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Unlocking the unsustainable rice-wheat system of Indian Punjab: Assessing alternatives to crop-residue burning from a systems perspective

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ABSTRACT

Crop residue burning in Indian Punjab emits particulate matter with detrimental impacts on health, climate and that threaten agricultural production. Though legal and technological barriers to residue burning exist – and alternatives considered more profitable to farmers – residue burning continues. We review black carbon (BC) emissions from residue burning in Punjab, analyse social-ecological processes driving residue burning, and rice and wheat value-chains. Our aims are to a) understand system feedbacks driving agricultural practices in Punjab; b) identify systemic effects of alternatives to residue burning and c) identify companies and financial actors investing in agricultural production in Punjab. We find feedbacks locking the system into crop residue burning. The Government of India has greatest financial leverage and risk in the current system. Corporate stakeholders have little financial incentive to enact change, but sufficient stakes in the value chains to influence change. Agricultural policy changes are necessary to reduce harmful impacts of current practices, but insufficient to bringing about sustainability. Transformative changes will require crop diversification, circular business models and green financing. Intermediating financial institutions setting sustainability conditions on loans could leverage these changes. Sustainability requires the systems perspective we provide, to reconnect production with demand and with supporting environmental conditions.

1. Introduction

Black Carbon (BC) emissions from crop residue burning in India is a topical example of the classic sustainable human development dilemma: where the reduction of poverty and hunger as come at the cost of environmental sustainability – until the environmental consequences themselves overwhelm efforts to prevent poverty and hunger. This paper presents a systems' approach to understand the ecological, social and economic dynamics that underlie crop residue burning in the Indian state of Punjab. Using a novel combination of methods, we show how these system dynamics intersect with agricultural value chains and we identify where leverage for systemic change exists (sensu Abson et al., 2017), with a particular focus on financial investors.

The central government of India (GoI) enacted several major policy changes in September 2020 to reduce government interventions in the production and trade of the staple grains that underlie crop residue burning (Jakhar, 2020). The intended effects of these acts did not bear out – as the acts were repealed in November 2021, after a year of sometimes violent farmer protests. The intentions and ultimate failure of these acts represents a unique opportunity to explore how policy changes and support for alternatives to residue burning may – or not – pave the way for sustainable and just agricultural systems in Punjab.

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BC is an especially toxic component of the particulate air pollution that causes more than 1 million premature deaths in India each year (India State-Level Disease Burden Initiative Air Pollution Collaborators, 2021; Janssen et al., 2012). Although associated with large uncertainties, the climate warming impact (quantified through radiative forcing) is estimated to be second only to CO_2, with a strong regional impact in high loading regions such as South Asia. Reducing BC emissions (from here-on referred to as BC) is therefore necessary to stabilize the climate system (Ramanathan and Carmichael, 2008). The toxic smog to which BC aerosols contribute causes road accidents and has diverse adverse socio-economic effects, such as school closures (Sarkar et al., 2018).

Given a comparably short atmospheric lifetime ($\sim$ 1 week, compared to >100 years for CO_2), reductions of BC would have almost immediate benefits (Ramanathan and Carmichael, 2008). However, continuous emissions contribute to the formation of Atmospheric Brown Clouds (from here-on brown clouds). Brown clouds influence the Indian summer monsoon (Ramanathan et al., 2005), which is a tipping element (Steffen et al., 2018) – an Earth system phenomenon that could trigger abrupt changes in the climate system, and for which there is a high level of uncertainty (Lenton et al., 2008). Furthermore, South Asia – and specifically the Indo-Gangetic Plains at the foothills of the Himalayas – represent a brown cloud and BC hotspot, where studies highlight the role of BC in driving the retreat of Himalayan glaciers, including potentially jeopardizing continuous fresh water supply of the region (Li et al., 2016; Ramanathan et al., 2007; Ramanathan and Carmichael, 2008). In addition, the complex interplay between brown clouds and the regional climate systems are projected to be detrimental for agricultural crop yields (Ramanathan et al., 2001, 2005).

Crop residue burning (from here-on residue burning), particularly within Punjab and Haryana states, is an important source of the BC that forms the South Asian brown cloud (Bikkina et al., 2019; Gustafsson et al., 2009). During the dry and high-loading winter period, when a lot of residue burning takes place, westerly winds push BC along the Indo-Gangetic Plains, with air quality impacts felt in the megacity Delhi (population > 25 million) (Bikkina et al., 2019; Sarkar et al., 2018). Total annual BC from other sources, like transport and households, are higher than residue burning emissions, but high seasonal emission spikes that stem from agriculture contribute to already high background pollution levels, and have acute effects on health and biosphere.

Residue burning is part of the rice-wheat cropping system central to food grain sufficiency in India, where persisting hunger still leads to the stunting of nearly 40% of children under the age of 5, and undernourishment is close to 15% of the population as a whole (SDSN, 2019). Yet burning is not a traditional, optimal or preferred way of managing agricultural residues, not only because of its impacts on air quality, human health and the environment. Indeed, farmers burn residues largely because groundwater conservation policies reduce the time-frame between harvesting and sowing the next crop (Chakravartty and Nasim, 2015; Gupta, 2019). Crop residue burning is however illegal and potentially subject to fines – though enforcement in Punjab is not strong (Express News Service, 2021). Many benefits are also forgone when residues are burned – such as their use as fodder; construction material; to produce ethanol, or for soil quality and nutrient retention by tilling left-over residues back into the land (Gupta, 2019; Singh and Sidhu, 2014).

Alternatives to residue burning have been proposed, many of which are, theoretically at least, feasible and more profitable than burning (Shyamsundar et al., 2019). Yet, despite time, effort and investments, no alternative has effectively replaced residue burning. This persistence of residue burning in Punjab has multiple likely causes. First, alternatives are often promoted in isolation and rely on changes in farmer behaviour (Government of India, 2018). Yet uptake rates are low as farmers perceive immediate costs and risks of these changes outweigh potential benefits of alternatives to residue burning (Gupta, 2019). Second, most alternatives do not address root causes of residue burning – i.e. the system of policies relating to food security and water conservation that have increasingly constrained and moulded farmer behaviour (Gupta, 2019). For example: support for crop diversification does not outcompete the security provided by the subsidies and ensured procurement that maintain the rice and wheat production system, and novel effective harvesting and sowing machines represent difficult investment and logistical choices given the short time-frame of use. Behavioural studies in Northern India suggest that it is not only the quality of the solution that leads to its uptake, but also the popularity of the alternative – implying the need for a 'critical mass' of farmers using new approaches before new practices are spontaneously taken up. Furthermore, self-interest is more likely to push individual farmers away from herd-behaviour than is an interest in common good: implying that understanding detrimental effects of burning on soil quality is more relevant to trigger change in farmers than information on air-quality impacts for society at large (Lopes et al., 2020; Raza et al., 2019). An understanding of the wider distribution of benefits and risks that changes in agricultural practices can imply – as well as a systems' understanding of the connected drivers of residue burning – could therefore help identify how to leverage change, by whom and for whom, and thus incentivise support for a transition away from residue burning.

Using a novel combination of methods, this paper attempts to deliver such understanding. We start by providing an overview of BC estimates from residue burning in Punjab state. We then review the literature to identify dominant ecological, social and economic dynamics that shape current outcomes of the Punjab rice-wheat system. Using the reviewed literature, we construct a causal loop diagram to outline the system-wide cascading effects of burning and of alternatives to residue burning. Our final analytical steps involve mapping the rice and wheat value chains of Punjab's agricultural system, and identifying the main sources of investment capital associated with these value chains. Financial institutions – currently understudied in relation to their roles in influencing India's agricultural systems – function as intermediaries between actors or companies with (temporary) financial surpluses or deficits and agents looking to take on or to reduce their financial risk profiles. Financial institutions therefore have the potential to tailor their intermediation to cater for social and environmental risks (Scholtens, 2017). This last analytical step allows us to highlight the potential roles of financial actors in promoting alternatives to residue burning and unlocking current dynamics.

