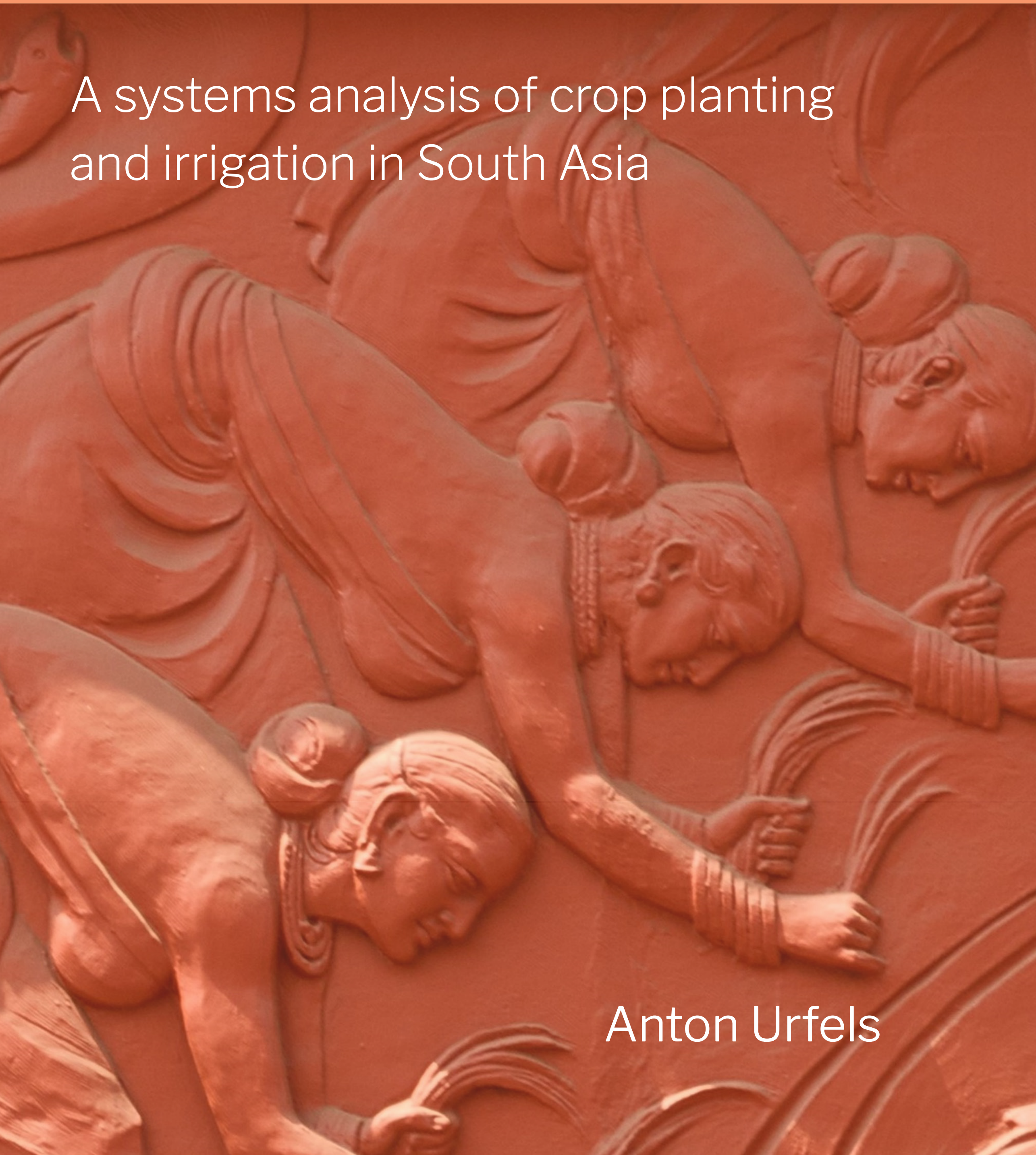
Managing water and time:



A systems analysis of crop planting and irrigation in South Asia

Anton Urfels

Propositions

1. Irrigation is no silver bullet for tackling water scarcity and climatic variability. (this thesis)
2. The rice-wheat systems' capacity to contribute to food security and poverty reduction is severely constrained by its social-ecological variability across space and time. (this thesis)
3. Computational science generates novel insights into complex systems but relies on field data, tacit knowledge and lived experience for its societal impact.
4. Sustainable agricultural research requires continuous dialogues based on equality between farmers and scientists.
5. The histories and evolution of rural economies and landscapes are an underappreciated source of insight for sustainable agriculture.
6. The future of society largely depends on the future of the countryside.
7. World citizenship is more important than technology for addressing global issues.

Propositions belonging to the thesis, entitled

Managing water and time: a systems analysis of crop planting and irrigation in South Asia

Anton Urfels

Wageningen, 2 November 2021

Managing water and time: a systems analysis of crop planting and irrigation in South Asia

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Managing water and time: a systems analysis of crop planting and irrigation in South Asia

Anton Urfels

Thesis

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at Wageningen University
by the authority of the Rector Magnificus,
Prof. Dr A.P.J. Mol,
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List of abbreviations

$PPP	Purchasing Power Parity dollars
APSIM	Agricultural Production Systems sIMulator
BMGF	Bill and Melinda Gates Foundation
CACP	Cost of Cultivation Report
CART	Classification And Regression Tree
CBS	Central Bureau of Statistics of Nepal
CCAFS	CGIAR Research Program on Climate Change, Agriculture, and Food Security
CGIAR	Consultative Group of Agricultural Research Centres
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station Data
CIMMYT	International Maize and Wheat Improvement Center
CSISA	The Cereal Systems Initiative for South Asia
CSRD	Climate Services for Resilient Development
DAP	Diammonium phosphate
ECMWF	European Centre for Medium-Range Weather
EGP	Eastern Gangetic Plains
ENSO	El Nino Southern Oscillation
ET	Evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
FG	Farm gate price
GAM	Generalized Additive Model
GECROS	Genotype-by-Environment interaction on CROp growth Simulator

GIMMS	Global Inventory Modelling and Mapping Studies
GSDE	Global Soil Dataset for use in Earth System Models
HDI	Human Development Index
HP	Horsepower
IBI	Intensification Benefit Index
ICAR	Indian Council of Agricultural Research
ICRAF	World Agroforestry
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IGP	Indo-Gangetic Plains
INR	Indian Rupee
IWMI	International Water Management Institute
KVK	Krishi Vigyan Kendra
MNRE	Union Ministry of New and Renewable Energy
MODIS	Moderate Resolution Imaging Spectroradiometer
MOL	Ministry of Labour, Employment and Social Security of Nepal
MSP	Minimum Support Price
NASC	National Agricultural Sciences Complex of India
NY	New York
PDI	Personal daily incomes
PM-KUSUM	Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyaan
pSIMS	Parallel System for Integrating Impact Models and Sectors
PV	Photovoltaic
SD	Standard Deviation
SDG	Sustainable Development Goals

SENSE	Graduate School for Socio-Economic and Natural Sciences of the Environment
SES	Social-ecological system
SPI	Standardized Precipitation Index
USA	United States of America
USAID	United States Agency for International Development
USD	US Dollar

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Abstract

Progressively erratic monsoon patterns threaten the ability of the rice-wheat system in South Asia's Eastern Gangetic Plains to provide food and livelihoods for their food insecure and impoverished people. Ongoing research has identified early crop planting and improved irrigation use as key entry-points to overcome these challenges. However, there are critical knowledge gaps on the complex feedback mechanisms of these activities resulting in their low and incomplete adoption. These feedback mechanisms comprise of intertwined factors beyond classic water challenges in the rice-wheat system, including temperature rise, pest and disease pressure, value chains, and policy discrepancies between household and national scales. This thesis investigates and evaluates farmers' planting and irrigation activities in the rice-wheat system through a socio-ecological systems framework to fill the knowledge gaps – thus identifying constraints and opportunities to overcome water-related challenges for food security and poverty reduction. Empirical data on farmers' perspectives of planting and irrigation activities were collected and analysed – indicating that farmers and policymakers alike aim to synchronize crop planting with the monsoon onset, but that irrigation use at planting and during in-season dry spells is frequently delayed by uncertainty in weather signals, groundwater availability and availability of other inputs. Simulated crop yield patterns were then used to indicate the potential of synchronizing rice planting with the monsoon onset and fully utilizing irrigation to buffer against drought to contribute to food security. The results suggest that this strategy may indeed increase productivity and resilience in the Eastern Gangetic Plains – but not in the Western Gangetic Plains. However, an analysis of large-scale household survey data on crop production indicate that the poverty reduction potential of productivity increases is limited to the largest farmers, while most farmers need to rely on additional income streams for significantly boosting their incomes. This is followed by a concluding reflection on rice-wheat system contribution to sustainable development, building a framework for managing water and managing time in agroecological systems, and the merits, challenges, and current potential of interdisciplinary mixed methods approaches to tackle complex issues in sustainable agriculture. Lastly, this thesis discusses the implication for irrigation development and management, resilience to climate change and adaptation pathways, the role of the monsoons for sustainable agriculture, and future potential for better targeting of interventions and policies.

Keywords: social-ecological system; rice *(Oryza sativa)*; wheat *(Triticum aestivum)*; smallholder farmers; South Asia; Indo-Gangetic Plains; water management; sustainable intensification; climate change; big data; computational science; participatory research; mixed methods; crop modelling; sustainability science; irrigation; sowing dates; poverty reduction; food security

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Chapter 1

General introduction

Hunger, poverty, and sustainable agriculture in an era of big data and digital innovation

Global hunger and food insecurity are on the rise for more than five consecutive years, thwarting the progress that has been made over the last decades. Efforts to meet the Sustainable Development Goals (SDGs) in 2030 are off-track (FAO et al., 2021). Food systems play a key role in the effort to put the SDGs back on track and to meet the grand challenges of the current decade (2020-2030) as articulated by the Global Food Summit convened in summer 2021 by United Nations Secretary-General António Guterres. The complexities of sustainable agricultural development during an intensifying climate crisis (Ortiz-Bobea et al., 2021) requires a food systems perspective that can capture the intersecting dynamics of ongoing social and ecological global change processes and develop new ways of thinking and action in food systems. With the impact of climate change materializing through changes in the water cycle and temperature regimes, understanding how these climatic factors impact crop management decisions constitutes an essential bedrock for delivering progress in sustainable food production. Advancing the knowledge base around climate related crop management decisions, their limits, and their implications for building context-specific and targeted interventions constitute a new research frontier whose advancement is instrumental for delivering progress towards food security, poverty reduction and several other SDGs by 2030.

At the same time, increasing amounts of data collection in the form of surveys, earth observation and simulation model outputs (big data) provide opportunities for making significant gains in developing a contextualized understanding of agricultural system dynamics at the landscape level. This big and spatial data promises to enable the development of spatially bounded interventions and policies that are targeted to specific household types, even in areas that have been and continue to be relatively data scarce. But new opportunities also pose new challenges. Using data without an in-depth understanding of local context and deploying models outside of the context they have been developed in bears significant risks. For example, relying on big data alone may lead to increased misinterpretation of the signal in the data and may result in trespassing the often already difficult to assess inference space of the data and models. These limitations hold true for both analytics and predictions alike. Concurrently, the increasing inter-connectedness between human activity and the environment challenges a conceptual separation between the two and cannot be upheld anymore (Biermann, 2021). Integrating the human and environmental aspects and building on conceptual efforts in natural resources management is required (Ostrom, 2009a). Locally relevant and adequate-for-purpose (Parker, 2020) conceptualization of the social and ecological dynamics of agricultural systems, and methodologies to study them, present itself as a challenging but crucial aspect for tackling global food security challenges. Subsequently, conceptual, and methodological developments to deploy data and models to answer questions about food security need to be grounded in empirical data at the field level and through community engagement. The development of such novel and integrated research approaches constitutes a promising area for the scientific advancement.

South Asia is experiencing some of the strongest impacts of climate change while it is also among the most vulnerable regions across the globe. High levels of poverty and food insecurity prevail, especially in the Eastern parts of the Indo-Gangetic Plains (IGP) – the region's breadbasket. Agriculture (and arguably most of human activity) in the Eastern Gangetic Plains (EGP) is dominated by the monsoon, which provides more than 80% of annual rainfall in just the four months from June to September (Figure 1.1). On average, the rainfall amounts to more than 1 m of precipitation but can fluctuate strongly to more than 40% above and below the average. The vagaries of the monsoon have long been studied and most climate scientists agree that overall monsoon rainfall is increasing (Jin & Wang, 2017; Katzenberger et al., 2021). However, it is the monsoon's increasingly erratic nature that poses challenges to the agricultural systems, causing widespread flooding and drought conditions in close spatial-temporal proximity.

In the Indo-Gangetic Plains, rice is cultivated by more than 90% of farmers during the monsoon season and mostly followed by wheat as a second crop that is grown during the mild winter months between October and March (see Figure 1.1). Crop yields for both rice and wheat in the EGP remain relatively low at around 2-3 t/ha as compared with 5-7 t/ha for both crops in the Western Gangetic Plains. Sustainably intensifying – i.e. raising agricultural production without comprising the environment (Struik & Kuyper, 2017) – the rice-wheat system in the EGP to provide high and stable yields is therefore regarded as a centrepiece of development pathways in the region (Kishore, 2013; Mellor, 2017).

Ongoing research has identified two critical activities to sustainably intensify the rice-wheat system of the EGP and cope with climatic variability: (i) timely crop planting and (ii) improving the use of irrigation (Keil et al., 2017; Kishore et al., 2014). But adoption of improved planting and irrigation practices remains incomplete despite sustained promotion, suggesting that key system dynamics and adoption factors remain unknown and constitute a critical knowledge gap. What is known (Figure 1.1), is that the cropping season in the EGP starts with the challenge of aligning the following activities with the increasingly erratic monsoon onset: rice nursery establishment, water intensive puddling operations, and labour-intensive transplanting of rice nurseries. Delayed rice planting not only leads to a late rice crop, but also complicate wheat cultivation by increasingly exposing wheat to high summer temperatures that cause large production losses (due to terminal heat stress). Similarly, more frequent monsoon breaks, and less reliable winter precipitation events further challenge crop production (Balwinder et al., 2015).

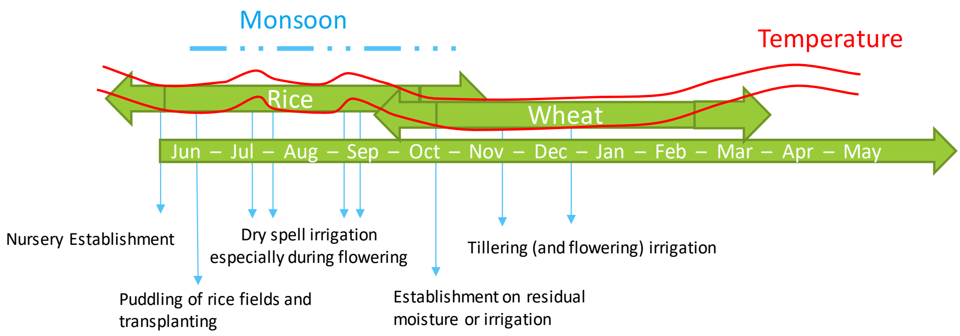

Figure 1.1 Conceptualization of the rice-wheat system including key events and patterns of interaction with the water cycle and temperature regimes.

To understand how farmers can cope with such challenges requires multifaceted analysis of the following factors:

1. High summer temperature exposes the wheat crop to terminal heat stress, making farmers less flexible to adjust the rice planting to meet the water challenges (Mondal et al., 2013);
2. Inadequate input availability may constrain the management decisions (Bai and Tao, 2017), which is further challenged by pest and disease pressure dynamics along with temporary flooding;
3. Policy goals at the national level may be at odds with household level goals on food self-sufficiency, management incentives, and livelihoods strategies (Struik & Kuyper, 2017).

This thesis contributes to resolving the above challenges through the use of a social-ecological systems framework to investigate the rice-wheat system and gain better insights into critical decision-making processes and social-ecological constraints for timely rice crop planting and irrigation activities. The social-ecological perspective handles the complexity of the rice-wheat system by disentangling the landscape into a set of sub-systems with a focus on the farming system. This approach allows to clearly delineate and study the interdependencies within the agro-ecological landscape. Another strong point of adopting a social-ecological systems perspective is that it allows the integration of qualitative and quantitative insights from several disciplines. This is critical as the different aspects of rice-wheat system dynamics require differing methods of inquiry but also benefit from integration. For instance, the social-ecological approach provides an intuitive platform to integrate the study of farmers' behaviour with crop modelling exercises (Arneth et al., 2014; Gregory et al., 2005). As a result, this study seeks to inform evidence-based policy making and the results of this study have been continuously fed into the Consultative Group of Agricultural Research Centres' (CGIAR) ongoing cereal systems work in South Asia and builds on CIMMYT's close relationship with the Nepal and Indian governments, national agricultural research systems, donor agencies, farmers, value chain actors, and other stakeholders to disseminate findings and translate them into actionable and impactful insights for both the public and private sector.

Objective and main research question

The overall objective of this PhD project is to produce knowledge that can assist farmers and policy makers in adequately managing water and time for sustainable agriculture in the Eastern Gangetic Plains. Based on this objective, the overarching research question follows as:

"How can water and time be managed successfully to sustainably intensify the rice-wheat system in the Eastern Gangetic Plains?"

