the foundations of human well-being (Arrow et al., 2012; Dasgupta et al., 2021; Fenichel et al., 2016; Polasky et al., 2015). To do this, we use data from previous studies on sustainability challenges in the agricultural system of Punjab (see Data Tables SD3–SD6 in Supporting Information S2). Finally, we apply our model to examine five potential interventions to the system (see Text S3 in Supporting Information S1 for details on interventions). For each intervention, 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 and inclusive wealth. Change in capital stocks 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, assuming uniform impacts across the time period (details in Text S4 of the Supporting Information S1). 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. Baseline Scenario (No New Policy) and Impacts on Sustainability (2019–2029)

We implement the interactions described in the pathways above in our quantitative model. Our model evaluation for the year 2019 (details in Text S2 of the Supporting Information S1) 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. Sensitivity analysis (Text S2 in Supporting Information S1) of key model outputs to model input parameters using a OAT approach (where we vary baseline model inputs by ±20%) shows: GHG emissions and PM2.5 are most sensitive to residue-to-product ratio (±10% and ±15% respectively) as more residues generated per ton of product lead to higher residue burning and associated emissions; and energy use is most sensitive to water table depth (diesel ±10% and electricity

±20%) as more energy is required to pump groundwater from greater depths for irrigation. Farming costs show low sensitivity (<2%) to agricultural inputs as they largely depend on crop yield and residue management costs. The challenge of conducting sensitivity analysis is the unavailability of uncertainty estimates of model input parameters from literature and further work can contribute toward developing realistic ranges for input parameters.

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. We estimate changes in premature mortality (human capital), farmers' income (human capital), groundwater extraction (natural capital) and carbon damages using Equations M, I, W, and G specified in Table 3. 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 532 billion INR (7.4 billion USD; at a discount rate of 5%) in public expenses (see Equation 18 in Text S1 of the Supporting Information S1).

3.2. Interventions and Impacts on Sustainability (2019–2029)

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. For changes in capital stocks, we estimate changes in premature mortality (human capital), farmers' income (human capital), groundwater extraction (natural capital) and carbon damages using Equations M, I, W, and G specified in Table 3. Details on each intervention are provided in Text S3 of Supporting Information S1, with detailed direct (structural) and indirect (quantitative) changes in Table S4 of the Supporting Information S1 and detailed quantitative impacts of interventions on sustainability metrics presented in Data Tables SD7−SD14 of the Supporting Information S2.

In the "*Ban*" 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) and 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; Ellis-Petersen, 2019; Slater, 2018; Yadav, 2019). Paying farmers to prevent residue burning may increase public expenses by about 22% (an additional 1.6 billion USD over 2019–2029) 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 530,000 lives saved due to lower $PM_{2.5}$ emissions, and reduction in GHG emissions by 46% over a 10-year period.

In the "*Residues for power*" 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 (Ghosal, 2017; Special Correspondent, 2017). Alternately, the Punjab Government sets up 600 MW 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 (Griffin et al., 2014; Singh, 2015a) 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 7.5 MW (Singh, 2015a)) 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 & 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, 2022)), this would utilize the rice residues previously burnt, preventing about 532,000 premature deaths, reducing GHG emissions by 10% and increase

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Table 3
Key Equations to Estimate Sustainability Impacts