We end by discussing the agency of financial actors in relation to the broader sustainability of Punjab's agricultural system, as it relates to i) health – through impacts of BC; ii) to the biosphere – by investigating the role of agriculture on climate, soils, and water; and iii) to equity – by investigating the distribution of risks and benefits, relative to power, in Punjab's agricultural system. Our aim is to provide novel system-based perspectives from which to rethink the design and implementation of more sustainable and just agricultural practices affecting the brown cloud.

1.1. *Background*

Residue burning in India is a well-recognised problem, arising and increasing since the late 1980s (Sarkar et al., 2018). It is the product of different but connected political, economic and environmental factors (Gupta, 2019). To unravel these connected factors, we centre our study on the Indian state of Punjab, which made full use of the policies and infrastructure related to price supports and input subsidies that incentivise the production and sale of key grains, in particular rice and wheat. Dubbed the granary of India, Punjab hosts India's most intensive large-scale agriculture (Grover et al., 2017). Punjab's agricultural landscape is relatively simple yet central to food security in India as a whole: the rice-wheat dual crop system covers at least 80% of the gross cropped area in Punjab (Grover et al., 2017). In 2015–2016, Punjab contributed about 27% of rice and 37% of wheat to the national stock, though the state represents only 1.5% of the country's geographical area (Grover et al., 2017). Punjab produces about 18% of the national residue surpluses, of which 80% are burned in fields (Government of India, 2014).

1.1.1. The complex agricultural policy legacy and landscape in India and Punjab state

For over half-a-century, India has driven a widespread agricultural intensification to ensure food security and self-sufficiency (Grover et al., 2017). Governments at national and state levels have extensively intervened in all aspects of agriculture, including input and output markets, and credit provisioning (OECD/ICRIER, 2018). Punjab was among the first states in India to experience the Green Revolution, by developing intensive rice and wheat cultivation through high-yielding seed varieties, chemical inputs, mechanised harvesting and irrigation (Grover et al., 2017, 2018; Gupta, 2019). In parallel, the Essential Commodities Act (1955) and the Agricultural Produce Marketing Committees Acts enabled output measures that have been central to shaping India's agricultural development in (at least) two ways. Firstly, by restricting the trade of key crops (including rice and wheat) to regulated state-level markets – so-called Agricultural Produce Markets or *Mandis*. *Mandis* aim to enable market access and fair and transparent prices locally to all farmers. *Mandis* collect charges, which contribute to state revenues (Chaba, 2020a; Saini and Kozicka, 2014). Commission agents operate in *Mandis*, providing services enabling farmers to sell produce to procurers and to speedily settle payments (Grover et al., 2017; OECD/ICRIER, 2018). Secondly, the current status of Indian agriculture has been shaped by the Minimum Support Price (MSP) – a price floor applied to many key crops (including rice and wheat). The Food Corporation of India (FCI) enforces MSP by purchasing grains at MSP in *Mandis* (FCI, 2022; Saini and Kozicka, 2014). FCI procurement ensures that market prices for all grain-transactions are no lower than the support price – and thus raises prices of all high-quality grain traded in *Mandis*. The FCI stocks and distributes grain to consumer states as part of the public distribution system, and can also sell it in the open market (Saini and Kozicka, 2014), and thus fulfils its mandate of contributing to food security and self-sufficiency in three ways: 1) ensuring sufficient returns to producers; 2) retaining buffer stocks of essential commodities and 3) keeping prices for certain consumer groups low and generally modulating market prices of these commodities. This complex agricultural policy system has supported the growth of India's agricultural sector and the achievement of food security and self-sufficiency at a national level (Saini and Kozicka, 2014). However, it has essentially decoupled production from demand, and decoupled production and demand drivers from environmental and market forces. The FCI is often described as inefficient in its coordination, reporting and monitoring (OECD/ICRIER, 2018); contributing to waste and poor quality grain (Saini and Kozicka, 2014). Furthermore, in conjunction with the low consumer-end prices supported by the food corporation, these output measures effectively exclude private traders in the market and have nationalized the production of these commodities (OECD/ICRIER, 2018; Saini and Kozicka, 2014).

1.1.2. Residue burning is a response to a problem

The increase in residue burning is closely linked to three agricultural intensification processes: an increase in the amount of residue produced, mechanised harvesting and groundwater use (Grover et al., 2017; Gupta, 2019). Water-intense agriculture in Punjab's semi-arid climate, combined with a state-level flat rate on electricity to pump groundwater for irrigation, has led to inefficient water use and severe ground-water depletion (Singh, 2009), where water demand is nearly double the water recharge (Gupta, 2019; OECD/ICRIER, 2018; Perveen et al., 2012; Srivastava et al., 2015). Water depletion triggered the Punjab Preservation of Subsoil Water Act (2009), which prohibits rice transplantation before a set date in mid-June (at the earliest) to increase the likelihood of it coinciding with monsoon rains. Delayed rice transplantation leads to delayed rice harvest, but the timing of wheat sowing– to which yields are sensitive – remains fixed (Gupta, 2019). This has shortened the time between harvesting the rice and sowing the wheat to about two weeks (Chakravartty and Nasim, 2015; Gupta, 2019). Mechanised harvesting only adds to the time-constraints because the machines used leave root-bound stems on fields that are costly, and time and labour intensive to remove (Chakravartty and Nasim, 2015; Gupta, 2019; Mukerjee, 2016). Burning has thus become the fastest and cheapest way of clearing wheat and rice stubble. Burning happens in April–May after the wheat harvest, and October–November – following rice harvest (Gupta, 2019). The subsoil water act has therefore unintentionally led to more frequent fires and has concentrated residue burning to a narrower window, significantly increasing the emission peaks from crop residue burning (Balwinder-Singh et al., 2019). Additional factors influencing rice-wheat dynamics include reduced availability and incentives for seasonal agricultural workers from different states to manually harvest and prepare the land in Punjab (Gupta, 2019; Mukerjee, 2016).

1.1.3. Changing the Indian agricultural system is a very current problem

The agricultural policy landscape in India involves two levels of government, the national (central) and the state. The central government cannot mandate state governments to follow specific policies that do not directly intersect with national responsibilities. Several policy changes were undertaken by the Central government to reduce the monopoly of *Mandis* and to encourage the entry of private markets. The GoI drafted model acts and recommendations between 2003 and 2017, intended as templates for states to enact their own laws. In June 2020, however, the central government made ordinances building on past efforts in the form of 'three farm acts', and then turned them into laws to support their implementation – despite strong opposition, as these laws are seen as infringing on state rights and responsibilities (DownToEarth, 2021a). These acts included: 1) an amendment of the 1955 Essential Commodities Act so that the central government's power to control production, supply, distribution, etc., of essential commodities could only be awarded in '*…extreme circumstances which may include war, famine, extraordinary price rise and natural calamity of grave nature* '(see GoI, 2020a – section 2). 2) The Farmers' Produce Trade and Commerce (Promotion and Facilitation) Act, 2020 (GoI, 2020b), to allow inter- and intra-state trade to occur freely outside *Mandis*, without government cess or tax. 3) The Farmers (Empowerment and Protection) Agreement on Price Assurance and Farm Services Act, 2020 (GoI, 2020c) to support contract farming schemes creation nationally, and ensure transparency and fairness in trade between farmers and wholesalers, agribusinesses and more.