Chapter 1

Theoretical framework: complex social-ecological systems and sustainable agriculture

In 1948, Warren Weaver was a director of the natural science department of the Rockefeller Foundation where he oversaw, among others, the establishment and funding of international agricultural research centres in Mexico and the Philippines that were key to launching the Green Revolution and later became core to the CGIAR. Pondering on the purpose and goals of science he wrote:

"[T]he future of the world […] requires science [...] over the next 50 years, [to] learn to deal with […] problems […] which involve dealing simultaneously with a sizable number of factors which are interrelated into an organic whole." (Weaver, 1948)

Weaver called this domain "problems of organized complexity" and his vision was that of an interdisciplinary scientific enterprise where researchers from all fields including natural science, life sciences and social sciences work together to tackle problems such as hunger, disease, prosperity, and peace. And Weaver suspected that very large computers would be critical to this enterprise. Shortly after and following a scholarship of the Rockefeller Foundation, Ludwig von Bertalanffy published his "An outline of general system theory" (Bertalanffy, 1950), setting the stage for the influential works on general systems theory in which Bertalanffy built on and aimed to provide a unifying framework for the work of many contemporaries dedicated to solving complex problems as Weaver described them. These ideas were subsequently further developed and introduced into several disciplines including agriculture and crop sciences (Yin & Struik, 2010) – although disagreements on some fundamental notions remain alive, such as discussions about the level of system predictability along the emergentist-reductionist spectrum (Gillett, 2016). While agricultural scientists expanded to embed their successful crop growth modelling approaches within a social context (De Wit et al., 1988), the concepts of social-ecological systems and their resilience that were popularized by Carl Folke, Elinor Ostrom and others (Folke et al., 2005; McGinnis & Ostrom, 2014), have arguably been more successful in bridging the human-nature divide (Colding & Barthel, 2019). However, as the social-ecological systems ideas entered the global discourse on sustainable development (Steffen et al., 2015), its core applications remained within the realm of natural resources management with the goal of finding "ways to match the dynamics of institutions with the dynamics of ecosystems for mutual social-ecological resilience and improved performance (Colding & Barthel, 2019)."

At the same time, sustainable agriculture had its own debate as the social-ecological systems work went underway. With global population growth projected to stabilize at 10.9 billion, almost 2 billion people moderately food insecure, and agriculture being a major contributor to climate change and environmental degradation – several scholars called for the sustainable intensification of agriculture (Garnett et al., 2013; Godfray & Garnett, 2014; Pretty, 1997). In essence, sustainable intensification aims to increase productivity and agricultural yields - especially in low-productivity regions - while reducing the impact of agriculture on the environment. However, how these goals are to be achieved and what role ecological principles and societal values play have since been debated (Struik & Kuyper, 2017; Tittonell, 2014). And after agroecology, regenerative agriculture is gaining popularity as the latest iteration of calls for an agriculture that raises yields where possible, honours ecological principles and justly negotiates societal interests (Giller et al., 2021). Meanwhile, the low success rates in mainstreaming successful technologies and best management practices have called for a more holistic approach to studying the potential and limitations of interventions in agriculture (Klerkx et al., 2010; Woltering et al., 2019). Against this backdrop, this study adopts a social-ecological systems lens to characterize the agroecological landscape and shine light on key question regarding the sustainable intensification of the rice-wheat system in the EGP. That is, through further study of both the social and ecological aspects of the system and their interaction, this thesis aims to develop a conceptual framework of the structure and interaction of the social and ecological components of the rice-wheat system that can inform how farmers and policy makers may best approach the management of water and (crop planting) time.

Agriculture through a social-ecological systems lens

The social-ecological systems framework depicted in Figure 1.2 presents an overview of the system and its features that I have applied in this study. The landscape constitutes an appropriate scale for the analysis of food systems as it ensures that key feedbacks between critical system elements are included in the analysis (DeFries & Rosenzweig, 2010; Sayer & Cassman, 2013; Therond et al., 2017). Within the landscape, the key focus of this study lies on the farming system which is comprised of the household and cropping system. The other landscape elements constitute the environment that constrains and enables activities in the farming system (see Figure 1.2). For simplicity, the interactions between the rice and the wheat subsystems that together form the rice-wheat system are not displayed. The study focuses on the wider social-ecological system components and takes advantage of the existing work on the rice-wheat interactions.

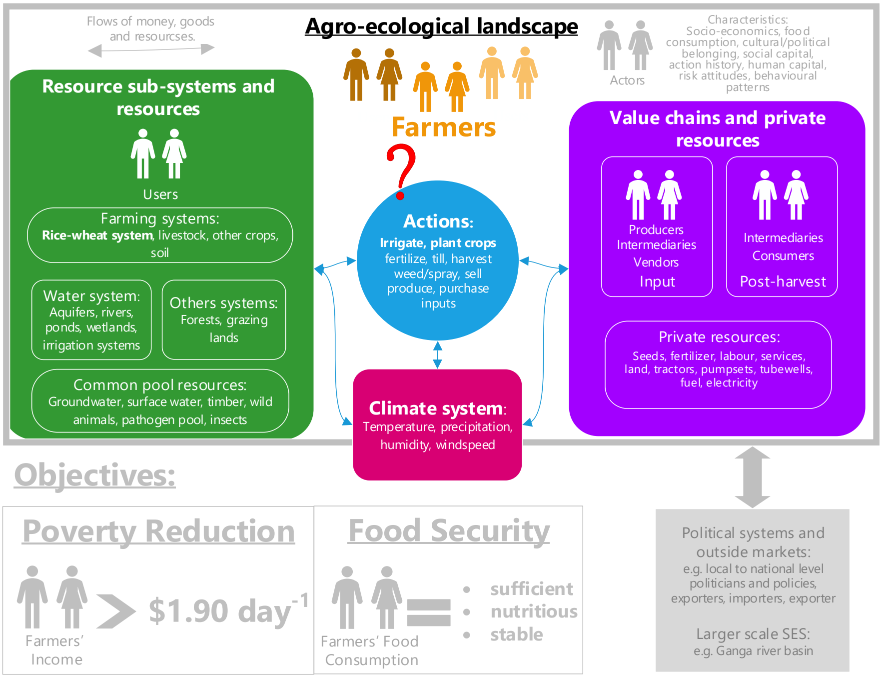

Figure 1.2 Overview of elements, activities and flows within the rice-wheat social-ecological system (SES). Adopted from Marshall (2015). Note: Only a sub-section of the complex dynamics of food security and poverty reduction is addressed within the scope of this project.

The social-ecological system includes actors and subsystems (coloured boxes and silhouettes) that, through interactions, sustain flows of resources, services, goods, and money between the system elements (arrows). Bio-physical-chemical and behavioural aspects (boxes and silhouette characteristics) are shaping the interactions (blue circle) resulting in potential changes of the system state (objectives below the landscape). The system state is defined as an equilibrium state of the system's flows of resources, services, goods and money (Ostrom, 2009b). For this research, food security and poverty are system states (or attractors), which are conceptualized through the levels of food provisioning services and income generation through cereal production (Folke et al., 2010). While several sub-systems and other farming or non-farming activities (including ones that are not depicted in the framework) may contribute to achieving the desired states, this project will concentrate its scope on analysing the potential contributions of the rice-wheat system and contrast it to other options in the current body of literature.

The landscape encompasses ecological interdependent resource-systems (green box) that are managed by users. This study focuses specifically on the heterogeneous set of farmers that are a subcategory of users (orange silhouettes). Farmers interact with the rest of the system through various actions (blue circle). Their actions in the rice-wheat system are shaped by their individual livelihood strategies and household characteristics as well as constraints and opportunities posed by other system elements such as value chains, climatic conditions, and the water system (Cote & Nightingale, 2012). These system elements vary across space and time (Folke et al., 2010; Janssen et al., 2007). This means that some farmers face different constraints and rely on different resources than others (Binder et al., 2013; Marshall, 2015). Politics, world markets, larger ecological systems such as the Ganga basin, or the climate system lie outside the system boundaries (grey/red box), as control over them is limited from the viewpoint of this study (Binder et al., 2013).

Managing water and time: from rice planting to selling the produce

Figure 1.3 depicts a concretized and simplified version of the framework that details the system elements and their configuration on which this study concentrates. The focus lies on the farming system. Farmers (1) plant crops, (2) irrigate, (3) harvest and (4) sell crop produce in interaction with environmental factors of the landscape. This sequence of activities forms the basis of the organization of the research chapters which each focus on one activity. Broadly, activities 1 and 2 correspond to the interventions/activities identified as crucial to manage water (irrigation) and time (crop planting) and form the basis for building farm typologies and modelling scenarios; activities 3 and 4 correspond to the system states (objectives) of interest. The flows inherent to activities 3 and 4 will also be used as indicators to measure the state of food security and poverty reduction in the system through crop and economic modelling exercises.

More specifically, the corresponding research questions for each aspect of the social-ecological system are outlined in Figure 1.4. At first, the farmer perspectives on the constraints and opportunities regarding changes in planting and irrigation activities will be analysed and complemented with survey data. Subsequently, the insights are used to design scenarios that predict the ability of planting and irrigation activities to move the system into improved states of food security and poverty reduction. Planting and irrigation are tightly linked as water is required for planting activities and planting dates condition exposure of different growth stages to drought. The key objective in planting activities is to synchronize the cropping and climate system, while irrigation is required to overcome periods of asynchrony between soil moisture and crop water demand. This means that studying both activities will have important cross-benefits, while understanding the decision-making and factors that drive and constrain each activity merits studying them for their own right, especially when doing so to better understand decision-making patterns.

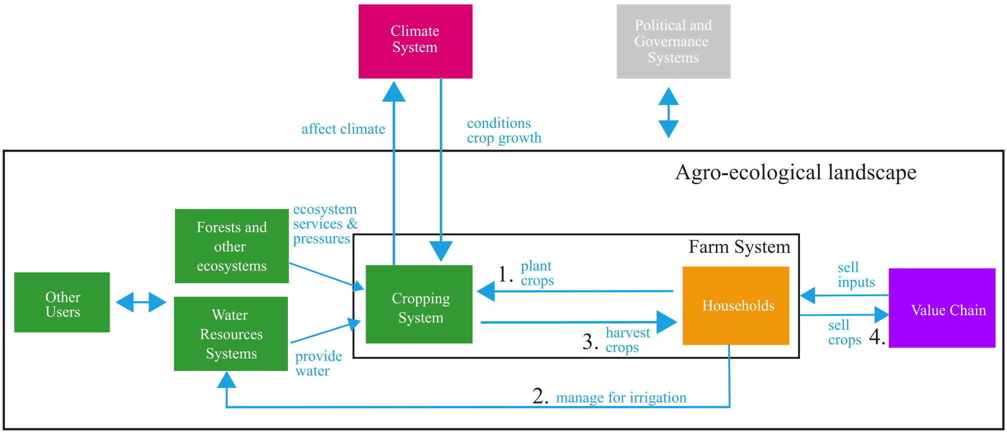

Figure 1.3 Specific social-ecological system depiction of the rice-wheat system used as an overall framework in this thesis.

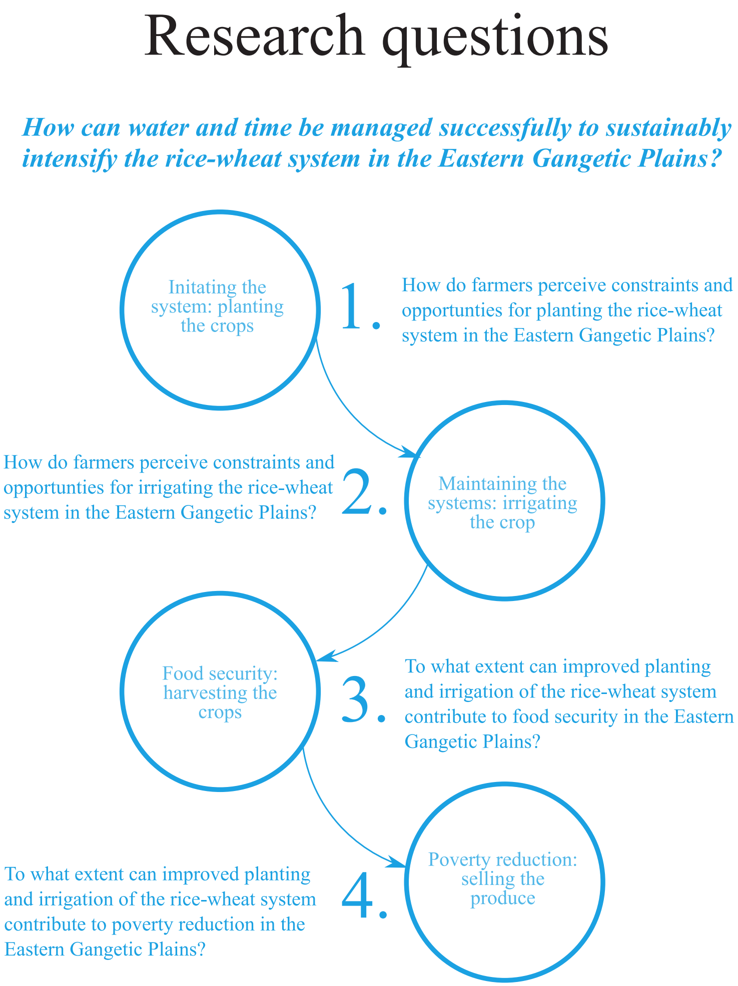

Figure 1.4 Research questions.

Methodology: community engagement, statistical learning, and simulations

The methodological approach adopted in this thesis is premised on the assumption that a context-specific understanding can be gained by using a mixed-methods approach that combines advances of the last decades in participatory and computational approaches to data collection and analysis. Building on the knowledge that has been generated across different relevant disciplines, this thesis aims to show that such an approach can bring together different fields and ideas to contextualize and characterize key system dynamics – allowing for the development of contributions to science as well as timely and practical recommendations to guide development programming. This section outlines the methods deployed for each research chapter and how they feed into each other. For more detailed information on the methods please refer to the individual Chapters.

Chapter 2 sets the scene and deploys a detailed survey in which scored causal diagrams were used to guide focus group discussions across three agro-ecological zones, where farmers discussed and ranked the factors that shape their decision on when to plant their rice crops. Scored causal diagrams allow for a relatively open and farmer-led discussion that establishes an ontology about the key factors, their relative importance, and how they interact at the village level to shape planting time decisions. The other benefit of scored causal diagrams is that they can be conceptualized as graphs so that graph theory tools can be leveraged to analyse the numerous scored diagrams computationally. Graph theory tools have also supported the emergence of network approaches for which several tools and statistics have been developed to analyse the data (Bodin et al., 2019). The participants were chosen from a subset of a larger landscape diagnostic survey on crop management and production practices that was collected shortly before the participatory survey and later used to validate the results of the detailed survey. After analysis, insights gained from the detailed survey were used to construct a random forest model – a non-parametric decision-tree based regression model – to analyse the importance and functional relationship of the different predictor variables on planting time. Importantly, the survey variables were complemented by bio-physical data on monsoon onset and groundwater levels that allowed to show the importance and critical threshold of pre-monsoon season groundwater tables for timely planting as identified during the focus group discussions.

Chapter 3 subsequently narrows down on the centrality of deploying irrigation - which is critical for planting but also, as survey data show, to buffer against drought and maintain high system productivity. The chapter uses ethnographic decision trees to take a deeper dive into the decision-making process around water use. This approach aims to elucidate the step wise process from initial triggers to start organizing for deploying irrigation to the final delivery of water to the field. Like the scored causal diagrams used in Chapter 2, the method allows for better understanding how the activity looks like from the farmers' perspective and helps to describe the decision points that lead up to the action of interest. In doing so, it helps to show how a decision that is generally seen as a binary decision, is in fact a sequenced cascade of decisions and activities that can help guide interventions for improving the action of interest. In addition, the study design for Chapter 3 pays attention to how different levels of wealth and exposure to drought may impact the decision-process to deploy irrigation and simultaneously seeks to enable a relatively long and deep engagement with the communities. To achieve this, the study selected three districts that are representative of precipitation and wealth gradients in the Eastern Gangetic Plain and in relative proximity to allow for easier follow ups during the investigation. The districts were chosen on the Nepal side of the Eastern Gangetic Plain, called the Western Terai, to integrate insights across different cultural and policy environments within the overall research design. Once the ethnographic decision-trees were established, they were used to trace and quantify the decision points that most affect individuals across the different study locations. To contextualize the findings, the study further used a larger scale production practices survey, like the one used in Chapter 2, and additional government data sources through which the decision-process could be situated within the broader framework of agricultural development of Nepal's Terai.

After the decision processes, factors that influence them, and their importance for managing water and time were investigated, **Chapter 4** turns towards the impact of changing management practices through interventions in planting dates and irrigation. This Chapter assesses how improvements in management may be bound by ecological, climatic, and social gradients, allowing for more differentiated targeting of interventions. To answer this question, crop model simulations are used to assess the impact of improved management practices on productivity and production stability across space and time. The last decade has seen a tremendous increase in the availability of earth observation data and the use of crop models to provide spatiotemporal assessments that mostly focused on the impacts of climate change at a global level. This Chapter uses the latest generation of earth observation data, and the tools developed for global crop modelling, to assess the interplay of regional climatic gradients and management decisions. This Chapter then studies key interventions studied in Chapter 2 and Chapter 3 and simulate their impact on yields and their stability over time. This approach enables a spatially explicit ex-ante assessment of the potential impact of the interventions and to identify sub-regions where the interventions might not deliver the expected impacts.