Capital stock		Human capital	Natural capital	Carbon damages
Sustainability metric	Premature mortality due to $PM_{2.5}$ emissions from residue burning and agricultural activities (ΔM = liveslost)[a]	Farmers' income per hectare (excluding rent)	Groundwater extraction for irrigation (cubic meters)	GHG emissions from residue burning, energy use and nitrogen fertilizer (urea) application (tonnes CO_2e)
Change in capital stock	$\Delta M = P * \frac{Y_{\text{baseline}}}{RR_{\text{baseline}}} * (RR_{\text{obs}} - RR_{\text{obs minus } z})$	$\text{Income per ha} = \left(\sum_{\text{crop}} \text{Yield}_{\text{crop}} * \text{MSP}_{\text{crop}}\right) - \left(\sum_{\text{fert type}} \text{Fertilizer}_{\text{type}} * \frac{\text{Cost}_{\text{fert type}}}{\sum_{\text{crop}} \text{Area}_{\text{crop}}}\right) - \left(\sum_{\text{crop}} \text{Pesticide cost}_{\text{crop,per ha}} * \frac{\text{Area}_{\text{crop}}}{\sum_{\text{crop}} \text{Area}_{\text{crop}}}\right) - \sum_{\text{uses}} \text{Diesel}_{\text{uses}} * \frac{\text{Cost}_{\text{diesel}}}{\sum_{\text{crop}} \text{Area}_{\text{crop}}} - \text{Other}_{\text{inputs}} - \text{HS}_{\text{rental per ha}} - \text{Residue management}$	$\text{Water} = \text{Tubewell}_{\text{share}} * \sum_{\text{crops}} \text{Area}_{\text{crop}} * \text{CWR}_{\text{crop}} * \text{Excess}$	$\text{GHG}_{\text{residue burning}} = \sum_{\text{species}} (\text{emf}_{\text{species,residue burning}} * \text{Residues}_{\text{burnt}}) * \text{GWP}_{\text{species}}$ $\text{GHG}_{\text{energy use}} = \sum_{\text{species}} \{(\text{emf}_{\text{species,power}} * \text{kWh}) + (\text{emf}_{\text{species,diesel,use}} * \text{Diesel}_{\text{uses}}) + (\text{emf}_{\text{species,fertilizer,type}} * \text{Fertilizer}_{\text{type}})\} * \text{GWP}_{\text{species}}$
	Equation M	Equation I	Equation W	Equation G
Notes	P = population exposed; Y_{baseline} = baseline mortality rate; RR_{baseline} = Relative risk due to $PM_{2.5}$ exposure in the baseline year of 2010; RR_{obs} = Relative risk due to observed exposure level in 2019; $RR_{\text{obs minus } z}$ = Relative risk associated with observed concentration minus the concentration z attributable to the agricultural system in 2019	$\text{Yield}_{\text{crop}}$ = yield per hectare $\text{Area}_{\text{crop}}$ = Area cropped by crop type $\text{Pesticide cost}_{\text{crop}}$ = Pesticide expenditure by crop type $\text{Fertilizer}_{\text{type}}$ = total fertilizer use by fertilizer type $\text{Diesel}_{\text{uses}}$ = Diesel used in pumping, generator sets for pumps, residue removal and Happy Seeder (liters) $\text{HS}_{\text{rental per ha}}$ *rentall cost of Happy Seeder*	$\text{Tubewell}_{\text{share}}$ = Share of irrigation requirement met by groundwater extraction using tubewell $\text{Area}_{\text{crop}}$ = Cropped area by crop type (hectares) CWR_{crop} = water required by crop type per hectare (meters) Excess = fraction in excess of recommended/ required usage	$\text{GWP}_{\text{species}}$ = Global warming potential of GHGs $\text{emf}_{\text{species, residues,burning}}$ = emissions (CO_2, CH_4, N_2O) per kg residues burnt $\text{emf}_{\text{species, power}}$ = emissions (CO_2, CH_4, N_20) per kWh $\text{emf}_{\text{species, diesel, use}}$ = emissions (CO_2, CH_4, N_20) per liter diesel for used in pumping, generator sets for pumps, residue management and Happy Seeder $\text{emf}_{\text{species, fertilizer, type}}$ = emissions (CO_2, CH_4, N_20) per kg fertilizer manufactured (urea, DAP, MOP)
	Concentration z is estimated (see Equation S5 in Supporting Information S1) from $PM_{2.5}$ emissions due to residue burning and other agricultural activities (emissions estimated from emission factors and residues burnt in Equations S4 and S15 in Supporting Information S1)	MSP_{crop} = minimum support price (MSP) for crops procured by the government $\text{Cost}_{\text{fert type}}$ = Subsidized cost of fertilizer by fertilizer type $\text{Cost}_{\text{diesel}}$ = Cost of diesel $\text{Other}_{\text{inputs}}$ = Costs of harvesting operations and seeds Residue management = Rental, labor and diesel costs associated with conventional residue management		kWh = annual electricity used in pumps (Equation S11 in Supporting Information S1) $\text{Diesel}_{\text{uses}}$ = diesel used in pumps and machinery (Equations S12 and S13 in Supporting Information S1) $\text{Fertilizer}_{\text{type}}$ = fertilizer use by type (Equation S9 in Supporting Information S1) $\text{Residues}_{\text{burnt}}$ = total residues burnt (Equations S1 and S2 in Supporting Information S1)