The legality and implementation of these acts was disputed at state levels, where an opening of markets outside controlled *Mandis* is perceived as a potential loss of revenue for state governments (Chaba, 2020a), and as a risk to farmers that their grain will not be purchased (Jakhar, 2020). These farm acts led to violent and prolonged farmer protests in North western India (Singh et al., 2021). In an unprecedented move, the GoI repealed the three acts just over a year later (November 2021), in response to the protests (Gosh, 2021; DownToEarth, 2021a, 2021b).

This complex and dynamic context of social, economic and environmental dynamics forms the basis of our analysis. The context therefore is a connected social-ecological system, that carries a historical legacy, and shapes processes beyond the state of Punjab. We argue that this connected systems' perspective is necessary to identify the incentives for change, the potential roles of different change makers, and effective means to implement change for a more sustainable and just agricultural system.

2. Methods

The analysis consists of four steps 1) reviewing BC emission inventories; 2) developing a causal loop diagram to understand processes that drive current agricultural dynamics and 3) analysing rice and wheat value chains that relate to Punjab's agricultural system to clarify their segments and actors involved and 4) identifying the financial actors invested in each segment of the value chains to assess their potential leverage in driving changes in agricultural practices away from residue burning. Detailed supporting materials and additional results can be found in supplementary materials 1, 2, and 3.

2.1. BC emissions from residue burning over Punjab

Emission inventories present fluxes from different sources of any gaseous and particulate matter emitted, over space and time. The emission of BC aerosols over a region for a specified time is calculated by aggregating all the sources of fossil-fuel and biomass combustion and their source-specific emission characteristics. BC emissions from residue burning are highly uncertain, reflecting the large variability in emission characteristics and estimations of amounts of fuel (Andreae, 2019).

We analysed five recent, peer-reviewed bottom-up emission inventories from the ECCAD emission inventory repository (https://eccad.aeris-data.fr/, see supplementary material 1 for selection criteria)– built from statistical analyses of agricultural activity data and country specific emission factors – that report BC emissions from the agricultural waste burning sector over India. We extracted the monthly crop residue BC emissions over Punjab from the five inventories and classified (a) April–May emissions as wheat residue burning emissions; (b) October–November emissions as rice residue emissions and (c) rest of the year agricultural waste burning-emissions as other residue burning emissions. Such rice and wheat-specific BC emission classification can be done only for Punjab where the rice-wheat cropping pattern dominates (Crippa et al., 2018; Jethva et al., 2019; Klimont et al., 2017; Ojha et al., 2020; Singh and Kaskaoutis, 2014; Venkataraman et al., 2018; Wang et al., 2014), and where only Kharif (autumn) rice varieties are cultivated (see supplementary material 1 for details).

2.2. System-wide description of the rice-wheat production system in Punjab

We created a causal loop diagram (CLD) to map drivers of residue burning and BC emissions in agricultural systems in Punjab (see supplementary material 2 for details on the methods and results). A CLD is comprised of elements (e.g. BC) connected by arrows, indicating either that an increase in one element leads to an increase in another (positive effect – e.g. increase in crop residue burning causes increase in BC) or that an increase in an element causes a decrease in the other (negative effect – e.g. increase crop residue burning causes decrease in soil quality). We started the diagram by focusing on residue burning leading to emissions, and then progressively built the diagram by searching the literature to specifically understand drivers and consequences from environmental, health and equity perspectives.

Following the effects of change in one element across several others and back to itself represents a feedback analysis. The product obtained by multiplying the positive and negative arrows on any feedback loop, indicate whether it is reinforcing (+ product) or stabilizing (− product). Feedback analyses are key to identifying vicious cycles in process dynamics (i.e. reinforcing feedbacks that drive undesirable outcomes). We identify existing feedbacks, and map how changes to the system might release, reinforce or break these feedback loops (Meadows and Wright, 2008).

We use the CLD to analyse the potential effects of implementation of residue burning alternatives, here defined as practices that lead to outcomes other than residue burning. The literature review served to identify alternatives and to explore how they may or may not alter system dynamics. System dynamics can be altered by, for example, adding or removing connections or elements, or changing the sign or direction of an interaction.

2.3. Analysis of value chains and ownership as a means to identify levers for change

A value chain is the series of activities and processes that companies and workers carry out to turn a resource into a product that can be used or consumed. The activities and processes can be carried out within single companies or across several companies, within a geographical location or across the globe (Gereffi and Fernandez-Stark, 2011). Value chain analyses – uncovering the steps and actors in the value chains – are an important part of bringing transparency to the increasingly globalised trade of commodities and products, which in turn is essential to sustainable production and consumption (Gardner et al., 2019; Mol, 2015).

Complementing the analysis of residue burning alternatives, our value chain analyses allow us to define value chain segments of the Punjab rice and wheat sector and identify the trading actors, as well as their main financiers. This approach rests on the assumption that financial actors, for instance investors with significant stockholding power and financial institutions that broker investments and risks, can influence the practices of a given investee company (Edmans, 2014; Galaz et al., 2018; Scholtens, 2017).

To identify financial actors linked to specific segments of the rice and wheat value chains in India, we used the approach of Galaz et al. (2018), that requires identifying companies involved in the rice and wheat value chains; analysing the ownership data of these companies and identifying stockholders with the power to influence corporate practices. This potential to influence was assessed by 1) looking at those that invest in most companies; 2) looking at those that invest most financial funds and 3) identifying the companies in which shareholders own more than 5% of the shares, and thus have more influence in voting situations (aka "“blockholding” power). It is important to note that absence of certain investors in our analysis does not equate with absence of investment, power or voice, but with lack of data, thus the top ten in each of these rankings represents the top 10 of our sample, given data availability.

To identify relevant companies, we used the Prowess database (https://prowessdx.cmie.com/). The data vintage is December 2019 and we selected all companies listed in the Bombay and National Stock Exchange Supersets. Next, we used the Orbis database (Dijk, 2002), to retrieve data on corporate ownership, for each identified company, when available (the full data analysis is provided in supplementary material 3).

3. Results

We first report estimated BC from crop residue burning in the state of Punjab. We next describe the CLD and system feedbacks that support crop residue burning. We then examine how proposed alternatives might influence the system, show companies and investors involved in the different segments of rice and wheat value chains, and discuss their leverage potential for affecting change based on the identified potential for unlocking entrenched dynamics identified in through the CLD.

3.1. Black carbon emissions from the rice-wheat sector in Punjab

The emission inventories show significant variability in BC estimates from residue burning – ranging between 27Gg to 83Gg annually for the whole of India, and 1.5 Gg to 47.2 Gg for Punjab (Table 1). Uncertainty is not uncommon for emission inventories, and highlights the need for continued research to refine approaches to assess BC emissions from residue burning.

Despite uncertainties, however, we find two striking patterns: In Punjab state, more than half of residue burning events occur in the post-harvest periods – nearly 30% during April & May and 68% during October–November (see Fig. A1) and although wheat is the most productive crop, rice residue burning contributes most to BC emissions, followed by wheat (Fig. 1).

Table 1
List of emission inventories used for studying the BC emissions from the residue burning sector in Punjab. Note that CRB here stands for Crop Residue Burning and is here used interchangeably with to the terms Agricultural Waste Burning (AWB) often referred to in inventories.