Lastly, to assess what role improvements in the farming system may play in the portfolio of income generating activities for poverty reduction, **Chapter 5** estimates farmer profits from intensifying irrigation of rice-wheat system on a dollar per day basis. The study leverages a large survey dataset to study the distribution of farm sizes and how they respond to increasing levels of irrigation use. It then uses a variety of statistical models to gauge the expected improvements of farm incomes from increased use of irrigation. Several detailed analyses of gross profits for different farm designs and crop management practices can be found in the literature. However, these largely focus on relative improvements of returns from land. The participatory engagements strongly suggested that farming is only one of many important income streams and farm management may not always receive the full attention of farming households. This poses a question, more broadly, on the monetary value of improving farm management practices for farming households in the region. This Chapter therefore focuses the analysis on calculating the Intensification Benefit Index, which indicates the dollar per day returns that farm households can generate from improvements in returns from land. The distribution of the Intensification Benefit Index then allows one to relate improvements on returns to land to poverty reduction measures in dollars per day and more generally regarding the international poverty line.

Outline of this thesis

This thesis consists of the current introduction chapter, four research chapters and a general discussion chapter. The research chapters each addresses one aspect of the overall research objective as elaborated in the theoretical framework and methodology. That is, each research chapter provides a detailed treatment of one research sub-question. Subsequently, the general discussion chapter reviews the findings of the four research chapters considering the overarching research question and objective and reflects on the contribution and implications of the findings for scientific progress and social issues and suggests future research needs.

Chapter 1. General introduction: hunger, poverty, and sustainable agriculture in an era of big data and digital innovation

This chapter introduces the background information and context to this thesis topic and provides an overview of the theoretical framework, research objective and research questions, methodological approach, general outline, and main findings of this thesis. This thesis seeks to advance science by answering questions about bottlenecks to the sustainable intensification of agriculture in the Eastern Gangetic Plains. It leverages a social-ecological systems framework to bring together insights from mixed-methods inquiry combining large datasets, community engagement, and computer simulations. This chapter closes with presenting details of methods deployed in each study and the main findings of each thesis chapter.

Chapter 2. How do farmers perceive constraints and opportunities for planting the rice-wheat system in the Eastern Gangetic Plains?

This Chapter studies the timing of rice planting activities in the Eastern Gangetic Plains. The timing of rice planting has important effects on the exposure of rice crops and following crops grown later in the year to climatic stresses such as cold, heat, or drought. This study finds that farmers are generally aware of the benefits of early rice planting. This Chapter further identifies ecological factors as the primary factors that shape the timing of rice planting – with water availability being the most important one. Social factors, however, play an important secondary role as the unavailability of inputs for planting frequently delays rice planting of farming households. In addition, heightened pest and diseases pressure for individual early planters deters farmers from early planting of rice in the absence of collective action that disperses these pressures across the landscape.

Chapter 3. How do farmers perceive constraints and opportunities for irrigating the rice-wheat system in the Eastern Gangetic Plains?

Groundwater irrigation has provided widespread access to water resources for farmers in the Eastern Gangetic Plains for several decades. But production surveys suggest that most farmers use irrigation too little and too late. This chapter studies farmers' decision-making process around deploying groundwater irrigation and finds that the cues that farmers use to start organizing for irrigating their fields, large soil cracks, already indicate severe drought stress. Moreover, after farmers decide to irrigate, insufficient infrastructure development results in queuing for pumps and borewells that delays water applications to the field. Unavailability of cash, lack of labour, and sparsity of mechanics to repair broken pumps in times of high irrigation demand further extend the delay period. These delay factors, however, differ across locations allowing targeted interventions that, together with earlier cues to irrigate, may boost productivity enhancing irrigation use.

Chapter 4. To what extent can improved planting and irrigation of the rice-wheat system contribute to food security in the Eastern Gangetic Plains?

Chapter 2 finds that farmers tend to 'wait for the monsoon' to start crop planting, which trades a reduction of early season irrigation for increased water demand and temperature stress later in the season. This may be addressed by either following the state recommended fixed planting dates or synchronizing rice planting with the monsoon onset. This chapter zooms out and compares these strategies using a gridded crop model across the entire IGP. This Chapter shows that regional temperature and monsoon onset progression patterns shape the effectiveness of the two planting strategies. Synchronizing planting dates with the monsoon onset is more effective in the Eastern Gangetic Plains – where the monsoon starts earliest, and temperatures are milder - while recommended fixed dates already work best in the western IGP. The impacts of the planting strategies on overall water use remain marginal. The chapter further discusses implications for the agricultural development pathways across the Indo-Gangetic Plains.

Chapter 5. To what extent can improved planting and irrigation of the rice-wheat system contribute to poverty reduction in the Eastern Gangetic Plains?

The previous three research Chapters find that significant scope exists to improve rice-wheat system productivity through adjusting irrigation patterns and planting dates. However, although many farmers showed strong interest in improving farming practices it surfaced that other livelihood activities are often prioritized over farming, posing the question on what contribution improved farming systems, e.g. more intensively irrigated ones, can make to the portfolio of income streams that most farmers manage for their livelihoods. That is, what do farmers gain from having some more crop produce to sell? Using the large-scale production practices survey already deployed in Chapter 2, this Chapter finds that only for the largest farms increased productivity translates into incomes that lift the households above the poverty line. The incomes of most households are rather insensitive for increases in productivity. This Chapter then discusses the implications of these findings for targeting of interventions and the importance of creating rural off-farm jobs to support poverty reduction.

Chapter 6. General discussion: reflections and ways forward for managing water and time for sustainable rice-wheat production in the Eastern Gangetic Plains

This final Chapter first revisits the research questions and answers found in this thesis, and then discusses the implications of these findings for future research and development programming. Specifically, after reviewing the findings, this Chapter critically engages with the scientific literature and reflects on the policy, theoretical and methodological implications of this thesis in light of the research objective. Lastly, this Chapter zooms out and discusses the findings' implications on the four relevant and cross-cutting issues of water for food, climatic stresses and shocks, the monsoon, and social science for the targeting of interventions and policies.

Chapter 2

Planting the crops

Social-ecological analysis of timely rice planting in Eastern India

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Abstract

Timely crop planting is a foundation for climate-resilient rice-wheat system of the Eastern Gangetic Plains—a global food insecurity and poverty hotspot. We hypothesize that the capacity of individual farmers to plant on time varies considerably, shaped by multifaceted enabling factors and constraints that are poorly understood. To address this knowledge gap, two complementary datasets were used to characterize drivers and decision processes that govern the timing of rice planting in this region. The first dataset was a large agricultural management survey (rice-wheat: n = 15,245; of which rice: n = 7597) from a broad geographic region that was analysed by machine learning methods. The second dataset was a discussion-based survey (n = 112) from a more limited geography that we analysed with graph theory tools to elicit nuanced information on planting decisions. By combining insights from these methods, we show for the first time that differences in rice planting times are primarily shaped by ecosystem and climate factors while social factors play a prominent secondary role. Monsoon onset, surface and groundwater availability, and land type determine village-scale mean planting times whereas, for resource-constrained farmers who tend to plant later ceteris paribus, planting is further influenced by access to farm machinery, seed, fertilizer, and labour. Also, a critical threshold for economically efficient pumping appears at a groundwater depth of around 4.5 m; below this depth, farmers do not irrigate and delay planting. Without collective action to spread risk through synchronous timely planting, ecosystem factors such as threats posed by pests and wild animals may further deter early planting by individual farmers. Accordingly, we propose a three-pronged strategy that combines targeted strengthening of agricultural input chains, agro-advisory development, and coordinated rice planting and wildlife conservation to support climate-resilient agricultural development in the Eastern Gangetic Plains.

Introduction

Timely crop planting: a critical decision-point for agroecosystem resilience

Attaining food security in the densely populated Eastern Indo-Gangetic Plains—a global poverty hotspot—requires the negotiation of trade-offs between productivity, risk, and the ecological footprint of agriculture, a challenge further compounded by the impacts of climate change (Ortiz et al., 2008; Park et al., 2018; Struik & Kuyper, 2017). Building agroecosystem resilience—i.e., the capacity to maintain core functions in the light of environmental and market shocks (Nystrom et al., 2019) — and thus maintaining high levels of crop productivity are often predicated on timely crop planting and harvesting (Balwinder et al., 2019a). Timely planting aligns crop cycles with favourable climate conditions resulting in higher and generally more stable yields. Specifically, timely crop planting raises system productivity by (a) mitigating risks of yield losses caused by pushing crop growth into periods of sub-optimal or extreme weather conditions such as cold and heat waves, drought, or flooding; (b) increasing resource use efficiencies; and (c) allowing for more crops to be grown per year on the same land (Acharjee et al., 2019). While several studies have analysed optimal time windows for planting, agroecosystem characteristics and farmers' decision processes that enhance or limit the potential to plant crops during optimal time windows have received less attention (Acharjee et al., 2019; Balwinder et al., 2019a; Mingxia et al., 2020).

With approximately 400 million people and a population density of more than 1000 people per km2, the Eastern Gangetic Plains encompass parts of north-eastern India, eastern Nepal, and Bangladesh. High incidence of poverty and food insecurity, as well as a primary dependence on agriculture, make it a priority location for achieving the Sustainable Development Goal 1: No Poverty, and Sustainable Development Goal 2: Zero Hunger (Jat et al., 2020). In this region, farmers predominantly grow rice during the summer monsoon, often followed by a wheat crop in the dry winter season. But erratic monsoon patterns increasingly cause both floods and droughts in close spatio-temporal proximity, threatening farmers' productivity. Research over the last decades has shown that timely planting of both rice and wheat is one of the most important response options that farmers in the region have to build resilient agroecosystems amidst changing climate regimes (Balwinder et al., 2019a; Keil et al., 2019; Ortiz et al., 2008). At the system level of rice-wheat cropping patterns in South Asia, timely planting of rice facilitates the efficient use of monsoon season rainfall and, just as importantly, planting of wheat within the first 3 weeks of November. The latter assures higher yield potential by avoiding both season-long and terminal heat stress during grain filling (Balwinder et al., 2019a). Due to the cascading influence of rice management on subsequent crops like wheat in the annual rotation, our study focuses on rice planting.

Rice planting is typically a two-step process as nurseries are first planted to raise seedlings that are then uprooted and transplanted into main fields (see Figure 2.1). For simplicity, and because the timing of the two activities is highly correlated, we refer to the process of nursery establishment and subsequent transplanting as "planting." Conversely, wheat tends to be broadcast sown after rice harvest following tillage to prepare fields. But a delayed rice crop can push back the timely planting of wheat and other dry season crops. As the planting time of rice is a keystone to the productivity of this cropping sequence, the lack of knowledge of the factors that increase the ability of farmers to adopt timely planting hinders effective and targeted agricultural development programming in the region, particularly in light of the high levels of social and agroecological diversity. We therefore hypothesize that farmers' capacity to plant on time is unequal and shaped by a host of binding constraints and enabling factors that are, at present, insufficiently understood.

Figure 2.1 Farmers transplanting rice seedlings on July 31st, 2017, in the Eastern Gangetic Plains – Bihar, India. Source: Anton Urfels

Farmers' capacity to adjust planting dates: a systems' perspective

In this study, we draw on social-ecological systems research as it pertains to resilience theory. We considered the work of Lescourret et al. (2015) and distinguished two different types of factors: (a) ecosystem factors that operate largely at the landscape level but exert influence on individual farmers' ability to plant on time and (b) social system factors (henceforth "social factors") that operate at the village and household scales and affect farmers' decisions regarding planting times.

Ecosystem factors include dynamic factors that change from year to year such as the onset of the monsoon, and pest and disease pressures, but also static factors that remain relatively constant over time such as pre-monsoon ground and surface water availability, and land types (e.g. the position of a plot within the drainage system where water tends to accumulate in lowlands or to runoff in upland areas).

Social factors are mainly associated with input and resource availability. Timely planting requires readily available seed and fertilizer, tractors for land preparation, and irrigation (e.g. mostly with groundwater, but sometimes also in the form of canal water), in addition to labour and capital to pay for crucial operations. These factors are influenced by household resource endowment, availability of farm machinery, market access, and many others. Since ecosystem factors operate largely at the landscape level, they can be regarded as boundary conditions for individual villages and households. Social factors at village and household levels then shape responses therein.

This study identifies and characterizes the main factors and decision processes that influence capacity to achieve timely rice planting in the Eastern Gangetic Plains. We deployed a mixed-methods approach to understand factors associated with the timely planting of rice—a key indicator of agroecosystems' resilience in the Eastern Gangetic Plains, particularly in the light of progressive climatic change. Specifically, we studied how social-ecological characteristics differ across early, medium, and late rice planters. We worked on the assumption that timely planting means early planting in most cases, as indicated by overall yield benefits to the rice-wheat system (Balwinder et al., 2019a; Ortiz et al., 2008). We present an approach in which we combine insights from two unique datasets, a detailed discussion-based dataset and a big picture survey. We analysed each dataset through novel methods and used the results from the detailed dataset to complement and inform interpretation of results from modern data-mining techniques that we used to analyse the big picture dataset. In the materials and methods section, we sketch out the broad research design and theoretical considerations and delineate how we addressed these considerations. This section is designed to allow a better understanding of our contributions to developing an innovative mixed-methods approach for gaining insights for resilience in social-ecological system from cross-sectional case studies (Bodin et al., 2019). In the results and discussion section, we present the results and (a) discuss the social-ecological factors that the study revealed as most important for timely planting, (b) assess the value of our mixed-methods approach to study complex social-ecological systems at regional scale, and (c) propose a practical strategy for building a resilient rice-wheat system in the Eastern Gangetic Plains through timely planting.

Materials and methods

Datasets: household selection, sampling strategy and data collection

We used two complementary datasets in this study that we call "big picture" dataset and "detailed" dataset. The big picture dataset is a farmer survey developed for crop diagnostics at the regional scale (rice-wheat: n = 15,245, out of which rice: n = 7597) for the 2017–2018 rice-wheat season in the state of Bihar and neighbouring parts of Uttar Pradesh. It was collected in 2017–2018 through a collaborative effort between the Cereal Systems Initiative for South Asia (CSISA; www.csisa.org) and the Indian Council of Agricultural Research and their network of Krishi Vigyan Kendra (KVK) offices that bring scientific expertise to the district level. We first selected 39 districts with 30 districts in Bihar State and nine in adjacent areas of Uttar Pradesh State. In each district, we randomly selected 30 villages. Next, a random draw from voter rolls was used to identify seven farm households to survey within each village. This produced a total of 210 household samples in each district (Figure 2.2) and a total of 8190 target sampling households for each crop. Some data points had to be discarded during data cleaning, producing the total survey size of 15,245. Survey responses were elicited for the largest rice field managed by each household. The survey was designed to elucidate patterns of production practices and yield outcomes across the region. Following geo-tagging of farmers' largest field, we elicited data describing crop management practices, bio-physical site characteristics, and causes of crop stress. Farmers were also queried regarding their level of market integration and orientation and social and household characteristics.

The detailed dataset is a survey based on focus group discussions with farmers in Bihar that characterizes farmers' perceptions of factors affecting the timing of rice establishment in their villages, with associated scoring of how much each identified factor affects the timing of planting and productivity on their own farms (n = 112 farmers in 22 focus groups with, on average, 5 farmers per focus group). For the detailed dataset, we subsampled—out of the big picture sample frame—five randomly chosen households in five villages in three study areas that represent different key agroecological zones (Figure 2.2). This relatively small subsample was chosen to provide a more qualitative in-depth perspective across social-ecological gradients in the region to help explain and inform results of the quantitative analysis of the big picture survey. The three study areas represent the two biggest agroecological zones of Bihar, as well as one drought-prone area with less reliable access to irrigation: (1) Muzaffarpur/Samastipur (good rainfall and aquifers, partial canal irrigation), (2) Bhojpur/Buxar (located at the tail end of a canal irrigation scheme with good aquifers and heavy soils), and (3) Nalanda/Jehanabad (a small canal irrigation scheme with poorer and more heterogeneous aquifers, lighter soils, and hence, more drought prone). The villages were chosen by local agricultural experts who were asked to select villages that represent the variation in social-ecological conditions within the study areas to ensure that inter-village variability is controlled for. The households within each village were chosen at random to control for intra-village diversity, and participation of different socio-economic groups was observed in the focus group discussions.