Note. See Text S1 in Supporting Information S1 for details on each parameter and Data Tables SD3–SD6 in Supporting Information S2 for values of each parameter.

[a]For intervention 5 ("Pulses procurement"), we also estimate the reduction in premature mortality due to greater protein availability (see Equations S17 and S28 in Supporting Information S1).

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)

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[a]	Farmers' income (excluding rent)	Groundwater extraction for irrigation	GHG emissions from residue burning and energy use[b]	GHG emissions from nitrogen fertilizer (urea) application[c]
Change in capital stock	760,000 lives[d]	–	762000 INR/ha (10600 USD/ha)	372 billion cubic meters	764 Mt CO_2eq	152 Mt CO_2eq
Change in monetary value of capital stock (billion USD)[e]	−(330–536)	–	43	−4	−(52–75)	−(10–15)
Impact on inclusive wealth	Net decline of 389–646 billion USD					

Note. Given the relatively constant cropped area and yield of rice and wheat in Punjab between 2010 and 2016 [103], we assume that rice and wheat production remains constant in Punjab over 2019–2029. [a]Protein constitutes 8.5% of total macronutrients by weight for rice and wheat grown in Punjab and supplied through the PDS. [b]Energy use includes electricity and diesel for irrigation and farm machinery, and fertilizer manufacturing. [c]Environmental impact of nitrogen fertilizer application is quantified in terms of carbon damages. [d]Loss of 690,000 lives attributed to primary $PM_{2.5}$ emissions from residue burning. [e]We estimate the change in monetary value of capital stocks by multiplying the change in capital stock (as estimated by our model) with marginal values of stocks as estimated in previous studies. See Text S4 in Supporting Information S1 for details.

farmers' income by 24%. Utilizing rice residues in 600 MW of biomass plants would prevent 167,000 premature deaths, reduce GHG emissions by 6%, and increase farmers' income by 5%.

In the "*Happy Seeder use*" 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 547,000 fewer premature deaths due to lower $PM_{2.5}$ emissions, 55%–56% lower GHG emissions and marginal reduction (2%) in groundwater consumption over a 10-year period. 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.

In the "*Subsidy reform*" intervention (Figure 1-*Pathway III-Intervention 4*), the Government of India and State Government of Punjab reform power or fertilizer subsidies to disincentivize excess use of agricultural inputs. We assume farmers reduce groundwater use for irrigating rice by 33% (studies show that farmers can reduce groundwater use by a third without adversely affecting yield (Dhillon et al., 2018; Kaur et al., 2010; 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, 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 & 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 (Chaba, 2019; A. Gulati & Banerjee, 2015; Jitendra, 2020). 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 (Monari, 2002; B. S. Sidhu et al., 2020), 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, without affecting yield. If electricity is currently available for 60% of the required time for irrigation (with diesel used for the remaining time) (Mukherji et al., 2009), guaranteed power leads to 16%–18% higher farmer income through lower diesel usage and marginally lower associated GHG and $PM_{2.5}$ emissions (2%–5%). Reducing fertilizer usage by about 29% (to levels recommended by Punjab Agricultural University) leads to marginally lower $PM_{2.5}$ emissions (2%–3%) and 7% lower GHG emissions, without affecting yield.

In the "*Pulses procurement*" 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, that is, 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 19% (1.8 billion USD) 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.