Emission inventory	Latest year data availability	Spatial resolution	Extent	Activity data compilation	Monthly gridded data availability	CRB-BC estimates over India (Gg/year)	CRB-BC estimates over Punjab (Gg/year)
ECLIPSE (Klimont et al., 2017)	2015	0.5° x 0.5°	Global	National-level	Yes	46	1.5
EDGAR (Crippa et al., 2018)	2015	0.1° x 0.1°	Global	National-level	Yes	44	2.3
PKU-Fuel (Wang et al., 2014)	2014	0.1° x 0.1°	Global	National-level	Yes	27	3.2
IIT-Bombay (Venkataraman et al., 2018)	2015	0.25° x 0.25°	India	State-level	Yes	83	47.2
(Paliwal et al., 2016)	2011	40 km × 40 km	India	District-level	Yes	64	7.6

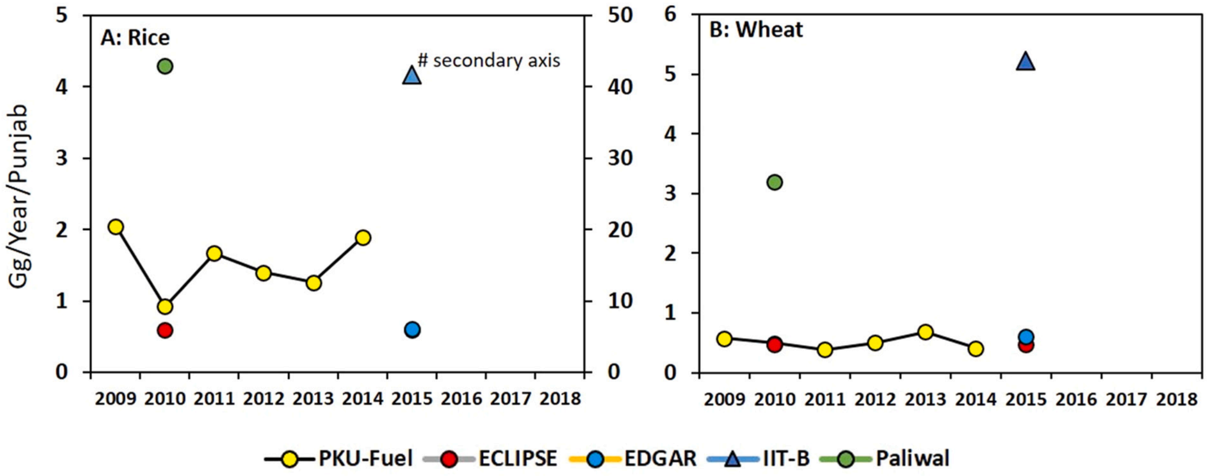

Fig. 1. Annual BC emissions from rice residue burning (A) and wheat residue burning (B). Despite large inventory-specific variabilities (see the vertical axes), the general pattern indicates that burning of rice residues generates more BC emissions than wheat, indicating a general agreement around the relative value of emission factors for these types of residues (see supplementary material 1).

3.2. A system locked into crop-residue burning

Our causal loop diagram represents 37 elements and 76 interactions connected to residue burning in the state of Punjab (Fig. 2, see supplementary material 2 for details).

We identified two types of reinforcing feedbacks that are 'vicious' cycles, in that they lead to increased industrial production and increased residue burning (Figs. 2a and 2b, respectively). The first loop drives the dominance of the rice-wheat system by disincentivizing alternatives and supporting intensification (Fig. 2a, 'Agricultural policy landscape' loop). The second loop represents the effects of the industrial-scale rice-wheat system – from the contributions of emissions to the monsoon variability that, in turn, exacerbates groundwater depletion. This then leads to strict regulation of the timing of rice transplantation, and subsequently to more residue burning and $PM_{2.5}$ /BC emissions, because of short crop-rotation time-frames (Fig. 2b, 'Pressure to burn' loop).

Our analysis shows that the vicious cycle policy loop (Fig. 2a) could potentially have been dampened by the three farm acts (pink arrows), if these had reduced the protection from risk that farmers have when staying in the rice-wheat system, and reduced the risk of diversifying or changing the cropping system. Indeed, if these acts had succeeded and led to establishing alternative cropping systems, the vicious cycle might have been broken by creating new system links and elements. However, in isolation, these acts could also have had negative effects on hunger reduction efforts.

We also identify two types of stabilizing feedbacks that represent the consequences of business as usual and include both environmental and socio-economic degradation feedback loops (Fig. 2c, loops E and S respectively). In the environmental variant, climate-level impacts of emissions negatively affect agriculture, which indirectly leads to reduced burning, for lack of a viable agricultural system. In the socio-economic variant, increased mortality in the long run negatively influences the means to continue driving large-scale mechanised agriculture and forces the system towards more burning until the environmental conditions no longer support agriculture.

The degradation loops (Fig. 2c) are caricatural in that they emphasize catastrophic outcomes because the CLDs do not incorporate processes of social adaptation, evolution or innovation that would certainly take place before human health and mortality impacts put an end to agriculture. Nonetheless, the absence of non-degradation or sustainable stabilizing loops coupled with the presence of vicious cycles that reinforce current dynamics indicate that the system is in a lock-in. Degradation loops illustrate a decoupling of production incentives from economic and environmental consequences of rice and wheat industrial production. Such decoupling represents both a common issue of 'unaccounted environmental externalities' as well as a perhaps an issue more specific to (though not unique to) the policy- and incentive-heavy agricultural landscape in India. Reconnecting production incentives, economic benefits and environmental consequences is therefore key to creating stabilizing, sustainable dynamics in the system.