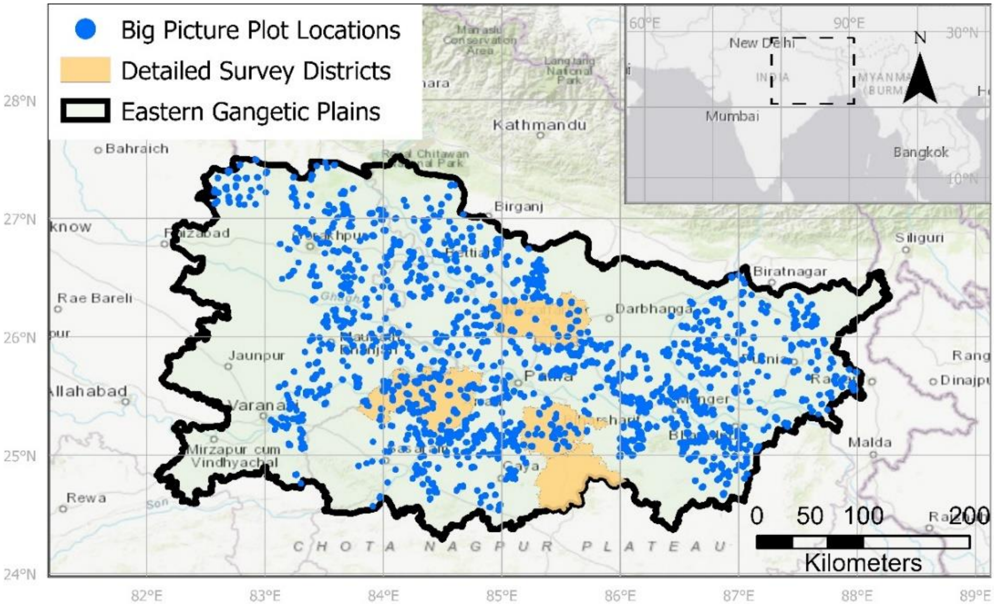

Figure 2.2 Map of the study area showing the locations of the plots of the big picture survey and the districts in which the detailed surveys were conducted.

The goal of the detailed survey was to elucidate a system description of planting date decisions based on the logic and language of the farmers (i.e. an emic perspective). To achieve this, we facilitated the group of the selected survey respondents to construct a causal diagram in each village (Dorward et al., 2007). Often, several other interested individuals joined the discussions which we allowed to source information from the largest possible group. We then placed a flipchart on the ground and wrote down the two items: (a) nursery establishment and (b) transplanting in Hindi and English in the middle of the flipchart. We then told the participants that we sought to understand the factors that govern the timing of the two activities and asked them to complete the flipchart by brainstorming all possible factors that could drive the timing of rice planting. Arrows were then placed between factors indicating cause and effect. This process was facilitated by local staff in Hindi and other local languages as required. After this exercise, we asked the previously randomly selected 5 households in each focus group (these all participated in the big picture survey and were randomly chosen from voting lists) in each village to individually score each cause and effect relationship from 0 to 10 depending on the degree that, on average across households, it mattered for their own management of planting dates over the last 5 years (Dorward et al., 2007).

Methodological approach: mixed-methods analysis of complex agro-ecological systems at the regional scale

The advantage of a mixed-methods approach is that they allow researchers to complement quantitative datasets with rich and contextual data (Bodin et al., 2019). We achieve this by combining the big picture and detailed dataset.

Big picture dataset: machine learning analytics for household survey data

The big picture dataset adds quantitative and spatial dimensions that could not be achieved with detailed surveys. But quantitative modelling to identify factors influencing rice establishment with the larger dataset presents its own challenges. Classical regression models require a priori selection of model form (linear, cubic, etc.) that is generally established through specific and extensive testing to check whether the data meet the assumptions and requirements of the statistical model. For our purposes, we required an analytical approach that (a) is capable of handling both numerical and categorical variables, (b) includes mechanisms for variable selection/importance rankings, (c) can handle non-linear relationships, and (d) produces interpretable results. Based on these criteria, we selected the random forest method for our analysis (Breiman, 2001). Random forest builds an ensemble of classification and regression trees to make predictions. The algorithm constructs several hundred decision trees that each predicts the outcome based on a set of randomly confined observations and predictors. It then predicts the outcome by calculating the mean of the predictions of all individual decision trees. Several freely available software packages have been developed to aid the interpretation of random forests, and we used the forestFloor package as it has been previously deployed for similar purposes and provides good documentations (Welling et al., 2016).

For the analysis of the big picture data, we focused on the timing of nursery establishment as the very first activity that also strongly correlates with transplanting time and provides a good predictor of rice harvest, wheat planting, and wheat harvest (not shown). We further checked for variables that had a correlation factor of higher than 0.7 or lower than -0.7 as they are known to decrease the accuracy of importance scores in random forest models. The only two highly correlated variables were cropped land and total landholding. We discarded the former but retained the latter, which thus represents both factors in the analysis.

In addition to the big picture survey variables, we estimated the monsoon onset for each survey point from Climate Hazards Group InfraRed Precipitation with Station Data (CHIRPS) 2.0 calculated based on agronomically relevant criteria: (a) the first day of two consecutive wet days cumulating in at least 35 mm rainfall and (b) no dry spell with a cumulative rainfall less than 5 mm within the 10 following days (Marteau et al., 2009). We also added pre-monsoon groundwater level from the Central Groundwater Resources Board from the year 2017 as a model predictor which was extrapolated through ordinary kriging to 0.05-degree resolution (Resources, 2020).

Next, for the factor importance ranking, we sought to identify the importance and relationship of each variable for shaping planting date (i.e., nursery establishment). For this purpose, we deployed the random forest model as implemented in the R package randomForest and plotted the variable importance score that is produced (Breiman, 2001).

For the partial dependency plots, as to permit the inference of interactions between predictors and outcome, we used the forestFloor package (Welling et al., 2016). Partial dependency plots show the functional relationship between model input variables and model predictions with all other variables held constant. These plots show how the model predictions partially depend on the value of the input variable.

Representative trees are another helpful visualization. While the power of random forests comes from being able to generate numerous trees, they may not differ significantly from each other if sample sizes are large enough. Also, randomForest does not offer a simple way to visualize interactions between predictors. By choosing a tree that is statistically closest to all other trees, one can elucidate interactions among independent variables. This has, for instance, been suggested as a mechanism to deduce decision heuristics for medical practitioners (Banerjee et al., 2019). As such, we present a pruned version of a representative tree of our random forest model to provide a visualization of the main interactions among predictors as well as a sense of the factor hierarchy that governs planting dates.

Detailed dataset: analysing discussion-based surveys with graph theory tools

The detailed dataset adds a qualitative dimension, and its results were used (a) to select variables that we subsequently included in the analysis of the big picture dataset, (b) to provide insights that bolster the interpretation of the results obtained from analysis of the big picture dataset, and (c) to identify missing or latent variables that were not directly captured in the big picture survey data, but which likely play a crucial role in explaining the reasons for untimely rice crop establishment. The detailed dataset is vital for developing conceptual models of systems because it is comprehensive, open-ended, and fully participatory. While results from the detailed dataset cannot be generalized to the regional scale because of its relatively small sample size, it does provide insights into the underlying factors associated with diverse establishment date outcomes. Building on this advantage, we relied on local agricultural experts to guide the village sampling strategy for stratification across precipitation, hydrology, and wealth gradients to capture a wide variety of possible cases. We used digital graph theory tools (igraph, GraphViz) to analyse scored causal diagrams created by the participants of each focus group discussion (Csardi & Nepusz, 2006; Ellson et al., 2001).

These scored causal diagrams were digitized manually as a network graph through the GraphViz software package and exported for analysis with the igraph package in R (Csardi & Nepusz, 2006; Ellson et al., 2001). For factor importance ranking, we calculated the weighted out-degree (sum of all outgoing arrows) for each factor of each individual farmer that scored the diagram. In the region, three different 2-week periods that are specified in the local calendar denote planting time: early (local calendar period called Rohini: 25th of May–7th of June, day of year 146–159), medium (local calendar period called Mirgishra: 8th of June–21st of June, day of year 160–173), and late (local calendar period called Adra: 22nd of June–5th of July, day of year 174–187). We recorded whether the farmers that scored the causal diagrams planted in each of the three periods. We then averaged the weighted out-degree scores of all farmers that planted rice nurseries in each 2-week period. Some farmers planted in multiple periods, mostly because they had plots on different land types and their scores were therefore counted in more than one period.

Results and discussion

Descriptive variable distributions of big picture dataset

For 2017, a normal monsoon year with onset around day of year 181, our data suggest that early planters (early period or before) are a distinctive minority (27%), while those falling into the medium category are the vast majority (50%), with late planters (late period or thereafter) in the minority (23%) (see Figure 2.3). Our data show three distinctive peaks in both the nursery establishment and transplanting distributions. For nursery establishment, the medium peak is likely related to the arrival of monsoon showers in the medium period. The early and late peaks likely relate to traditional farming calendars as they coincide with their starting day (see materials and methods section). Transplanting likely mirrors the pattern of nursery establishment through seedling age and monsoon arrival as a trigger for transplanting.

Some key numeric variables in our dataset have rather large outliers but are generally evenly distributed (not shown). Considering categorical variables, almost all farmers have access to irrigation, mostly from diesel-powered shallow groundwater wells, and grow wheat after their rice crop. The production in 2017 was widely perceived to be in line with the 5-year average. Surveyed farmers in the big picture survey reported to use the following heuristic for determining the timing for nursery establishment: calendar dates, pre-monsoon showers, and irrigation water availability, and, to a lesser extent, neighbours' practices, seed availability, and weather forecasts. For transplanting, dominant self-reported heuristics were seedling age, calendar dates, irrigation water availability, rain arrival, and, to a lesser extent, labour availability. The influences on planting time distribution of the different self-reported heuristics can be seen in the different shapes of the distribution curves for nursery planting and transplanting (Figure 2.3).

Explaining planting date variability from a social-ecological perspective

Monsoon onset date, results from both datasets suggest, plays a primary role in shaping the timing of rice planting (Figure 2.4 and 2.5)—ostensibly to avoid costly groundwater irrigation as most farmers rely on costly and inefficient diesel-powered groundwater irrigation (Shah et al., 2018a). This means that farmers who are socially constrained to access reliable and affordable irrigation face a trade-off between increasing their system resilience through early planting and increasing risks posed by potentially high irrigation expenses in the case of late monsoon onsets. Social factors, in general, act as secondary drivers of planting outcomes at the village and household levels, as farmers differ in access levels to agricultural inputs and services and investment capacity. For example, some villages reported that only one tractor is shared for ploughing at transplanting, so it requires ca. 30 days for the entire village to transplant. Likewise, labour for transplanting is often scarce as groups of migratory agricultural laborers are only available in each location at a given time so farmers need to pay a premium, wait, or actively import labour for transplanting. Similarly, farmers in remote villages require costly transportation to the nearest market to purchase quality seed and fertilizer. But they may not have the capacity to mobilize the community and organize collective transportations for accessing inputs from market towns and thus rely on village-level shops that offer goods with varying quantities, qualities, and prices. In this way, secondary factors may cause rice planting delays even when water-related factors do not limit early planting.

Non-water-related ecosystem factors such as wild grazing animals (e.g. blue bulls [*Boselaphus tragocamelus*]; locally called nilgai) and pest and disease pressures play another important role. Pests, wild animals, and disease pressure did not emerge as a critical factor for contemporary decision-making in the big picture dataset. But these factors were mentioned in the detailed survey in almost all villages as a barrier to early planting, especially if neighbouring farmers were not planting in synchrony. Village-level commonalities in management also hint at the existence of "village tales" that shape a common understanding of optimal management that influences planting date decisions beyond variables that are collected in the big picture survey.

Our datasets demonstrate, for the first time, that water-related ecosystem factors play a primary role, but access to inputs and socio-economic stratification act as critical secondary factors, especially for resource-poor households. The big picture dataset also shows the limitation of small, detailed surveys that do not fully capture ecological regional variations such as variations in groundwater levels. To summarize the findings, Table 2.1 provides an overview of the characteristics that increase the probability of a farmer to plant early, medium, or late.

Landscape level: Ecosystem factors

The water-related factors monsoon onset and irrigation availability appeared as critical factors in both the detailed dataset and the big picture dataset. In the detailed dataset, monsoon onset was rated as the most important factor in determining the date of rice planting for early, medium, and late planters. Monsoon onset was evaluated as the third most important variable in the random forest model which likely underestimates its importance as the big picture survey, on which the random forest was built, and only contains data from the year 2017. Monsoon onset is likely more important when explaining inter-annual variability, given that intra-annual variability in monsoon onset was limited in 2017 (data not shown).

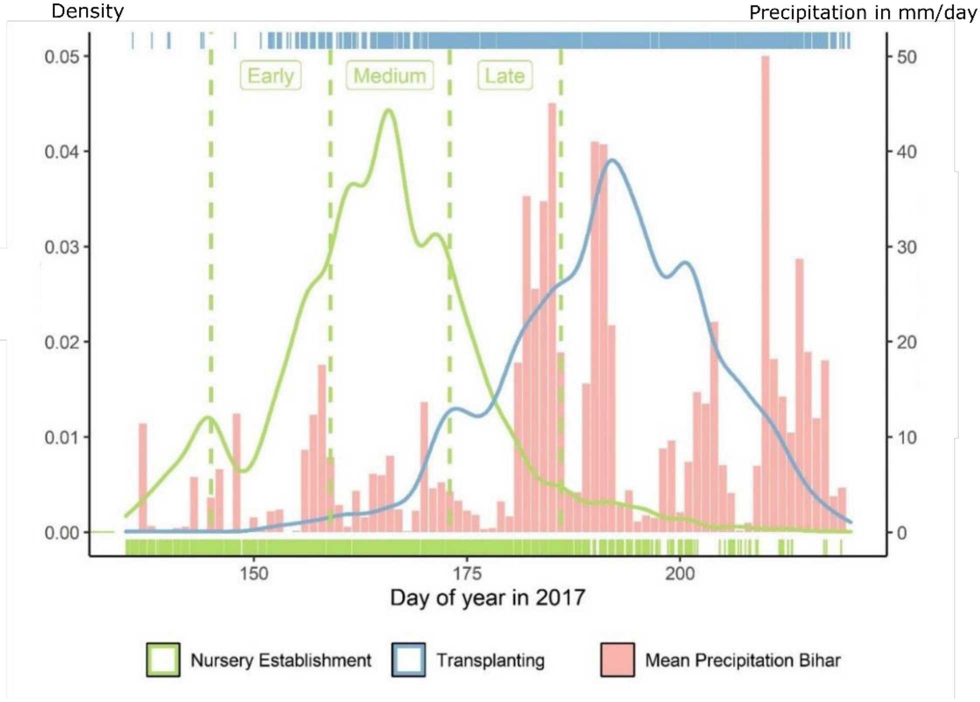

Figure 2.3 Distribution of rice nursery establishment and transplanting dates (n = 7597) in Bihar and Eastern Uttar Pradesh in 2017, including early, medium, and late time windows for nursery establishment and daily mean precipitation across the study area derived from CHRIPS. Farmers plant rice crops across more than 1 month. Peaks in nursery establishment occur with the onset of the early and late periods (denoting local farming calendars) as well as with the onset of sustained rainfall during the medium period. Transplanting activities follow nursery establishment patterns.

Groundwater depth scored second highest among the detailed dataset factor rankings and was the most important factor in the random forest model. The random forest results suggest that, at the regional scale, irrigation availability is primarily a function of shallow pre-monsoon groundwater levels, rather than machinery availability. The representative tree uses the groundwater depth variable as the first split and then further narrows down the predictions by splitting for different social variables as well as groundwater depth and monsoon onset at subsequent splits (Figure 2.6). This splitting pattern further indicates that water-related variables are of primary importance, and other variables provide context on the degree to which early planting is (socially) constrained. The partial dependency plots further show that farmers tend to plant later if pre-monsoon groundwater levels pass a threshold of ca. 4.5 m (Figure 2.7). This is likely explained by technical characteristics of centrifugal pumps that predominate the landscape. Centrifugal pumps, in theory, cannot lift water from more than 9.81 m below them, and in practice, friction losses commonly decrease this threshold even more (Kahnert et al., 1993). In addition, the operation cost of centrifugal pumps increases sharply with deeper groundwater levels, which further amplifies the already high irrigation cost of diesel pumpset irrigation. At the village level, irrigation water in the region is generally made accessible by pump owners to other farmers on a pay-per-hour basis, so that variability in prices and availability can further constrain timely planting even where groundwater levels are in operable levels (Shah et al., 2018b).

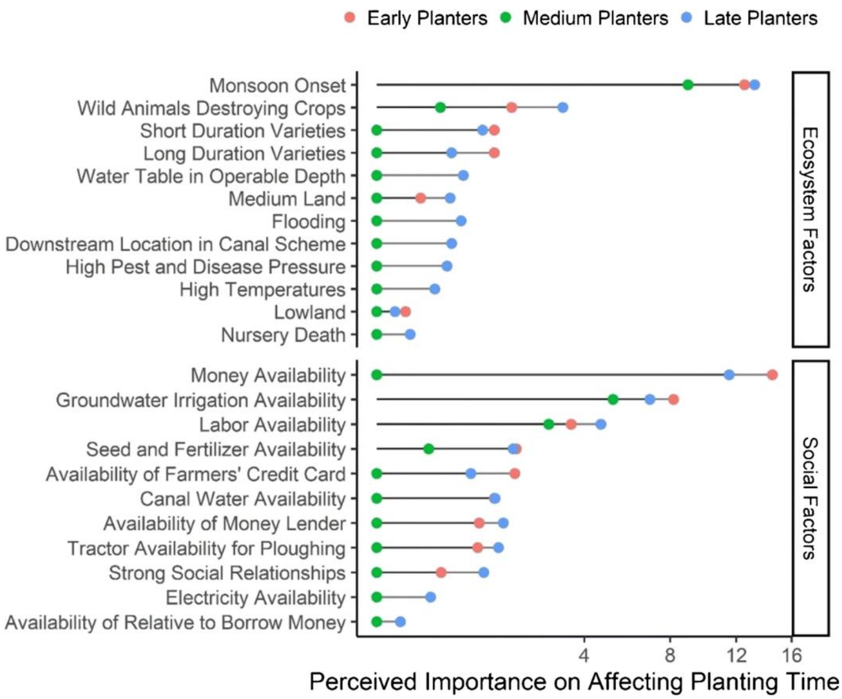

Figure 2.4 Factor importance rankings for the time of planting of the detailed survey. Water-related factors (both ecosystem and social) predominate. Wild animals, labour availability, and financial resources as well as timely availability of inputs further affect planting time.