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 (Singh, 2020b)) would prevent almost 418,000 premature deaths due to lower $PM_{2.5}$ emissions, as well as prevent about 210,000 premature deaths by increasing the protein availability through crops grown in Punjab by an additional 1.2% (an estimated benefit of 103–169 billion USD in health capital relative to our base case). This shift from rice to pulses would also reduce GHG emissions by 40% and groundwater consumption by 21%. 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% 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, "*Pulses procurement*" provides the largest increase in inclusive wealth, followed by "*Happy Seeder use*." 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, "*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.

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 relative to a base case where no new policy is implemented (logarithm of increase in inclusive wealth relative to No New Policy scenario represented as the size of circles with values specified alongside interventions). 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, "*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. Figure 2 also shows "*Ban*" and "*Residues for power*" induce few indirect changes (narrow range of impacts), but at the same time provide a large sustainability benefit. These interventions primarily reduce

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Table 5
Impacts of Interventions on System Structure and Sustainability Metrics (2019–2029)

Degree of change in system structure				Impact on sustainability metrics								
Direct changes needed in interactions			Interventions	Premature deaths: $PM_{2.5}$ emissions from residue burning	Premature deaths: $PM_{2.5}$ emissions from other sources	GHG emissions (CO_2, CH_4, N_2O)	Annual urea use for rice-wheat cropping	Annual groundwater draft	Protein content: Public Distribution System crops	Farmers' income	Public expenses on farm subsidies	Changes in Inclusive wealth
Politically challenging	Technological changes needed	Indirect changes induced in interactions	Base case: No New Policy (2019–2029)	690000	70000	764 million tonnes	22 million tonnes	372 billion cubic metres	8.50%	10,600 USD/ha	7.4 billion USD	−389 to −646 billion USD
1	1	4	Subsidy reform: Optimal use of urea		−2%	−3%	−29%	–	–	0.7%	−11%	−586 to −637 billion USD
1	3	3	Ban: On residue burning	−69%	–	−49%	–	–	–	–	22%	−133 to −159 billion USD
0	5	4	Residues for power: 600 MW biomass	−21%	4%	−6%	–	–	–	5%	31% (1)	−313 to −419 billion USD
0	5	4	Residues for power: cofiring 10% (or 4.4GW) of coal	−69%	20%	−10%	–	–	–	20%	34.5% (1)	−155 to −167 billion USD
1	1	8	Subsidy reform: groundwater use for rice reduced by 33%		4%–7%	1%	–	−22%	–	7%	15%	−388 to −646 billion USD
0	1	20	Happy Seeder use: tripled	−69%	−4%	−50%	−15%	−3%	–	3%–6% (2)	−5 to −8% (2)	−129 to −164 billion USD
0	2	21	Pulses procurement: 50% shift from rice to pulses	−53%	−19 to −22%	−42%	−20%	−21%	1%	−11%	−18 to −20% (3)	−78 to −142 billion USD

Note. Range of inclusive wealth impact represents range of marginal values of stocks. Interventions are organized in order of increasing inclusive wealth relative to No New Policy scenario.

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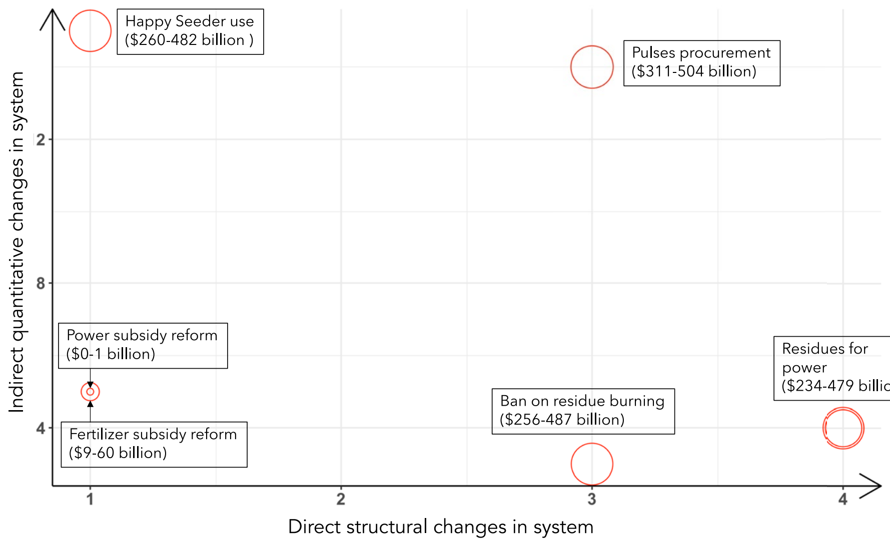