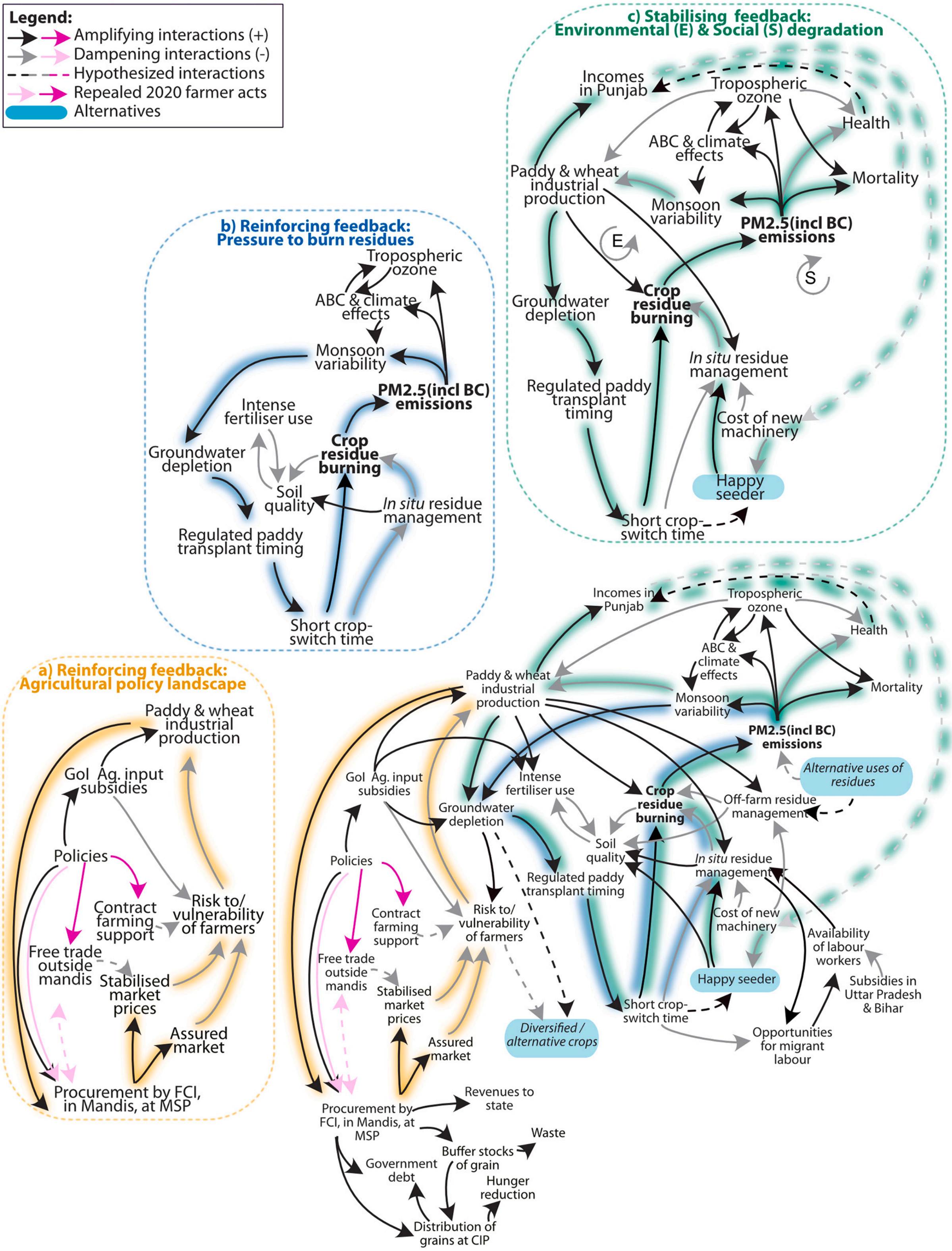

Fig. 2. Causal-Loop diagram of the Punjab rice-wheat cropping system. Panels a-c represent three distinct feedback loops, broken out from the main ausal loop diagram and elaborated further in the text. The full-sized and detailed CLD and references supporting all interactions can be found in supplementary material 2.

3.3. Means of reducing black carbon emissions through residue burning alternatives

Below we outline a set of alternatives to residue burning for which scholarly evidence exists. We return to these when discussing how financial actors can promote change.

3.3.1. Alternative uses or management of residues

Alternatives to residue burning range from on-farm uses of residues, off-farm uses, a mix of off-farm processing and on-farm use to not producing residues at all (Table 2). From a system-dynamic perspective, off-farm uses of residues could reduce or stop residue burning, as they break both the 'Pressure to burn residues' reinforcing loop and the 'degradation' stabilizing loops. This potential is only realised if residues are not subsequently used in ineffective combustion (e.g . biofuel-based indoor lighting, cooking or residential heating), that emits BC. The uptake of off-farm uses of residue alternatives requires both demand for the residues and financial and logistical investments in harvest and post-harvest machinery (Table 2). Though large investments have been made to improve the effectiveness and availability of residue management machinery (for instance the Happy- and Super-seeders) the uptake is low, in part for logistical reasons, in part because of farmer scepticism (Kurinji and Prakash, 2021). To be effective, interventions to increase demand and logistical support need to address the direct driver of residue burning – i.e. the short crop rotation time and/or misconceptions on the effectiveness of harvesting machinery. We find no links connect the source of the problem to creating demand for alternatives (Fig. 2, lack of connections towards '*Alternative uses of residues*'). This indicates that unless residue supply-demand interventions are integrated in current system dynamics, these interventions risk creating parallel processes that at best compete with, but do not necessarily replace, residue burning.

While important for reducing BC emissions, alternative uses of residues cannot in isolation make Punjab's intensive rice-wheat agriculture system sustainable, as they have no apparent effect on long-term water overuse or on the financial (in)viability of Government subsidized procurement, storage and sales. For this, other strategies are needed.

3.3.2. Alternative crops and diversification

Alternative crops to rice and/or wheat could, if chosen appropriately, significantly reduce residue burning and even water use. However, any system that is as specialised as the current one will face similar vulnerabilities to crop failures, demand shocks and price drops, and may therefore not represent a 'solution' that builds resilience into the agricultural system (Gunderson and Holling, 2002). Though crop diversification is often understood as a win-win from environmental and socio-economic perspectives (Chhatre et al., 2016), pathways to crop-diversification in Punjab are not obvious and will involve significant state-funded infrastructure and skill development, to support long-term success and to ensure that the risks of diversification are not borne entirely by the farmers.

Prior efforts at crop diversification, recommended repeatedly for Punjab (e.g. in 1986 and again in 2002), and engaged in sporadically (between 2002 and 2006, and again from 2014) have largely not succeeded for two reasons: 1) returns to alternative crops are lower than the rice-wheat pattern (despite support prices for many alternative crops); 2) the resultant water savings are not monetised, since farmers do not anyway pay for electricity usage (needed for water pumps). Consequently, while diversification is likely societally beneficial in the longer-term, there is no short-term path where the farmers' revenue is not lost (Government of India / Ministry of Agriculture, 2014; Sarkar and Das, 2014; Srivastava et al., 2017).

A sufficient uptake of alternative or diverse cropping systems in Punjab that significantly reduces residue burning will require removing the incentives that currently lock in the rice-wheat system. The 2020 farm acts were insufficient to represent such a shift in incentives, indicating perhaps on the one hand the extent to which the agricultural system is in a lock-in, and on the other hand the importance of distributed agency: in India's democracy, top-down measures that propose significant change – and do not meet local and state level concerns and needs – face strong opposition from beneficiaries in the current system.

Basmati cultivation has been proposed as an alternative to non-basmati to address the issue of residue burning (Kapil, 2019), and we elaborated on it here as an illustration of how residues are managed in the absence of time pressure and entirely under the influence of market forces. Indeed, basmati residues are generally not burned in Punjab state: left over stems are easier to till into the ground because basmati is mostly manually harvested, and its residues make good fodder because basmati has a lower silica content than non-basmati (Kapil, 2019) (thus promoting on-farm uses of residues and reducing the need to address supply-demand dynamics for residues noted above). Nonetheless, a complete shift to basmati cultivation is unlikely to be an effective solution to residue burning because if the same time-constraints for crop shifting remain, and production is scaled up to the current production level of non-basmati, it would likely become prone to residue burning, as is the case in neighbouring Pakistan (Ahmed et al., 2015). Basmati can however represent an example of what might happen to rice and wheat more generally if the agricultural policy and trade landscape in Punjab were to change. As a luxury commodity, basmati is traded freely and is not included under the Essential Commodities Act, and it can therefore serve as a thought model on which to explore leverage points for inserting sustainability criteria, at the nexus of corporate and financial interaction.

3.4. Rice-wheat value chains and the role of financial actors

Our Orbis search yielded data for 125 rice and 55 wheat listed companies. Of these companies, 14 are involved in both sectors, yielding a total of 166 companies analysed, and 1776 unique shareholders identified. Ownership data was available for 133 companies.

We identified 220 prevalent shareholders (i.e. invested in both wheat and rice value chains). Among these, we find that the Government of India (GoI), Dimensional holdings Inc., and Blackrock hold shares in most companies (15, 10 and 7 respectively). However, of these three, only GoI and Blackrock are assumed to be able to influence company governance, through their blockholding power. This power (typically assumed for investors with ownership >5%), is synonymous with the ability to apply 'voice' by voting on company management issues, or by 'exiting' (impacting company share values by selling shares) (Jouffray et al., 2019). Blackrock and Vanguard group Inc. achieve blockholding power if one looks at their cumulative shares across portfolios (see supplementary material 3, c.f. Galaz et al., 2018). Other investors with blockholding power include ICICI bank and an Indian state agency (Table 3, superscripts with a #).

The top 10 prevalent shareholders, each owning shares in at least four companies, together invest in only 25 of the 166 companies (Table 3). Of these 25, the GoI has ownership in 15. Despite uncertainties in the effectiveness of our company search – we identified companies that hold a key role from an investment perspective (as illustrated by the number of superscripts for many companies in Table 3). There is a difference between government shareholding and corporate shareholding in these 25 companies. Only a handful of companies have only private investors (this includes food retail and processing companies, and one Basmati company), while another handful have a mix of state and corporate owners (Table 3).