Access to canal infrastructure also emerged as an important factor. In canal areas, rice planting is often delayed. Farmers reported that they do not align rice planting with the monsoon onset, but with the opening of the canal system, which takes place after monsoon onset as monsoon rains are required to fill the canals. Farmers reported that farming in canal areas comes with the drawback that, in most regions, more water is released into canals than they can carry. Widespread flooding is the result, and farmers reported that fields are often submerged for several weeks at the start of the monsoon period. Farmers accordingly tend to raise submergence-tolerant seedlings and transplant them before flooding. The factors of flooding in the area are complex and, for instance, discussed in the study of Muthuwatta et al. (2017). Importantly, and mentioned by farmers during the focus group discussions, lack of transboundary cooperation between different states and countries plays a key role in causing the uncontrolled flooding.

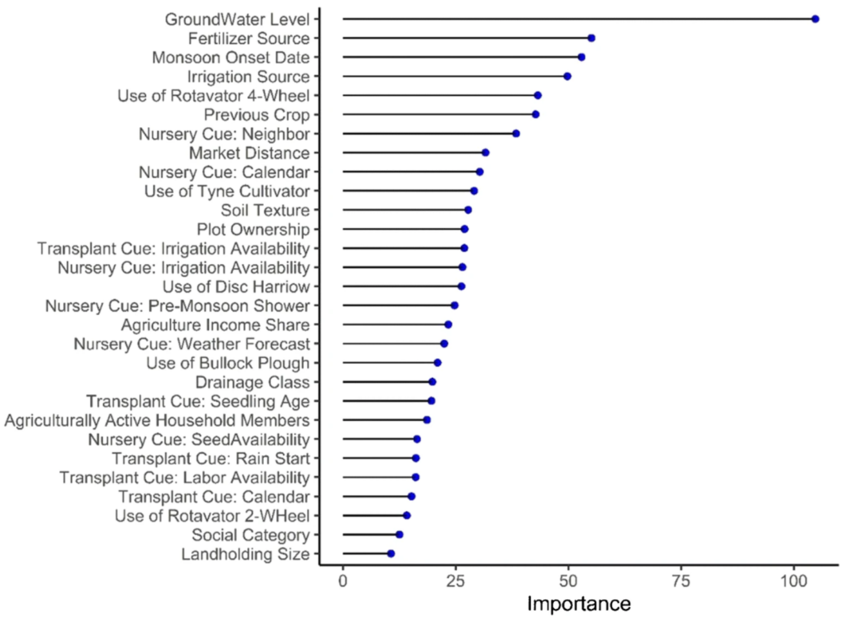

Figure 2.5 Factor importance rankings for the time of planting of variables in the big picture survey. Confirming the detailed survey, groundwater depth, monsoon onset, and irrigation source (all water-related factors) predominate. Other factors such as input types and availabilities, soil types, and decision-making factors further shape planting time.

Table 2.1 Overview of the characteristics our data indicate to be associated with farmers that plant rice early, medium, or late in the Eastern Gangetic Plains.

	Early planters	**Medium planters**	**Late planters**
Monsoon onset	Early monsoon onset	Normal monsoon onset	Medium or late monsoon onset
Blue bulls (*Boselaphus tragocamelus*)	Little to no blue bull presence	Little to medium blue bull presence	Blue bulls commonly present
Soil types	Heavy soils	Heavy to medium soils	Medium to light soils
Irrigation availability	Access to pre-monsoonal irrigation	Access to irrigation with monsoon onset	Only late access to irrigation (e.g. rental, canal dependent)
Tillage machinery availability	Timely availability of tillage machinery	Generally timely availability of tillage machinery	Little mechanization in village, long waiting times
Seed and fertilizer availability	Timely availability of seed and fertilizer	Generally timely availability of seed and fertilizer	Far away from markets and/or inadequate seed and fertilizer availability
Labour availability	Insufficient household labour and large landholding	Sufficient available household labour or small landholding	No timely labour available or renting out household labour
Collective action	High rate of other early planters	Some other early planters	Few to no other early planters

The study revealed two further, non-water-related, ecosystem factors that feature a collective action component and appear to constrain timely planting in some places: wild animal grazing and pest and disease pressures. Wild animal grazing specifically refers to blue bulls, the largest Asian antelope which is widespread in the region. Farmers reported that they frequently destroyed crops as they graze in large herds. While the government allowed farmers to cull blue bulls in 2015, their status as a holy animal adds a layer of complexity to the issue. To defend against them, farmers install whistling tapes, scarecrows, and fences, but these methods are not always effective, and herds of blue bulls can still trample or graze on nurseries and young rice plants. While not directly affecting planting dates, the problems caused by blue bulls do increase the level of risk faced by rice farmers. Those that plant earlier than others are more at risk of damage as their nurseries and fields are more prominent and attractive for grazing.

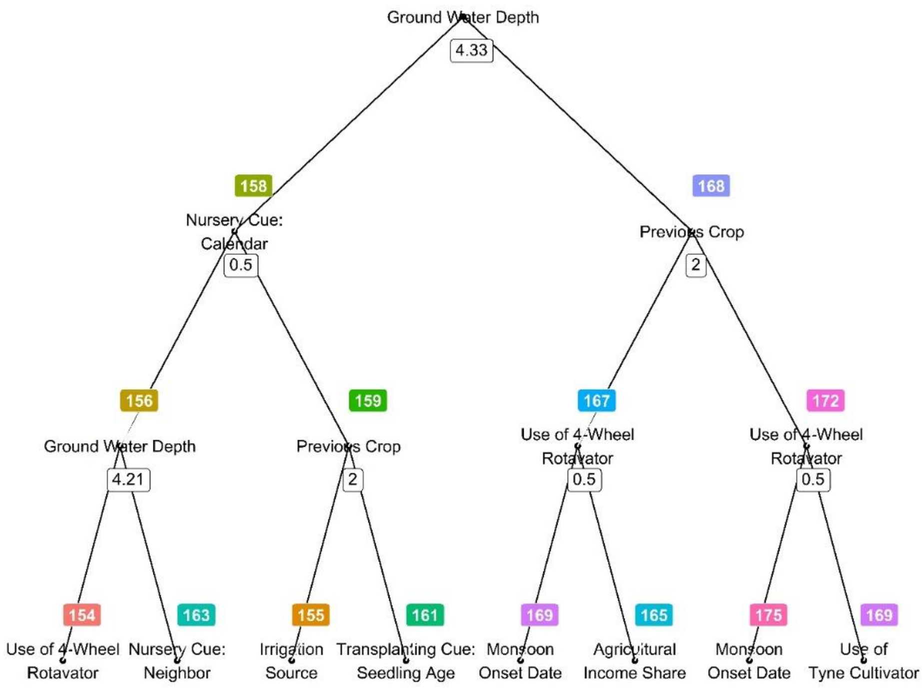

Figure 2.6 Representative tree (pruned) of the random forest model. This tree is closest in Euclidean space to most other trees and helps to derive heuristics from the model. Groundwater depth is a key separator for predicting planting time.

The same logic applies to pest and disease pressures as has been observed in other locations (Tscharntke et al., 2012). Farmers reported that they cannot plant much earlier than neighbouring farmers as their crops would otherwise succumb to heightened pest and disease pressures with pressure concentrating on the plots of early planters rather than being diluted across the landscape. Thus, early planting in a village is not only determined by access to resources, inputs, and technologies managed by single farmers. Rather, timely planting also depends on the ability and desire for synchronous early planting of neighbouring farmers—a challenge further complicated by high and increasing levels of land fragmentation in the region (Keil et al., 2019).

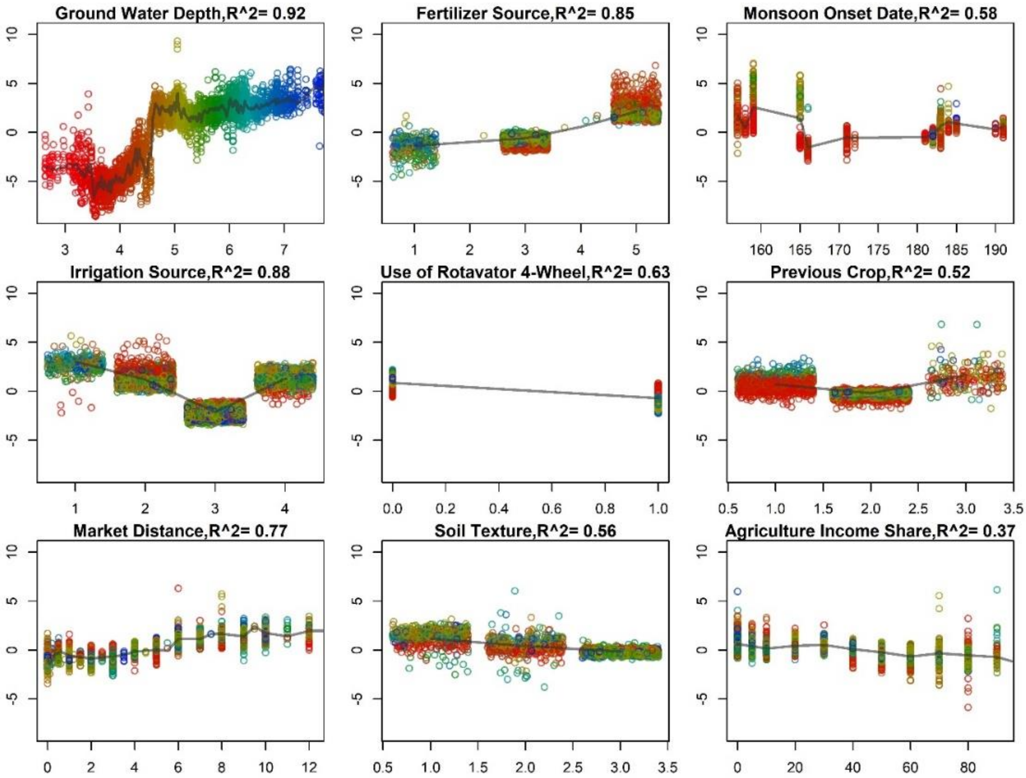

Figure 2.7 Partial dependency plots of the selected variables from the random forest model with observation points coloured by groundwater level. Larger values on the y-axis indicate later planting and, for the groundwater level, clearly show a critical threshold at ca. 4.5 m.

Village and household level: social factors

At the village level, timely availability of cash, labour, machinery for land preparation and irrigation, seed, and fertilizer at adequate qualities and prices constitute additional factors that influence planting dates. In contrast to water availability, these social factors tend to have only a few high scorings per village and different factors appear to be more relevant depending on the village in question, resulting in lower scores of the factor importance ranking across locations from the detailed dataset (Figure 2.4). Social factors were also attributed less importance by the random forest model, which may be because there were fewer social factor variables in the big picture survey and post-sampling social stratification was not feasible due to the large sample size and random household selection in each village. The factor rankings suggest that, at the regional scale, social variation at the village level (e.g. market distance, machinery availability) is more important than household-level differences within a village. Nevertheless, farmers did report that households with a low socio-economic standing generally face more hardship for accessing inputs. Altogether, it seems that not only availability of a given input is important; rather, farmers' capacity to purchase and use the input effectively is also crucial. This metric, however, was not captured in the big picture survey and therefore also not reflected in the random forest model.

Similarly, farmers reported that labour constraints are increasing and especially impactful for households with larger landholding who tend to rely on hired labour that is difficult to find after the onset of the monsoon when most labour is then engaged in transplanting rice on their own plots. Larger landholders with cash available thus tend to plant rice earlier than their neighbours to avoid labour shortages. Farmers in remote villages also noted that, in addition to machinery inputs and labour, quality seed and fertilizer at subsidized rates are not always available on time. For timely supplies, remote farmers would have to travel to distant market towns which is costly. And, the lack of collective action models complicates the mobilization of collective transportation, which would reduce individual costs.

In addition, finance to purchase inputs and labour scores highest among the social factors as a constraint to timely planting in the detailed survey. This is likely to reflect the difficulty to avail cash when needed. Some farmers reported that they use a credit card that is provided and subsidized by government initiatives, but most farmers borrowed cash from relatives or local moneylenders. Although credit sources were not explicitly recorded in the big picture survey, metrics for market integration such as distance to market and fertilizer sources may be good proxies. However, moneylenders and microfinance alone cannot provide a solution to these constraints. We therefore focus our subsequent discussions on increasing profitability, resource use efficiency, and business models for input and service provisioning that cater to different farmers' needs.

Soil and crop variety types also emerged as variables affecting timely planting in the detailed survey. Farmers indicated that different drainage classes (land types) tend to prompt different planting dates and variety choices. Differences in soil moisture retention led to a shorter growing season on land with faster drainage and thus shorter-duration rice varieties and later planting. If irrigation was available, however, farmers reported that, on preference, they made use of the early drainage of upland areas to plant vegetables after short-duration rice varieties. Many lower lying lands, on the other hand, were also prone to waterlogging and thus required earlier planting of longer-duration varieties so that transplanting and harvesting could both take place at desired soil moisture levels.

Enhancing farmers' capacity for timely rice planting in the Eastern Gangetic Plains

Ecosystem factors

Our results suggest that water-related factors most strongly shape rice planting date patterns in the Eastern Gangetic Plains. Research suggests that improving unreliable and expensive irrigation infrastructure is a pre-requisite for sustainable agricultural development in the Eastern Gangetic Plains (Shah et al. 2018). Two major initiatives are currently being promoted by governments and development organizations in the Eastern Gangetic Plains: (i) a centrally led initiative to electrify the countryside and (ii) a subsidized effort to scale-out solar irrigation. Both are promising initiatives that may significantly reduce the operational costs of pumping. The risk of depleting groundwater in the Eastern Gangetic Plains—that generally accompanies groundwater development—has been largely dispelled by previous studies (Muthuwatta et al., 2017; Shah et al., 2018b). If successful, many more farmers could gain pre-monsoon irrigation access because of these initiatives. They could be empowered to plant their crops in a timelier manner and reduce the level of climatic risks associated with delayed monsoon onset.

Spatial targeting in conjunction with supplementary investments in existing technologies could potentially enhance the effect of the regional initiatives to scale out low-carbon and affordable irrigation technologies. Our results suggest that areas with pre-monsoon groundwater tables below 4 m require alternatives to centrifugal pumps, such as electrically or solar-powered submersible pumps to provide affordable pre-monsoonal irrigation (Shah et al., 2018b). But, in areas with pre-monsoonal water tables at depths less than 4 m, increasing access to efficient diesel pumpsets may prove a more cost-effective approach in the near term (Urfels et al., 2020). For solar, the current subsidy schemes substantially reduce the capital investment costs for solar-powered irrigation systems. Its manufacturing costs are also decreasing and may enhance economic viability for future deployment, potentially superseding diesel pumpsets in the Eastern Gangetic Plains over the next decades (Shah et al., 2018b). Although several studies have been conducted on sustainable groundwater use in the area, including managed aquifer recharge systems, specific recharge processes and detailed aquifer maps remain a knowledge gap that needs to be filled to confidently design sustainable groundwater use scenarios (Reddy et al., 2020).

Wild grazing animals and pest and disease pressures further shape farmers' capacity for timely planting as individual early planted plots are more likely to face concentrated biotic pressures. These dynamics, although crucial for agricultural practices and critical for ungulate conservation, are not easily quantified (Prestele & Verburg, 2019; Tscharntke et al., 2012). Development of new survey instruments and use of new analytical methods are likely required to capture them. These shortfalls highlight remaining challenges in ecosystem services research and the design of agricultural development pathways that align with broader conservation targets. In addition, our findings highlight that building agroecosystem resilience involves developing solutions to collective action problems which need to be addressed at larger spatial scales than the plot or household level (Prestele & Verburg, 2019).

Social factors

A strong agricultural goods and service economy (i.e., market integration) appears to contribute to farmers' ability to plant early. Specifically, our data corroborate evidence that access to labour, tillage, and subsidized seed and fertilizer markets frequently prevents timely planting and requires innovative solutions (Keil et al., 2019; Shah et al., 2018b). Strategies to strengthen land preparation machinery service markets could consider the spatial gradients of commercial orientation and mechanization both at the community level and at the household level. Subsequently, it is not necessarily large-scale infrastructure projects, but locally targeted investments that are tailored to farmers' needs, that may allow farmers to better tackle specific bottlenecks and increase their flexibility in making decisions.