Figure 2. Mapping the impacts of interventions on system structure and improvement in inclusive wealth relative to No New Policy scenario (2019–2029). Note: Size of circle represents logarithm of change in inclusive wealth relative to a No New Policy scenario; values alongside interventions represent change in inclusive wealth relative to No New Policy scenario.

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.

4. Conclusions

Of the interventions considered, "*Happy Seeder use*" and "*Pulses procurement*" 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 228–372 billion USD saved) compared to a 50% shift in cultivation from rice to pulses (an estimated 179–292 billion USD saved). However, if the health impact of higher plant protein intake from pulses is taken into account (estimated benefit of 104–169 billion USD), 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. This is the only intervention in this study that may lead to a net increase in inclusive wealth (an estimated 72 billion USD between 2019 and 2029), if air pollution from residue burning is completely eliminated.

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 changes in a system can lead to a broad range of impacts and large quantitative improvement in sustainability as measured by an inclusive wealth-based approach.

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 366–594 billion USD, with an additional 104–169 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 62–86 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 (Ekins et al., 2003; Neumayer, 2010; Polasky et al., 2015). 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 (Fenichel et al., 2016; Keeler 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 location-specific marginal values of capital stocks can help in better evaluating the impact of interventions on overall sustainability.

This work's quantitative estimates of key attributes of components for 2019 show close agreement with estimates from previous studies and reports (Text S2 in Supporting Information S1). However, the challenge in comparing our future projections with other studies is the unavailability of similar projections in existing literature. Our analysis of sustainability impacts of interventions is additionally limited by the assumption that impacts are uniform across time and interventions are implemented independent of each other. Our goal was to use distinct interventions in rice wheat cropping system of Punjab to exemplify varying degrees of change within a system and compare the magnitude of their impacts. Future research can contribute toward developing projections of sustainability impacts that account for temporal aspects of impacts, quantify overlapping impacts in the case of combined interventions, and evaluate realistic ranges for input parameters and uncertainties.

5. 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: "*Ban*" *on residue burning*, "*Residues for power*," "*Happy Seeder use*," and "*Subsidy reform*" aim to improve the existing cropping system through better agricultural practices; while "*Pulses procurement*" by the government 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. We showed that both improving the existing cropping system (through "*Happy Seeder use*") and fundamentally shifting cropping patterns (through "*Pulses procurement*") can lead to wide-ranging and substantial sustainability benefits.

There are some considerations needed in implementing "*Happy Seeder use*" and "*Pulses procurement*" 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 toward 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 Text S3 in Supporting Information S1 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 toward 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 (George & McKay, 2019; Puri, 2017).

In this work, we showed 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, that is, how farmers and consumers interact with agricultural markets. Previous studies have associated crop diversification with a transformative change in the agri-food system including supply chains and markets (Magrini et al., 2016; Meynard et al., 2013). 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 and requiring a shift in consumption patterns, 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 (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 (Hussain, 2020; Krishnamurthy & Chatterjee, 2020; Singh, 2020a). Further work could examine the impacts of agricultural liberalization on the interactions between farmers, markets and institutions, crop diversification, and 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 187 billion USD in human health impacts across India between 2019 and 2029, but simultaneously reduce Punjab farmers' income by 5 billion 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 (B. S. Sidhu et al., 2020; Singh, 2012). Future studies can use the analytical approach developed in this work to examine the distributional impacts of policy interventions.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The code (two R scripts) used to implement the HTE framework within a quantitative model and generate results is accessible at Maji & Selin, 2023a. This includes accompanying data files for the R scripts. Additional details about quantitative model set-up and validation/sensitivity analysis, methodology and equations to evaluate sustainability impacts of interventions, and detailed quantitative results are accessible at Maji & Selin, 2023b.

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