Our analyses of value chains and investors together show that investors with the potential for influence – by being invested in many companies, or through blockholding power – tend to be associated with companies on the 'edges' of the value chain, through inputs (e.g. fertilizers) or food processing that includes by-products (e.g. gluten) of these value chains. Basmati companies, that are vertically integrated (KRBL, LT Foods, and GRM Overseas ltd.) are an exception here

Table 2

Proposed alternatives to crop residue burning – Note: these are not mutually exclusive and can be interdependent. In beige, direct on-farm uses of residue; in blue, purely off-farm uses of residues; in green, off-farm use and processing of residues that could be followed by / combined with use of residues on farms; in pink, alternatives that imply no residue production. [1]Gupta 2019; [2]Shyamsundar et al. 2019; [3]Mukerjee 2016; [4]Kurinji and Prakash 2021; [5]Sidhu et al. 2015; [6]Singh and Sidhu 2014; [7]Chaba 2020b; [8]Dhillon 2016; [9]Goyal 2019; [10]Stegmann et al. 2020; [11]Chhatre et al. 2016; [12]Grover et al. 2017; [13]Chaba 2015.

Alternative	Barriers	Biosphere and equality effects	Supporting processes needed
In situ residue management	- Short time between harvest and sowing[1, 2.] Reduced availability of migrant workforce to manually harvest and till land[3].	- Improved soil quality - Employment (? – but what quality)	- Time & labour or machinery - Laws / (de-)regulations - Demand for residue - Income from residue sale
Happy & super seeder[4]	- High upfront individual cost - Only used for a brief period each year[5] - Insufficient demand for collected residues - Insufficient number of happy seeders - Does not work when straw is wet with dew[6] – or rain[7]	- Improved soil quality[8, 9] - Economically more profitable than burning because of lower input needs and better yields[2, 8] - Reduced labour dependence and costs to farmers.	- Financial machinery support to cooperatives, not only individual farmers. - Availability of happy seeders at right time - Resolve farmer misconceptions
Using residues for biopower[1, 6]	- Lack of infrastructure and demand to match the supply[1] - If the biofuel is e.g. briquetting, then it is used in furnace or domestic cooking devices, the residues are still being burned inefficiently and thus contributing to BC emissions. - Need mechanization / labour and infrastructure to remove stubble and residue from fields, so that burning is not required. - Residue removed from soil leads to soil impoverishment	- If biofuels replace fossil fuels, this alternative reduces both BC and GHG emissions. - Biofuels could potentially power cold-chain of alternative high-value crops - Biofuels could be used to support irrigation, and reinforce the rice-wheat agricultural production reinforcing loop. - Biofuels could compete with other clean energy developments.	- Financial & logistical machinery support to farmer cooperatives, not only individual farmers. - Connecting biofuel demand and supply – through entrepreneurship and an enabling policy environment. - Circular business models
Crop residues as biochar[6]	- Little research done on biochar for residue use in India - If residues are exported and biochar not returned to soil – could lead to impoverished and eroded soils - Need mechanization / labour and infrastructure to remove stubble and residue from fields, so that burning is not required.	- Residue pyrolysis can produce bioenergy – reducing field burning and use of fossil fuels - Biochar back on fields can improve soils, reduce methane emissions, sequester carbon in soils	- R&D on Innovation in biochar uses in India - Circular production models to ensure biochars are returned to soils. - Financial & logistical machinery support to farmer cooperatives, not only individual farmers
Residue use for material production (e.g. cardboard and paper industries[6])	- Need mechanization / labour and infrastructure to remove stubble and residue from fields, so that burning is not required. - Residue removed from soil leads to soil impoverishment	- Can be a recycling step in biomass use before conversion to biofuel[10]	- Innovation, and startups for different uses of residues - Financial & logistical machinery support to farmer cooperatives, not only individual farmers - Circular business models to ensure material is recycled without emitting BC (or GHGs & aerosols)
Using residues for fodder or manure[6]	- Non-basmati rice has too high a silica content to be used as good fodder[1]. - Need mechanization / labour and infrastructure to remove stubble and residue from fields, so that burning is not required. - Manual collection of residues for composting and use as manure not appreciated by farmers[6]	- Composted rice straw can be better than Farm Yard Manure (FYM)	- Financial & logistical machinery support to farmer cooperatives, not only individual farmers - Innovative business line in residues for fodder & manure
Diversifying crops to non-burning varieties	- Increased risk to farmers as other crops are not subject to MSP and other government support[11]. - Lack of facilities for post-harvest handling of high-value, perishable crops (e.g. fruit & veg). - Punjab lags behind in food-processing value-addition industry[12]. - Vulnerability to international market drops[13]	- Choice of non-water intensive crops would address the water-use issues[11]. - Diversification builds resilience and adaptability to environmental and economic fluctuations at the regional / state level. - Non ECA, high-value commodities could have higher economic potential across the value chain and increased competitiveness on international market	- Infrastructure for processing and transporting of commodities - Policy changes in favour of high-value crops relative to rice-wheat

Table 3

Value chains of rice, wheat and basmati-rice and the companies that top 10 shareholder (superscripts) invest in. 1) GoI; 2) Dimensional Holdings Inc.; 3) Blackrock Inc.; 4) Vanguard Group Inc.; 5) Bank of New York Mellon Corporation; 6) ICICI Bank Ltd.; 7) Fidelity International Ltd.; 8) FMR LLC; 9) Investor Education and Protection Fund Authority; 10)Grasim Industries Ltd. In blue, those companies that only government invests in, in orange those companies that have corporate investors only, in green, those that see investments from government and corporate investors, # Indicates that the shareholder owns more than 5% shares in the company. * Heavily subsidized segments, where companies might have an unstated involvement. Electricity/ power appears to be traded or produced by most companies, whether this energy acts as an input to the rice and wheat value chains is unclear. We find two models of rice-wheat cropping systems and associated value chains: the basmati-wheat system, that dominates in the state districts bordering Pakistan, and the non-basmati-wheat system which represents 80% of the rice cropping area. The Basmati value chain is highly vertically integrated, with companies operating from farm-gate to export. NOTES: a) this analysis *does not indicate* what portion of each segment or sector is represented by the companies (as noted above) – i.e. the relative importance of each company to each segment / to the sector. b) we assume that companies that declare working with rice or rice and derived products include basmati as well as non-basmati, but that companies that only name basmati do not work in the non-basmati value chain. c) The role of different companies in the value chains is inferred from descriptions on Orbis and when possible, on a company website.