Innovating agricultural input markets to support timely planting will inevitably reveal synergies and trade-offs with other sustainability targets. These should be considered by policy makers to increase investment effectiveness, as has been recently shown in other places. For example, zero-tillage wheat, which is mainly provided on a pay-per-hour/ha service by private machinery owners, has been shown to provide "win-win" scenarios for farmers, but adoption is largely inhibited by a lack of awareness among poorer farmers. The possibility to use tractors for both zero-tillage wheat and direct seeded rice planting may further enhance attractiveness to farmers and service providers. But while mechanical rice planting continues to face problems, improvements in custom hiring of tillage services may provide welcome synergies for timely planting until more effective models of mechanized rice planting that are also attractive to poorer farmers are positioned for large-scale adoption. In the meantime, tillage service providers may play a crucial role in coordinating synchronous planting, hence saving fuel by reducing travel between villages and assisting farmers to overcome landscape-level ecological pressures. Highlighting the labour-saving benefits of mechanical planting is another consideration. But, just as with irrigation, investing in human capital and strengthening the supporting industry of mechanics, vendors, and other private sector actors along the value chain are required to leverage cross-sectoral benefits and provide potential employment options for agricultural laborers that, in some areas, may be put out of business.

Our results further highlight the value of developing spatial datasets of social variables to build resilient agroecosystems. Spatial variation of agroecosystems matters for sustainable agricultural development pathways because nuanced differences in the social-ecological setup produce different decision-making patterns. For example, investments in irrigation should be guided by differentiations between upstream/downstream and flooded/non-flooded canal areas, submersible pumps, and centrifugal pumps with pre-monsoon groundwater levels below or above 4.5 m. Furthermore, data on access to inputs and the quality and timeliness of service provision can be collected at the household or village level. The number of tractors per capita at the village level might, for instance, be a useful overall measure, but ideally, data on all key inputs should be collected.

Embellishing climate services and dynamic planting date advisories constitutes another channel through which farmers' capacity for timely planting can be enhanced. Both farmers and agronomists use cropping calendars to characterize planting and harvesting times of crops in different agroecological zones. Streamlining activities such as application of irrigation, fertilizers, pesticides, and herbicides into these calendar-oriented formats that align with the phenological development of crops can consolidate research findings for effective communication with end-users (Subash & Gangwar, 2014). Our study showed that farmers in the region use a local calendar of 2-week periods for temporal orientation. We therefore recommend that farmers' temporal heuristics could be integrated and consolidated in extension efforts to ease communication barriers and enhance the potential for farmers' adoption of resilience enhancing practices.

Building resilient agroecosystems through timely planting

Building sustainable and resilient agroecosystems constitutes a major global policy target, but understanding regionally specific incentive structures, factors, and barriers to catalyse transformative changes remains a crucial challenge. Our findings provide new methodological and practical insights on agroecosystems as social-ecological systems with special regard for climate change and food security. Integrated research frameworks in the field of food security and climate change have been continuously refined for more than two decades. Digitalization and ongoing advances on spatial and detailed data collection, analytics, and decision support systems can and must be leveraged for fine-tuning the evidence base by crystallizing regionally specific elements that influence behaviour and outcomes. Critical future steps include (a) producing and comparing results to other regions and social-ecological systems to better understand their differences, (b) including the factors and processes that our analysis unveiled in regional modelling and integrated ex-ante assessments, (c) leveraging synergies and trade-offs with other sustainable agricultural technologies, (d) increasing the availability of high-resolution spatial data, and (e) developing targeted and evidence-based programs with a spatially specific and holistic theory of change (Van Noordwijk, 2019).

In addition to the research needs outlined above, policy makers in the Eastern Gangetic Plains can support farmers through multifaceted efforts to improve access to irrigation, labour, tractors, and seed and fertilizer, as well as conserving wild animals in ways that reduce risk of crop damage. Specifically, metered electricity connections and submersible pumps should primarily be encouraged in areas with pre-monsoonal groundwater tables below 4 m. Solar irrigation systems should be targeted for centrifugal pumps in areas with shallower groundwater tables. Similarly, scale-appropriate agricultural mechanization with pro-poor models of service provision to facilitate smallholder access to machinery requires acceleration in areas of low technology penetration (Paudel et al., 2019). Furthermore, seed and fertilizer markets as well as other inputs should be made more easily available to remote villages, e.g. through stimulating private sector extensions of agricultural input providers. And, conversely, policy should also focus on encouraging improved resource use efficiencies to reduce input needs. Collective action models for achieving more synchronous planting as well as early warning systems should be established to avoid damages from wild animals, pests, and diseases with information disseminated through existing extension networks and the private sector.

Studying agroecosystem at the regional scale through a mixed-methods social-ecological approach: challenges and opportunities

Our mixed-methods approach identified key issues and dynamics for timely rice planting in the Eastern Gangetic Plains. Using machine learning tools to analyse a combination of big picture and detailed survey datasets assisted in (i) uncovering diverse pathways through which different variables shape farmers' planting behaviour, (ii) highlighting non-linear critical thresholds of important variables (e.g. groundwater level) and interaction effects between variables (e.g. where certain social conditions reduced or amplified the effect of groundwater level), and (iii) identifying factors that the big picture surveys do not reveal, such as grazing wild animals and unwillingness to plant early due to heightened pest and disease pressure—both of which contain properties of classical collective action problems. Our approach can be used for future studies to build systematic evidence for key sustainability challenges in complex social-ecological systems amidst increasingly rapid global environmental change. The approach offers a balance of analytical depth and size of the inference space. Ideally, big picture surveys should follow and be informed by the detailed surveys, which should be taken into consideration for future study designs. We found that potentially valuable variables, especially social variables, that measure the timeliness of village-level service provision were not included in the big picture survey. We can only recommend for these to be included in future data collection efforts and act as a tool to stratify the sampling. We aimed to show that such an approach can effectively complement the shortcomings of the two types of datasets and methods of inference each one makes possible, and thus contribute to spanning the gap between regional programming and context-specific interventions. These will be increasingly important to ensure a sustainable transition of the food system in the future.

Major challenges also pertain to the conceptual development of agroecosystems as social-ecological systems and resilience in agricultural development. While several authors have developed social-ecological systems frameworks for sustainable agricultural development and pointed at required modifications, few examples of their operationalization exist (Lescourret et al., 2015). From a user-centred perspective, farmers' capacity to adapt to the environmental change and build resilience against environmental shocks such as late monsoon onsets depends on their levels of access to resources (e.g. water) and markets (e.g. labour, fertilizer) and is partially mediated through technology (e.g. pumps, tractors). The system boundaries can be scaled from the farm to the community and to the landscape level—with important interactions between the scales and different possibilities for interventions at each scale. From this perspective, timely planting requires flexibility regarding the use of water and other agricultural inputs. At the landscape level, this means that farmers' resilience hinges on the response of the resource base (e.g. water resources) and input markets in the face of external shocks (e.g. multi-season drought effect on groundwater or oil market price fluctuation for tractor service provisions). Enhancing farmers' timely access to inputs, while coupling these efforts with management practices to improve resource use efficiency, enables them to raise profits and yields amidst progressive global change, while enabling access to water resources beyond critical technological thresholds buffers farmers against moderate environmental shocks. But our research cannot immediately be extended to drastic disturbances in the climate system as the effects on input markets and the resource base might differ and invoke other tipping points. Achieving agroecosystem resilience beyond the level discussed in this study requires further research to reveal the effects of more complex and more drastic global change processes and find entry points to increase farmers' resilience against such disturbances (Schipanski et al., 2016).

Conclusion

Smallholders in the Eastern Gangetic Plains rely on timely rice planting for building resilient agroecosystems amidst progressive environmental change. In this study, we used a novel, social-ecological systems informed, mixed-methods approach. This approach revealed for the first time that farmers' capacity for timely planting is primarily predicated on the timely availability of pre-monsoonal irrigation, while social factors such as timely access to farm inputs and machinery act as secondary constraints for timely planting for many farmers in the region. In addition, absence of collective action in the form of synchronous rice planting to reduce pressure from pests, diseases, and grazing animals on individual plots emerged as an additional, but not quantified constraint.

Based on these finding, we argue for advanced research to support spatial targeting of pro-poor investments to overcome spatially explicit barriers to timely use of irrigation, machinery, and farm inputs. Doing so will require new data collection efforts that quantify the spatial structure of these barriers. In addition, finding models that can solve collective action problems, at times perhaps through creation of new service models in the private sector, and improving resource use efficiencies to make farmers less reliant on external resources will also enhance farmers' capacity for timely planting and thus agroecosystem resilience. Lastly, the sustainability of some of these interventions also depends on the resilience and sustainability of the resource base as well as input, machinery, and labour markets. Understanding these will require research beyond the agroecosystem, e.g. on the food system, on how these system components behave amidst global environmental change.

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Chapter 3

Irrigating the crops

Drivers of groundwater utilization in water-limited rice production systems in Nepal

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Abstract

Most rice farmers in Nepal's Terai region do not fully utilize irrigation during breaks in monsoon rainfall. This leads to yield losses despite abundant groundwater resources and ongoing expansion of diesel pumps and tubewell infrastructure. We investigate this puzzle by characterizing delay factors governing tubewell irrigation across wealth and precipitation gradients. After the decision to irrigate, different factors delay irrigation by roughly one week. While more sustainable and inexpensive energy for pumping may eventually catalyse transformative change, we identify near-term interventions that may increase rice farmers' resilience to water stress in smallholder-dominated farming communities based on prevailing types of irrigation infrastructure.

Introduction

Feeding a projected global population of 9 billion in 2050 will require focused efforts to address trade-offs and capitalize on synergies between natural resources management and food security objectives, necessitating broad-based transitions to sustainable intensification technologies and management approaches (Pretty & Bharucha, 2014). The Eastern Indo-Gangetic Plains of South Asia host the world's highest density of rural poor, pervasive yield gaps, and relatively abundant water resources (Bharati et al., 2016; Jain et al., 2017). They are therefore a global priority for sustainably increasing food production while ensuring that yield gains are accompanied by acceptable social and environmental costs and that long-term viability of the resource base is maintained.

Despite an overall abundance of water resources, water stress is one of the main factors limiting staple crop productivity in the Eastern Indo-Gangetic Plains. Increasingly erratic monsoon-season (kharif) precipitation poses a particular threat to the rice-based production systems that dominate the landscape (Turner & Annamalai, 2012). Many farmers in the Eastern Indo-Gangetic Plains apply supplementary 'life-saving' irrigation to overcome rainfall deficits during kharif, which is enabled by shallow water tables and broad coverage of groundwater irrigation infrastructure. Nevertheless, several studies suggest that irrigation use is typically 'too little, too late' and that even resource-poor farmers may improve yield, profitability, and resilience with more judicious water use (Kishore et al., 2014). Helping more farmers transition from 'life-saving' to 'productivity-enhancing' irrigation strategies will therefore be crucial for establishing pro-poor sustainable intensification pathways in the Eastern Indo-Gangetic Plains, particularly in view of contemporary climate variability and progressive change.

In contrast to the Western Indo-Gangetic Plains in India and Pakistan, where groundwater decline jeopardizes sustainability, abstraction in many parts of the Eastern Indo-Gangetic Plains is judged to be well within the limits of safe operating space, with significant scope for increased use (Bharati et al., 2016). Government of Nepal estimates suggest that groundwater use in the region could increase more than fivefold before breaching sustainable abstraction thresholds (Shrestha et al., 2018). Meanwhile, diesel-powered shallow tubewells are quickly growing in number, whereas investment in large canal infrastructure is diminishing (Bharati et al., 2016). This presents an opportunity to increase productivity-enhancing irrigation use in the Eastern Indo-Gangetic Plains, with the proviso that recurrent monitoring and adaptive management are essential to detect and mitigate early signs of receding groundwater levels.

However, studies increasingly recognize that infrastructure development alone is insufficient to achieve optimal use of water resources (Qureshi et al., 2015). Shallow tubewell-based irrigation is encouraged or discouraged by farm- and community-scale decisions, along with broader economic and policy incentives (Kishore et al., 2014). Understanding and harnessing these socio-hydraulic dynamics is particularly important in regions like the Eastern Indo-Gangetic Plains that are dominated by smallholder agricultural systems in which farmers face seasonal cash liquidity constraints, the costs of pumping are high, farmers are risk averse, and tenancy arrangements often discourage investments in intensification (Jain et al., 2017; Sugden et al., 2014a).

This study characterizes drivers of shallow tubewell irrigation use to identify development support pathways that are likely to increase irrigation use and climate resilience among rice farmers in Nepal's component of the Eastern Indo-Gangetic Plains, the Terai – the country's 'breadbasket' lowland region, which runs parallel to its southern border with India. To understand the complexities of socio-hydraulic systems, an interdisciplinary perspective is essential (Massuel et al., 2018). We use a mixed-methods approach to characterize shallow tubewell irrigation infrastructure and farmers' decision processes around its use for kharif rice. Emphasis was placed on diesel-pump-based systems, the dominant form of irrigation in much of the Terai. The Terai is similar in physiography and cropping patterns to the neighbouring Indian states of Bihar and eastern Uttar Pradesh, and also north-eastern Bangladesh, although in Nepal agricultural policies and support programmes are less generous and rural infrastructure is generally underdeveloped (Shah et al., 2009).

Study area

This study was conducted in three districts of Nepal's Terai: Rupandehi, Banke and Kailali. These districts span a co-varying gradient of precipitation and wealth (Figure 3.1). They were chosen in consultation with senior irrigation policymakers who verified the district's representativeness for the Terai. In each of these districts, around 80% of the precipitation and river discharge occurs from July to October, during the monsoon (Shrestha et al., 2018). Flooding is common during this period. River flows diminish significantly shortly thereafter, hindering the use of canal-based surface water irrigation on a year-round basis (Bharati et al., 2016). A large part of Nepal's cultivated land area (ca. 40%) is reportedly reached by canal irrigation schemes, but considerably less is actually used. But an estimated 42% of the Terai's farmers do have access to shallow tubewells, according to the Nepal National Sample Census of Agriculture 2011–2012 (CBS, 2012).

The aquifers in the Terai are complex and consist of poorly ordered alluvial sediments that generally become finer towards the south. An unconfined aquifer extends to a depth of around 50 metres below ground level but varies in thickness, sometimes even at the village scale. These unconstrained aquifers may be underlain by a confined aquifer that can extend to a depth of 200 m (Bonsor et al., 2017). Well yields vary from a few litres per second to more than 10 L/s. Bharati et al. (2016) report an average annual water table depth of 4.6 m across our study areas, with a seasonal fluctuation of about 3 m and a peak in August following recharge from monsoon precipitation. However, no reliable long-term water table data are publicly available, and levels may vary between locations.

Methods and data sets

Mixed-methods approach

To identify drivers of rice irrigation practices in areas where shallow tubewells predominate in the Terai, we employed a mixed-methods approach including semi-structured interviews with farmers, policy makers, and farming communities. These were coupled with household surveys and ethnographic decision-tree models (Roth & Botha, 2009). Interview and survey data were used to define the variables and sequences of decisions represented in the decision-tree models. An overview of data sets, figures and tables, and analytical approach used in their development is presented in Figure 3.2.

Site selection

We used time-series estimates of net primary productivity from remote-sensing imagery to identify villages using a range of irrigation practices. Net primary productivity values correlate with crop water uptake (Ciais et al., 2005). Therefore, areas with high temporal variation in agricultural net primary productivity generally have unreliable access to or sub-optimally applied irrigation, while areas with low net primary productivity variation can be understood as having less moisture limitation of agricultural productivity.

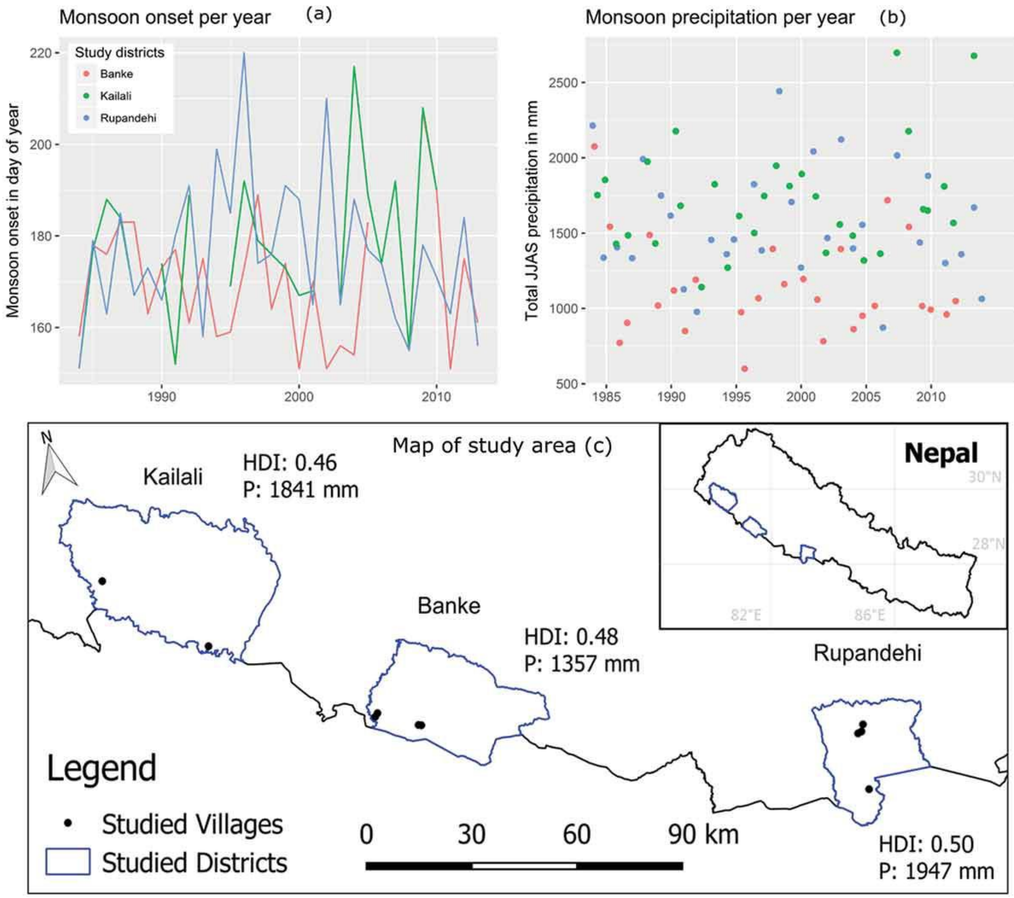

Figure 3.1 Study area: (a) monsoon onset by district; (b) variability in total June–September precipitation; (c) locations in the Terai of Nepal where household interviews and surveys were conducted.

As a proxy for irrigation, we used MODIS17A3H annual net primary productivity raster data from 2000 to 2014 (500 m2 grids) to calculate the standard deviation of net primary productivity for each cell over a 14-year period. Then, we identified areas with a large range of irrigation use surrounding them by assigning each cell the standard deviation of its 3 × 3 neighbourhood. We identified the villages in the upper 10% of variability in access to irrigation surrounding them using a village location database based on a village data shapefile obtained from the Survey Department of the Ministry of Agriculture, Land Management and Cooperative. These villages (four in Rupandehi, three in Banke) were earmarked for our study. Selected locations were cross-checked with agricultural experts in each district to verify the presence of kharif rice production and shallow tubewells. This method produced results for

Rupandehi and Banke, but the results for Kailali were problematic due to high occurrence of non-cropped areas. Thus, we omitted the neighbourhood calculation for Kailali and selected one village in the upper 10% and one village in the lower 10% of interannual net primary productivity variability.

Interview and survey data

Data were collected between September and December in 2016. Key informants (27) were chosen from government organizations with a mandate related to irrigation. These included senior officers of the Department of Irrigation, Department of Agriculture and Department of Electricity at the district level. These officers were approached at least twice, once at the beginning of the study and once at the end, to reconfirm responses. At the local level, Village Development Committee secretaries and other local leaders were interviewed on a recurrent basis as questions arose.

At the farm level, semi-structured household interviews (116) and more formal household surveys (94) were conducted. At least 12 household heads were randomly interviewed in each village, covering all sub-village administrative units (blocks). Following interviews, short ad hoc group discussions were often held with neighbours. Data from these sources were used to cross-check previous results and were added to the household interview data set. We also used secondary data from the Nepal Agriculture Survey and the National Census of Agriculture, collected in 2011–12 (CBS, 2012), along with data from rice production practice surveys (1052 households) in the Terai collected by the Cereal Systems Initiative for South Asia (CSISA) in 2016 (Paudel et al., 2017).

Shallow tubewell irrigation characteristics

To develop the context in which decisions are made and to aid interpretation, we used several auxiliary data sets to complement the ethnographic decision-tree models. The spread of shallow tubewells was estimated with data from the Nepal Agriculture Survey (2011) and the CSISA production practice survey, as described earlier. Pricing data and technical specifications for pumps and tubewells were collected from machinery dealers and well drillers. Irrigation costs paid by farmers were estimated through surveys and household interviews. Interview data were triangulated with several key informants and farmers.

Potential profits from supplementary irrigation applied to kharif rice were estimated by combining operational cost data for irrigation from our own surveys with 'farm gate' price data for rice from the Food and Agriculture Organization of the United Nations (FAO) and the incremental yield benefits of additional irrigation estimated by linear regression from the CSISA production practice survey. An asymptote regression fit would be appropriate, but we lacked sufficient observations of farmers applying more than three irrigations. So we focused on the yield increase associated with one, two and three irrigations, which can be described by a linear fit (Figure 3.3). The benefit is expected to level off for higher numbers of irrigations, as other inputs such as seed or fertilizer may become limiting factors; it will also vary significantly by year, depending on rainfall patterns. We take the increased profit from additional irrigation (in USD per hectare) to be

$$(FGP \times YI) - (IP \times ID \times 10{,}000 \times EF) \qquad (3.1)$$

where FGP is the farm grate price of rice (USD/kg), YI is the yield increase per irrigation (kg/ha), IP is the irrigation water price (USD/m^3) translated from hourly rates charged in the field at an assumed discharge of 10 L/s, ID is irrigation depth (m) (Sudhir-Yadav, Humphreys, Kukal, Gill, & Rangarajan, 2011), and EF is water losses of 33%, commonly found in basin irrigation. The SD in yield per hectare translates to USD 18 per hectare using the same assumed irrigation costs. We assumed USD 1 per litre of diesel, USD 3 per hour of pumping as a pump rental price (based on key informants), USD 260 per ton of rice produced (based on FAO information), and 368 kg rice yield increase per irrigation (based on linear model fit to rice crop cut survey data; coefficient 368.46, standard error 36.34, $p \leq 2e\text{-}16$).

Precipitation information (1984–2013, Figure 3.1) was drawn from government data from stations in Bhairawa (Rupandehi), Nepalgunj (Banke) and Sandepani (Kailali). The monsoon onset dates used in Figure 3.1 (a) were calculated using the methods of Fitzpatrick, Parker, and Willetts (1998). Human Development Index (HDI) is based on United Nations Development Programme (2014). The land fragmentation figures in Figure 3.3 (a) are based on Central Bureau of Statistics (2012) data.

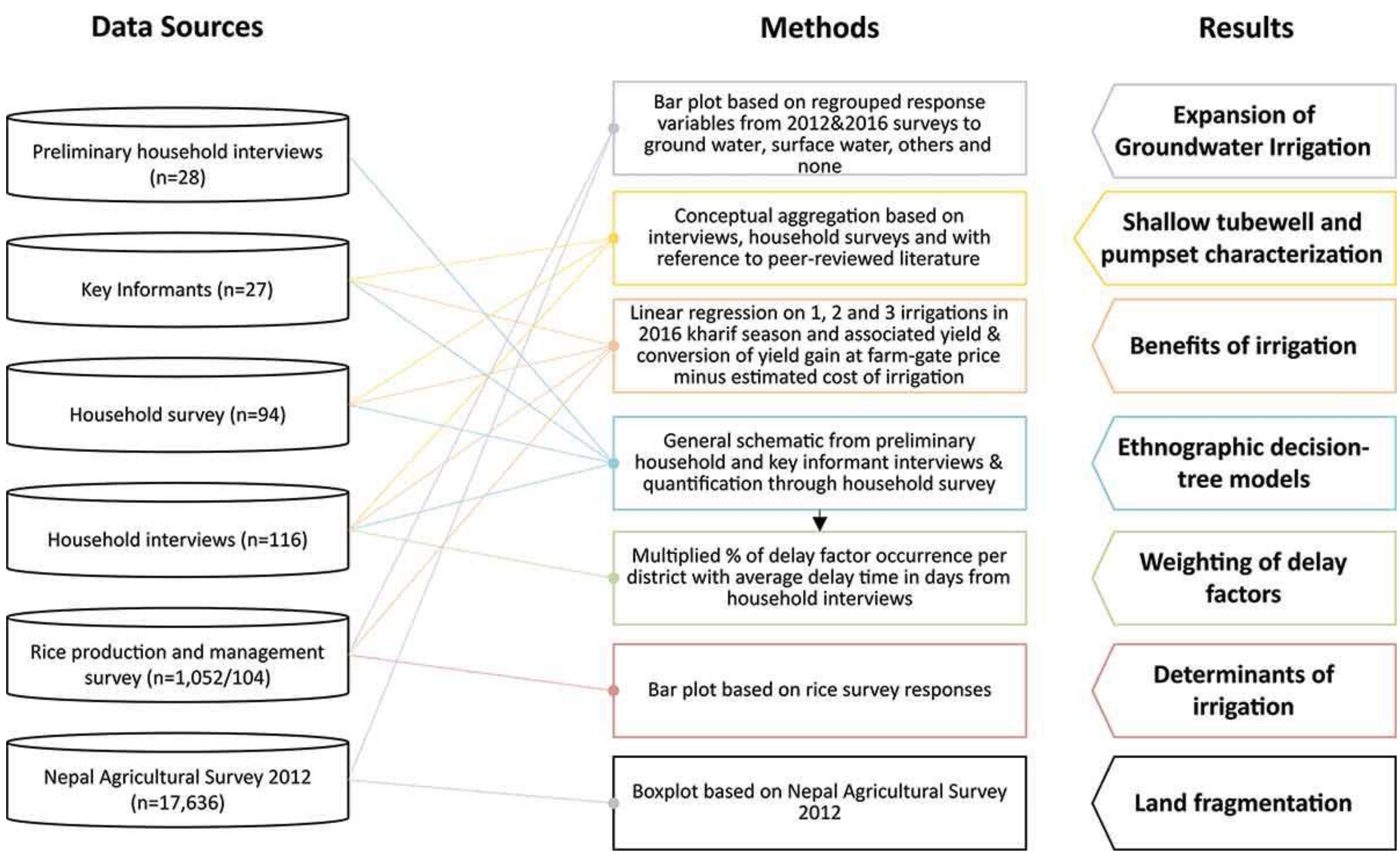

Figure 3.2 Overview of the data collected, methods employed, and results utilized in this study.

Ethnographic decision-tree model construction

Ethnographic decision-tree models are flow charts that aim to capture decision-making processes from the language and concepts respondents use rather than a predefined conceptual framework. They are based on interviews and subsequent cross-validation (Roth & Botha, 2009). They are suitable for representing decision processes of rather homogeneous groups, such as farmers within an agro-ecosystem or entrepreneurs within a city (Roth & Botha, 2009). Our model was based on preliminary unstructured interviews with farmers to identify factors that influence the choice to provide supplementary irrigation to rice. Factors that negatively influence or delay farmers from choosing to provide supplementary irrigation were also identified. Our approach followed Roth and Botha (Roth & Botha, 2009) and was based on evidence that farmers' general perceptions are sufficiently reliable indicators of local trends and patterns (Banerjee et al., 2018). We first built a generalized decision schematic through key informant interviews with farmers and their perceptions of decision points and factors that influence them. To quantify these relationships, results from the household survey were used to assign each branch of the decision tree a weight reflecting the proportion of farmers making that decision. We then compared the quantifications across districts.

Ethnographic decision-tree models were only constructed with farmers that have access to shallow tubewells for supplementary irrigation. The decision process is initiated by farmer assessments of the need for irrigation and may be reset at any point that sufficient rainfall is received before irrigation has been applied. Similarly, to highlight bottlenecks for the use of supplementary irrigation for kharif rice, we represent changes in decision preferences only in the case of irrigation delay, not for situations in which farmers choose to irrigate unencumbered.

The ethnographic decision-tree models have two components: irrigation triggers and delay factors. The first refers to when and under what circumstances farmers decide to apply supplemental irrigation. The CSISA production practice survey (Paudel et al., 2017) indicates that plant (59%), soil (56%), weather (43%) and neighbouring farmers' practices (31%) play a role. Farmers indicated that disagreements among them on the status of their crops or soil were relatively rare. The terminology used to describe crop and weather tended to be subjective and idiomatic (e.g. 'plants smile', 'clouds look fatter'). Soil moisture was most commonly described in terms of the width of cracks that form as rice fields dry over successive days without floodwater. These were taken as 'no cracks/hairline cracks', 'small cracks' (up to 2.5

cm wide), and 'large cracks' (over 2.5 cm). Since the soil criteria are readily observed by farmers and fairly consistently applied as a management rule, we decided to limit ethnographic decision-tree model quantification to soil conditions to maintain parsimony, reduce translation error and ease comparison between farmers.

Irrigation delay factors are the second component. Shallow tubewell delays are irrigation lags associated with turn-taking as farmers wait to use shared well infrastructure. Energy delays happen when electricity or fuel (depending on the type of pump) is needed but unavailable. Liquidity delays refer to the inability of farmers to pay for energy or rental of a pumpset when required. Pumpset delays are caused when a farmer must borrow or rent a pump. Transport delay refers to the transport of pumps to boreholes in command areas lacking road access. This because moving engines across established fields can damage crops; it is generally only permitted if neighbouring farmers have already irrigated. Labour delays refer to a dearth of farm labour to oversee irrigation. As irrigation is generally considered a task for men, some households engage relatives or friends if male members are not present. Finally, maintenance delays refer to the time it takes to source spare parts or engage a technician to repair a broken pumpset.

Results: shallow tubewell irrigation characteristics and use patterns

Key shallow tubewell irrigation characteristics

Pumpsets deployed for shallow tubewells in the Terai are described in Table 3.1. Using standards described by Bom et al. (2001), oversized and inefficient pumpsets of 5 horsepower or more are common. Farmers and agricultural machinery dealers differentiate between large pumps (5–10 HP, not easily transportable) and smaller and more portable pumps (3–5 HP). These might seem more suitable for vegetable cultivation. But at a constant discharge, the horsepower requirement of a pump depends on system head (the pressure required to move water through the system). With well yields of ca. 10 L/s, and only a few metres of system head, the smaller pumps are adequate. With increasing system head (e.g. because of several hundred metres of delivery pipes) higher horsepower is warranted, or discharge may decrease.

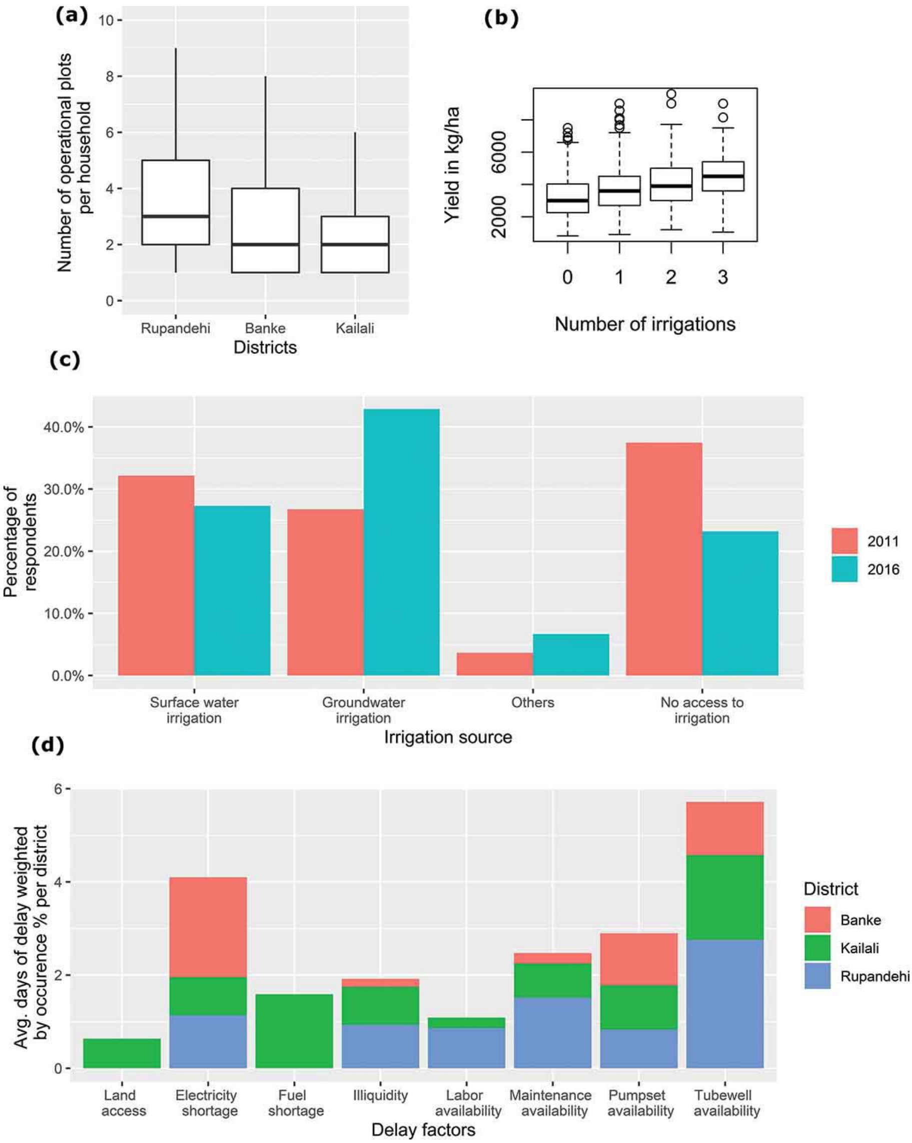

Figure 3.3 Shallow tubewell irrigation characteristics: (a) land fragmentation in western Terai; (b) yield increase per irrigation (Paudel et al., 2017); (c) use of groundwater and surface water irrigation across study districts in 2011 and 2016 (d) relative importance of supplementary irrigation delay factors reported by kharif-season rice.

Table 3.1 Overview of locally available pumpsets.