<table>
<tr><th colspan="2" rowspan="2">Value chain segment</th><th colspan="7">Sector</th></tr>
<tr><th>Other</th><th>Rice</th><th>Wheat</th><th colspan="4">Basmati</th></tr>
<tr><td colspan="2" rowspan="2">Producers</td><td colspan="7">Prag agro (1; 2; 3; 4; 5; 6; 7; 8)</td></tr>
<tr><td colspan="7">Pavan Poplar Ltd (1; 2; 3; 4; 5; 6; 7; 8)</td></tr>
<tr><td rowspan="6">Inputs</td><td>Electricity*</td><td></td><td></td><td></td><td colspan="4"></td></tr>
<tr><td rowspan="2">Fertiliser</td><td colspan="7">MMTC Ltd (1)</td></tr>
<tr><td colspan="7">Andhra sugars Ltd (2)</td></tr>
<tr><td>Irrigation*</td><td></td><td></td><td></td><td colspan="4" rowspan="3"></td></tr>
<tr><td>Pesticides</td><td colspan="3">Hindustan Unilever (2; 3; 4; 5; 7; 8)</td></tr>
<tr><td>Seeds*</td><td></td><td></td><td></td></tr>
<tr><td rowspan="3"></td><td rowspan="3">Machinery</td><td colspan="7">ADM Agro Kota &Akola Pvt. Ltd. (2; 3#; 4#; 5; 7; 8)</td></tr>
<tr><td colspan="7">MMTC Ltd (1)</td></tr>
<tr><td colspan="7">Monnet Industries Ltd. (1)</td></tr>
<tr><td colspan="2">Procurement</td><td></td><td></td><td rowspan="3">Naga Ltd. (1)</td><td rowspan="6">KRBL Ltd. (1; 2; 3; 4; 5; 9)</td><td rowspan="6">LT Foods Ltd. (2; 3#)</td><td rowspan="6">Chaman Lal Setia Exports Ltd (9#)</td><td rowspan="6">GRM Overseas Ltd. (9)</td></tr>
<tr><td colspan="2" rowspan="2">Milling / processing</td><td colspan="2">Oil Palm India Ltd. (1#)</td></tr>
<tr><td colspan="2">Graintec India Ltd. (6#)</td></tr>
<tr><td colspan="2" rowspan="2">Packaging</td><td colspan="3">Essel Propack Ltd (1; 2; 10)</td></tr>
<tr><td colspan="3">Neo Corp Int. Ltd (1)</td></tr>
<tr><td colspan="2" rowspan="2">Export / Trade</td><td colspan="2">Anik Industries Ltd. (9)</td><td></td></tr>
<tr><td colspan="7">MMTC Ltd (1)</td></tr>
<tr><td colspan="2">Wholesale</td><td></td><td></td><td></td><td colspan="4"></td></tr>
<tr><td colspan="2" rowspan="8">Byproduct in other-value chains / Further processing into different commodities</td><td colspan="7">Avanti Feeds Ltd. (1; 2; 3; 4; 9; 10)</td></tr>
<tr><td colspan="7">KSE Ltd. (9)</td></tr>
<tr><td colspan="2">Prakash solvent extraction Ltd. (1#)</td><td></td><td colspan="4">Prakash solvent extraction Ltd. (1#)</td></tr>
<tr><td colspan="7">Gujarat Ambuja exports Ltd. (2; 9)</td></tr>
<tr><td colspan="7">Hindustan Unilever (2; 3; 4; 5; 7; 8)</td></tr>
<tr><td colspan="7">Oswall Agro Mills Ltd. (1)</td></tr>
<tr><td colspan="7">Rasoi Ltd. (1)</td></tr>
<tr><td colspan="7">Coromandel Agro products and Oils Ltd. (1#; 6#)</td></tr>
</table>

(Table 3). We find little information on investments in milling and storage of non-basmati and wheat and assume that this is because most local or specialised rice and wheat milling companies are privately owned and not publicly listed, and/or because rice and wheat milling is also the task of companies involved in food processing more generally, but is not captured in the description of company revenue streams.

While our value chain analysis does not include the consumer end, it is worth noting that destinations of the commodities examined differ for each commodity. Punjab exports 60% of its non-basmati rice production to other states, but only 17% of its wheat production (Government of India/MoSPI, 2018– data from 2015 to 2016). Only 6–7% of national rice and wheat production is exported internationally – which is nonetheless a significant quantity, since India is the world's largest exporter of rice (Simoes and Hidalgo, 2011) – while 90% of national basmati production is exported internationally (Government of India/MoSPI, 2018 data from 2013 to 2014).

4. Discussion

The current agricultural production system in Punjab is unsustainable, and through social and environmental feedbacks it threatens the viability of agricultural activities in Punjab (Sharma et al., 2018). This is exemplified by the issue of residue burning and BC emissions. We provide a transdisciplinary perspective of Punjab's rice-wheat agricultural systems, connecting environmental, policy and financial aspects that shape and are shaped by crop residue burning. Our findings support the idea that sustainability transitions require focusing not on individuals and their unsustainable practices (such as farmers), but on the systems within which individuals operate, so as to enable and support sustainable and just practices that align the production of commodities with demand, and with the availability of resources and conditions to sustain such production.

Four key findings emerged from our study. First, addressing burning of rice and wheat residues in Punjab is an effective means to reduce BC and other toxic emissions that have health & environmental impacts at local, regional and global levels. Second, the presence of undesirable reinforcing feedback loops and the absence of non-degradation stabilizing loops in Punjab's agricultural social-ecological system locks producers into current residue management practices. Current input and output support measures render residue burning the most profitable option for farmers in the short-run, disincentivising changes towards more sustainable agricultural practices by ensuring that farmers bear the entire risk involved in changes. Third, leveraging change away from residue burning and towards a more sustainable agriculture in Punjab would require a combination of multiple proposed alternatives. Alternatives that include investing in supporting structures; promoting a diversified economy (where demand rather than policy drives production), and integrating novel investments into system dynamics by ensuring they address or resolve the key driver of residue burning (e.g. the short time-frame available to switch crops). Fourth, our analysis indicates where leverage exists for the financial sector to support these changes. The government of India has the greatest potential for reducing the harm of current practices, by virtue of being the single largest investor in Punjab's rice and wheat value chains. Other powerful investors, such as Blackrock and Vanguard Inc. also have an opportunity to lead the way in driving for sustainability standards at low risks and impact to themselves.

In light of these findings, we discuss the incentives that different actors in the agricultural system have for change, and then elaborate on how different alternatives to residue burning leveraged by different actors could contribute to unlocking the current unsustainable system of residue burning.

4.1. Who can drive change: why and how?

The unsustainability of current agricultural production poses risks to the people and governments of Punjab and India as well as to companies and shareholders that are invested in rice or wheat value chains in India. These risks ought to be an incentive to make the agricultural system of Punjab more sustainable.

The government of India has the strongest incentives to change the system – not only because of the financially material risks it is exposed to through its ownership in the agricultural sector – but also through the high costs of maintaining the inefficient system of procurement and distribution of the Food Corporation of India. State governments, however, including Punjab – are reluctant to shift away from this system, which benefits them through GoI support and via revenues from *Mandis*, and underpins the entire rural economy in many states. The three farm acts' failure has illustrated that the GoI's political leverage to change the agricultural system of Punjab is limited – but the GoI has yet to realise its 'financial' regulatory leverage. The acts' cancellation also highlighted strong state-level political power, where incentives for change are yet to be defined, but would potentially be shaped by the opportunities available to and taken by farmers, entrepreneurs and those who invest in change. Importantly, India made dramatic pledges at the 2021 United Nations' 26th Climate Conference of the Parties in Glasgow. We here make explicit the tight connections between crop residue burning and climate impacts, and thus emphasize how climate mitigation is a relevant incentive for changing practices in Punjab's agricultural sector, and how residues as sources of energy can – if used appropriately – support the effective phasing out of fossil fuels.

As we show, corporate businesses and most corporate financiers in the rice-wheat sector of Punjab traced here have low direct exposure to the risks of unsustainability, because of their diverse revenue streams and investment portfolios. With such low risk-exposure comes a lack of incentives to invest time and resources for pushing for sustainable change. However, businesses and investors alike are increasingly exposed to reputational risks of being associated with unsustainable practices (Jung et al., 2018). There are therefore emerging incentives to act, and our findings indicate that corporate actors can be leaders in the necessary sustainability transformations at low risks to themselves, given the diverse revenue streams and investment portfolios.

Where incentives and political will exist, change can be levered by 'green' as well as conventional financial institutions, such as banks, stock exchanges, pension funds and more. Indeed, because financial institutions help organizations achieve production, they too are instrumental in the production of economic goods and their negative externalities (or economic 'bads') (Kitzmueller and Shimshack, 2012). Green institutions explicitly aim at fair and sustainable economic systems, but their influence is too limited to achieve the required transformation on their own (Sinha et al., 2020). Their efforts must therefore be complemented by conventional financial institutions that are mediators between companies seeking financing and risk management, and entities that have surplus funds and seeking to leverage risks (Scholtens, 2006, 2017). These institutions can condition investments by stipulating criteria designed to promote or steer practices of investee companies in directions deemed relevant for reducing various material risks (Galaz et al., 2018; Jouffray et al., 2019) – some of which are outlined in this paper.

Our value chain analyses suggest that the most immediately relevant financial institutions are India's national banks, who could place sustainability conditions on the loans to the food corporation; and the (Bombay) stock-exchange, that could add requirements for disclosure of emissions and sustainability performance on listed companies. Foreign institutional investors could also screen investments and exclude companies that do not comply with certified sustainability standards, or emerging indicators of sustainable practices (Jouffray et al., 2019).

Financial supervisors also have potential agency to affect systemic change by requiring disclosure on company extra-financials (Batten et al., 2017; Kedward et al., 2020). Furthermore, bi- and multi-lateral development finance institutions can directly co-finance domestic agencies and influence microfinancing institutions to shape criteria of microfinancing schemes for farmers, thus supporting sustainable practices.

4.2. What changes can be enacted, and where?

Unlocking the unsustainable dynamics of Punjab's agricultural system will require the dual strategy of 'doing less harm' by curbing unsustainable practices, such as reducing BC emissions, and 'doing good', by promoting and implementing solutions that help create novel and sustainable system feedbacks – where residue burning is no longer a choice.

4.2.1. Doing less harm

Reducing harm implies addressing root causes of unsustainability, such as policies and incentives that drive or support residue burning in the first place. In Punjab, root causes of residue burning include quick-fix policy responses to more systemic aspects of unsustainability, such as the mismatch of growing water intensive crops in a semi-arid environment. As the consequences of this systemic unsustainability increasingly manifest themselves in environmental and health impacts, quick-fix policies (e.g. Earn Money on Saving Water scheme (Sandu, 2018); or financial incentives to not burn (Press Trust of India, 2020)) – that do not address the root causes and potentially reinforce unsustainable practices – risk multiplying. Reducing harm will therefore entail a broader change to the policy matrix and – as the 2020 farm acts cancellation indicates – such changes in the policy matrix requires engaging actors at local and state levels, to support sustainable practices while protecting farmers from income loss and high risks. Protecting farmers from risks, losses and costs, while informing on the benefits to them of alternatives would also support necessary behavioural changes at the farmer level (Lopes et al., 2020; Raza et al., 2019).

By adhering to sustainability criteria to reduce burning and other unsustainable practices when engaging in various active ownership strategies (Sjöström, 2020) and proxy voting (Edmans, 2014), stockholders can actively contribute to shifting practices in the rice and wheat value chains. Finally, greater focus and effort could be placed by equity investors on mapping sectoral impact on multiple SDGs (van Zanten and van Tulder, 2020). The causal loop diagrams provided in this paper offer the ideal basis for such analysis by interested investors.

4.2.2. *Doing good*

Using 'causal loop' language, investments in innovations of products and processes are an important way of introducing new links and system components. Our analysis has identified a number of possible ways to break self-reinforcing feedbacks, and helps provide the conditions for alternative (non-degrading) stabilizing feedbacks to become established.

Circular business models – where waste from one value chain or process is input to another (see for instance alternative uses of residues, Table 2) – can support producing novel processes and dynamics in a system (Raworth, 2017). Opportunities to introduce or support circular business models exist for a variety of actors in the rice wheat value chains. The GoI, for instance, has recently built agreements with companies to produce biofuels, in line with national policy (Gupta, 2019; OECD/ICRIER, 2018). Companies in which government agencies hold shares highlighted in this analysis – such as Anik Industries and Gujarat Ambuja Exports – are also involved in biopower production. However, the degree of circularity of their business models is not clear – i.e. where the biofuels are sourced, or what biomass they are from.

Green microfinancing could provide incentives for farmers or farm-gate entrepreneurs to create or support residue removal and different uses of residues with the aim of making agriculture sustainable (Huybrechs et al., 2019). Similarly, these are interesting avenues for business angels or impact investments that target innovations and entrepreneurial efforts to make alternative use of crop residues (e.g. http://www.kriyalabs.co.in/); provide agricultural support for residue clearing (e.g. http://www.em3agri.com/), connect providers and users of residues (http://reneyou.in/) or develop machinery deployment schemes for farmers or processors of residues. Circularising business models and engaging novel entrepreneurs and funders with sustainability agendas could constitute the 'low hanging fruit' – first steps of a sustainability transition, as the barriers to such system interventions are fewer, it is more a question of building opportunity and scaling existing initiatives.

Diversifying the agricultural system also has potential to remove residue burning from agriculture and could be transformative. However, with this transformative potential also comes a lot of uncertainty and risk for unpredictable or even unwanted cascading effects, for instance on food security. A relevant example is basmati production, which, at first glance, is a straightforward replacement of non-basmati rice that does not lead to residue burning. However, basmati suffers from two drawbacks. On the one hand, it is too similar to non-basmati – in that it is a water-intensive crop, and should it become cultivated at large scale, it would probably also be subjected to burning. On the other hand, basmati is a cash-crop – luxury commodity that is nearly exclusively exported and does not contribute to national food security. To ensure that changes in the cropping system do not lead to more or differently unsustainable outcomes, it is important to a) identify the multi-dimensional, system-wide roles of different crops; b) mitigate negative impacts through true diversification; c) meet and understand the demand for different commodities, and d) provide the necessary infrastructure for storage, processing and transport.

While we focus our analysis on the State of Punjab, it is important to remember it is an important producer, but not consumer of rice and wheat. For Punjab, the lock-in is driven by the state's dependence on procurement, not production. Diversifying crops in Punjab, and addressing the demand for other crops within Punjab and India can be done hand in hand with shifting sustainable rice and wheat production to states with better suited climates, and closer to demand.

4.3. *Conclusions*

Through a systems perspective we highlight how the problem of residue burning is not farmers, but the combinations of regulations, constraints and needs that farmers who burn their fields are responding to. When addressing these problems, it is essential to not further constrain, and instead enable farmers at the heart of wheat and rice production for India. India's agricultural system has been designed to support the most vulnerable – protecting producers and consumers from market volatility (OECD/ICRIER, 2018). Though it does not fully achieve poverty and hunger eradication, the agricultural system successfully provides food and employment for millions of people (Grover et al., 2017; OECD/ICRIER, 2018). It is therefore crucial that the breaking of current unsustainable practices is done in concert with steps that empower and ensure resource provision by and for those that depend the most on current system dynamics. By identifying actors in the value chains of rice and wheat, we flag who has the power to make changes. Such power comes from benefitting – oftentimes disproportionately – from existing system dynamics. Herein can lie a dilemma: incentives for change do not always align with the power to change (Hamann et al., 2018). Creating different incentives targeted at power-holders – such as leadership opportunities for instance – does not necessarily lead to altering the power imbalances (Huybrechs et al., 2019) and to more equitable benefit distribution, and may therefore fail to fully support the achievement of poverty and hunger eradication. Added accountability – for instance through transparency of reporting, and accounting for not only financial but also resource flows and environmental impacts – might be a mechanism by which unsustainability is made even more obvious, supporting momentum for change and ensuring that transformations can have more equitable and sustainable outcomes. Supporting farmers and fostering opportunities for entrepreneurs to innovate and create new – sustainable – pathways in the system and value chains could also support more equitable outcomes of change.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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