	Capital expenditure (USD)	Operational expenditure (USD/h)	Power (HP)	Mobility	Popularity of *kharif* rice irrigation
Large diesel pumpsets	350–650	1–2 (0.003/m^3)	5–10	Immobile, transported by bullock cart	High. Regarded as strong and durable. Status symbol.
Small diesel pumpsets	250–450	0.3–0.7 (0.014/m^3)	3–5	Mobile, transported by bicycle	Low. Regarded as weak and easily damaged.
Electric pumpsets	150–250	0.07–0.12 (0.042/m^3)	1.5–2.5	Mobile, transported by bicycle	Medium. Inexpensive and efficient, but depends on unreliable and hard-to-get electricity.
Rented pumpsets	0	3–4.5 (0.083/m^3)	3–10	Depends on rented pumpset	High, but depends on availability, social capital and cash/credit availability.

The distribution of small and large pumpsets is nonuniform: 72% of small pumpsets owned by surveyed households were found in Banke District, but only 18% of large pumpsets. The reasons for this disparity are not clear, but household survey respondents said that high mobility of the pumps, a lack of financial liquidity and a relatively high irrigation frequency with lower energy costs are the main drivers of the preference for small equipment. The smaller pumps, primarily imported from China, are perceived as less durable, while the larger pumps, primarily from India, are considered strong and more reliable, although their higher cost and power make them a worse fit for most shallow tubewell infrastructure.

Between 2011 and 2016, groundwater abstraction in the Terai using shallow tubewells increased by approximately 15%, while surface water irrigation decreased by roughly 5% (Figure 3.3). Data from the CSISA production practices survey also suggests future growth in shallow tubewell infrastructure, with nearly half of the respondents planning to provide supplementary irrigation to kharif rice more frequently. In addition, 34% of farmers surveyed indicated their intention to purchase shallow tubewell technologies (e.g. boreholes, pumps, piping) in the next year. This is not surprising given that yield benefits may bring substantial economic benefits (Table 3.1). Even in a 'good' monsoon, clear yield benefits can be expected from increasing supplementary irrigation intensity. The 2016 CSISA survey shows that farmers produced 368 kg/ha more rice, on average, when irrigating a first, second or third time (SE 34 kg/ha); very few farmers irrigated four or more times. The impact of additional irrigations, as well as the timing of irrigation and growing-season weather, are important but beyond the purview of this analysis. Based on current practices in the Terai of Nepal, applying additional irrigation is generally lucrative for pump owners and potentially for pump renters, if rental prices can be reduced.

From the farmer and household survey, as well as key informant interviews, operational aspects emerged as another factor of considerable, and perhaps intensifying, importance to groundwater irrigation. Land fragmentation, measured as the number of operational fields maintained by a farm household, decreases from east to west, with an interquartile range of 2–5 non-adjacent plots per household in Rupandehi, decreasing to 1–3 in the far-western Kailali District (Figure 3.3). These data indicate that transaction costs for shallow tubewell use are much higher in Rupandehi than in Kailali.

Shallow tubewell irrigation use patterns

Most surveyed farmers decide to apply supplementary irrigation to rice in the kharif season based on visual observation of soil cracking as drying occurs; they wait until large cracks (over 2.5 cm) are present before irrigating (Figure 3.4). But criteria differ between districts, with 47% of the farmers in Banke waiting for large cracks, whereas 68% and 71% of farmers wait for large cracks in Rupandehi and Kailali, respectively. Key informant interviews indicated that Banke farmers tend to irrigate earlier because of access to electric pumps and prevalence of small pumpsets, which are less expensive to operate than the large pumpsets mostly found in Rupandehi and Kailali. Our data suggest that most farmers do not recognize the link between delayed irrigation and yield outcomes, as irrigation is often considered as a mechanism to save the crop rather than as a productivity-enhancing investment, and farmers often attribute yield penalties to inferior quality of groundwater compared to rainwater.

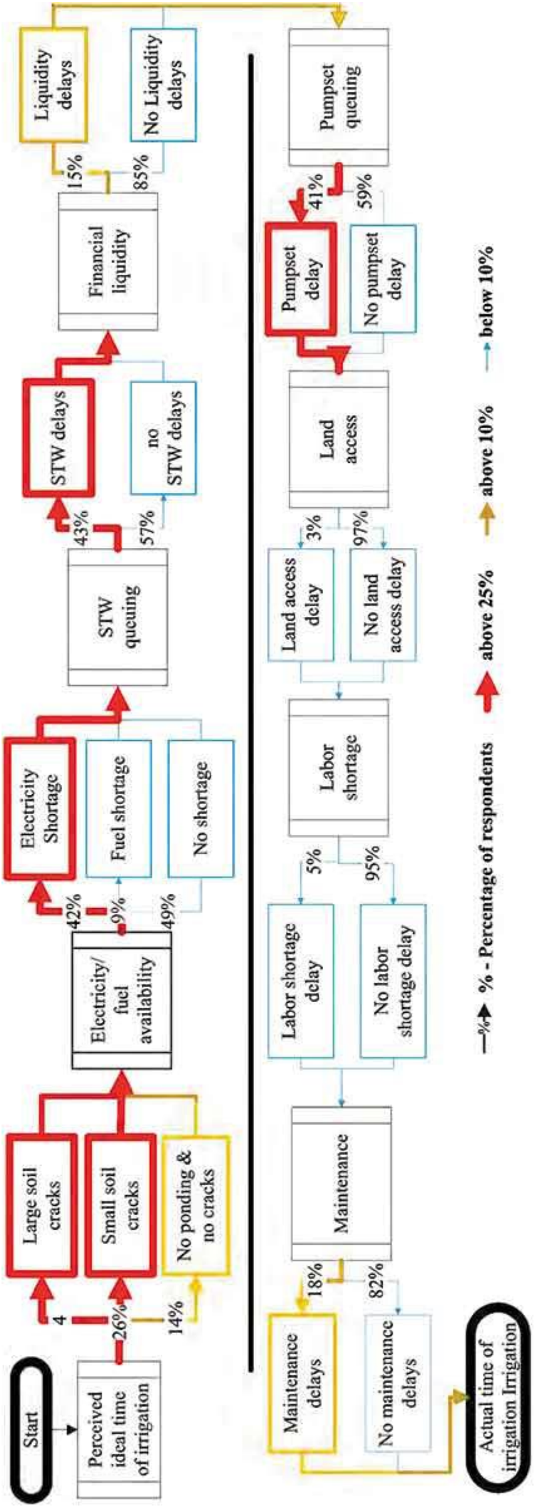

Figure 3.4 Quantification of ethnographic decision-tree models regarding the decision to use shallow tubewell irrigation, based on household survey results in all three study districts. The decision process can be restarted any time rain occurs.

Table 3.2 Irrigation delay factors reported by monsoon-season rice farmers, with average delay and percentage of occurrence in each district.

		Occurrence (%)		
Delay factor	Average delay (days)	Kailali	Banke	Rupandehi
Transportation	7	9	0	0
Electricity shortage	3	27	71	38
Fuel shortage	5	32	0	0
Illiquidity	3	27	6	31
Labour availability	5	5	0	17
Maintenance availability	4	18	6	38
Pumpset rental	3	32	37	28
Queuing at shallow tubewell	4	45	29	69

Factors influencing farmers' choice to delay kharif-season supplementary irrigation of rice, weighted by their percentage of occurrence and average time of delay, are presented in Figure 3.4 and Table 3.2. Pumpset rental and queuing at shallow tubewells are major delay factors in all districts. In Kailali and Rupandehi, maintenance and liquidity constraints cause delays, pointing to problems with the availability of overly expensive and high-horsepower diesel pumpsets, primarily from India. Differences between land access and labour availability reflect higher rates of male labour out-migration in Rupandehi than in other districts (MOL, 2017). Land access also reflects older and harder-to-transport pumpsets being used in Kailali. In Banke, electricity shortages and poor maintenance of pumps are important constraints. Based on these results, we discuss potential and complementary policies and development interventions that can be applied at relevant spatial scales and that could help optimize the use of supplementary irrigation for kharif-season rice in the Terai in the face of increasing precipitation uncertainty.

Nearly half (47%) of all delay pathways pertain to one of the following four pathways: only electricity supply constraints (23%); only shallow tubewell queuing (8%); only pumpset delays (6.7%); and all the three previous factors together (9%). Once a decision has been made to irrigate, on average farmers reported that total delay (after the decision) amounts to one week, and that irrigation takes place 13 days after the last rainfall event (12.9 days for electricity delays, 10.4 days for queuing delays, 11.3 days for pumpset rental delays, and 15.25 days for all three occurring together).

Discussion

All three districts seem to follow a similar overall development trajectory of increasingly erratic monsoon rainfall to which farmers respond through shallow tubewell expansion. But late irrigation scheduling and delay factors reduce productivity and production stability. This is reflected in generally long delays for queuing for wells and pumpsets in all districts. On closer inspection, however, precipitation and wealth differences between the districts arguably attune them to differing configurations of the same overall development trajectory. Most notably, Banke receives considerably less rainfall, leading to coordinated government investments in agricultural electrification and thereby incentivizing farmers to invest in electric pumpsets. This is reflected in the finding that unreliability of electricity is more critical in Banke than in the other two districts. Higher moisture stress and familiarity with smaller-horsepower electric pumpsets may also explain the prevalence of smaller-horsepower diesel pumpsets in Banke than in Kailali and Rupandehi.

Kailali and Rupandehi receive similar amounts of precipitation, but Rupandehi is wealthier. Increasing labour shortages (due to structural changes in the economy away from agriculture) and less fuel shortages are arguably a sign of this disparity. Similarly, land access issues persist in Kailali but not in Rupandehi, pointing at a larger use of bullock carts for transporting pumpsets to the field. Financial liquidity appears equally important in Kailali and Rupandehi but less so in Banke. This indicates that more frequent pump rental in Rupandehi and large inefficient pumpsets operated by resource-poorer farmers in Kailali remain a key issue in diesel pump irrigation, in contrast to areas where electric and small and efficient pumpsets are more common.

A single overall strategy to support farmers in responding effectively to monsoon breaks is therefore unlikely to suffice, because sustainable irrigation development needs to cater to contextual factors that vary geographically and even between households within the same community. Furthermore, groundwater development programmes risk widening existing social inequality between users (Wilson, 2002). This calls for pro-poor governance frameworks to ensure that different strata of water users benefit equitably from groundwater development. Recognizing these challenges, we propose three modular support pathways that correspond to nested spatial scales and can be prioritized for investment according to the socio-hydraulic characteristics of the target region. The main goal is to reduce the socio-economic barriers to groundwater use in an equitable and sustainable manner. Lastly, we briefly discuss the current state and potential of electrically powered shallow tubewell use and highlight the need to improve groundwater governance along with increasing use patterns.

As a general caveat, our findings should be contextualized within the longer-term change and development processes in this region. A recent drop in prices for solar panels has convinced many scientists, organizations and governments that solar-powered irrigation systems will be a key transformative technology for rural development in South Asia (Hartung & Pluschke, 2018). Similarly, policy imperatives for improved rural electrification, such as the ambition that Nepal could be the Battery for South Asia and India's initiative to bring electricity to 'the last village', suggest that grid-powered irrigation could plausibly increase in the nearer term, although large uncertainties remain about the pace and extent of rural electrification. The support pathways put forward in this article seek to identify options that are likely to encourage improved water use for diesel-powered irrigation until reliable grid- and solar-powered irrigation become widely available. Improved diesel systems could also be of use where electrically powered irrigation systems remain unfeasible. Understanding farmers' decision making with regard to current technologies could also contribute to better delineating problems and identifying target groups for scaling up solar and grid-powered irrigation systems. But such analyses remain outside the scope of this article.

Support pathway 1: efficiency gains at the farm level

Our findings point at two key interventions that could improve the water and energy efficiency of pumpset irrigation at the farm level to encourage farmers to move from 'life-saving' to 'productivity-enhancing' irrigation of kharif rice, one regarding irrigation scheduling and the other regarding operational efficiency.

Irrigation scheduling

Rice farmers in the Terai generally use the formation of large soil cracks as a cue for irrigation scheduling. This strategy can dramatically increase the costs of irrigation due to percolation losses from the root zone. Furthermore, allowing soils to dry past 40 kPa water tension can reduce rice yield by 50% in some soil types (Sudhir-Yadav et al., 2011); and large cracks typically form in even drier conditions. In addition to limited knowledge of the relationship between water stress and yield loss, late irrigation scheduling may also reflect farmers' tendency to be cash-investment averse rather than yield-or-profit-loss averse. In the case of marginal farmers, investment aversion in the Eastern Indo-Gangetic Plains is often linked to unfavourable tenancy agreements (Sugden et al., 2014b). Risk aversion has been observed elsewhere as a limiting factor to the adoption of climate-smart agricultural practices intended to increase resilience, a situation in which both awareness raising and policy measures may be needed to boost uptake (Rai et al., 2018). Changing farmer's perceptions of the value and profitability of timely irrigation of kharif rice, in tandem with lowering irrigation costs to reduce investment aversion, have been observed to raise crop production and farmers' income (Qureshi et al., 2015).

Another factor in farmers' willingness to implement timely scheduling is uncertainty about the occurrence of the next rainfall. In general, the surveyed farmers are understandably reluctant to irrigate if rainfall could occur. Unfortunately, weather forecast information and climate-informed advisories for irrigation have not yet been widely deployed in South Asia. The World Meteorological Organization has acknowledged the need to improve the availability of climate information to better inform decision makers, with specific attention to agriculture. The Global Framework for Climate Services and a number of pilot efforts have developed out of this (Hewitt et al., 2012). Another approach emerging in agricultural climate services is the sharing of crucial climate data made available by global producing centres with regional climate centres and national hydro-meteorological services. But the challenge is to build scalable decision frameworks that effectively leverage climate services and communicate them successfully to farmers to encourage behavioural change towards cost-effective and risk-reducing irrigation management.

Lastly, farmers mistakenly believe that groundwater is inferior in quality to rainwater. This can be addressed through clearer extension messaging. Scientific knowledge on irrigation scheduling is mainly anchored in assessing crop water requirements (e.g. Sudhir-Yadav et al., (2011)), and advisory and decision-support systems may benefit from addressing these findings in their trainings and messaging.

Improving operational efficiency

Late irrigation scheduling practices in the Terai are primarily influenced by cash-investment aversion, so lowering operation costs may be an additional strategy to encourage farmers to move from 'life-saving' to 'productivity-enhancing' irrigation of kharif rice. Our results suggest that the use of inappropriately sized pumps reduces operational inefficiency through wasteful energy consumption. Mismatching pumps is a common problem in developing countries, where information on pumpset efficiency is often lacking and the choice of pumps is limited (Bom et al., 2001; Bom & van Steenbergen, 1997). For example, a crucial efficiency issue is the problem of friction losses in water delivery pipes. After vertical pumping, many farmers only need to use delivery pipes for short horizontal distances, while others may have to convey water over hundreds of metres using lay-flat pipes. Pump power requirements are much lower for the former group, especially with larger-diameter lay-flat pipes.

Several measures can address the prevailing scenario of low pump efficiency. First, simply adjusting engine speed can reduce fuel consumption by more than 50%, from 1–1.5 L/h to 0.5 L/h, while maintaining the same level of discharge (Bom et al., 2001). Second, market availability of energy-efficient and lower-cost small pumpsets can be improved. However, spare-parts availability for small pumpsets is currently insufficient, so this is an important consideration in efforts to increase irrigation efficiency. Third, energy loss to friction in lateral distribution piping can be reduced by making strategic use of gravity flow through lay-flat pipes or elevated tanks with attached delivery pipes. Larger-diameter delivery pipes can also be used to reduce friction loss, though potential trade-offs with the cost of larger pipes requires further investigation. Fourth, local technicians can use better and cheaper shallow tubewell construction techniques to reduce fuel consumption by 30% per unit of water pumped (Bom & van Steenbergen, 1997) – e.g. using mosquito nets as screens to cover pipe suction holes, or cleaning the well borehole after construction to increase inflow.

In general, guidelines on pump choice, irrigation system design and well construction could be made broadly available through trainings, pump dealers, and state extension services, but gaps between existing information and local knowledge of technical systems must also be addressed. Social marketing campaigns could also be aimed at addressing perception biases towards larger pumps, to educate farmers as to the benefits of smaller and more efficient pumpsets. The development of a common database as a clearinghouse of independently measured technical specification for pumps could also help farmers and policy makers with irrigation investment decisions. Without accurate knowledge of the importance of proper pump choice, pump dealers currently have limited capacity to promote energy-efficient solutions. Shopkeepers are happy to sell more expensive and less efficient pumps, and farmers who lack information will continue to purchase them. Our surveys indicated that pump mechanics also recommend less efficient and more costly pumps to farmers because they receive commissions from machinery dealers. Thus, efforts are needed to align the supply of technically sound information on pump efficiency with incentives to promote the use of smaller but ultimately more suitable pumpsets for shallow tubewells and kharif rice irrigation in the Terai.

Support pathway 2: improving community-level water markets

Our data demonstrate that most farmers in the Terai have several small and scattered fields. This is a clear challenge to irrigation coordination, although it also represents an opportunity to share resources with neighbouring farmers through water markets, i.e., users renting out their pumping equipment, their borehole, or both to other users. In all districts, delay factors associated with borrowing pumpsets and queuing for shallow tubewell use are common. Informal water markets with monopolistic pricing schemes erode the profitability of groundwater use for many farmers (Shah et al., 2009; Sugden et al., 2014a). In addition to the well-known price distortions that may contribute to late irrigation scheduling, the observed coordination problems suggest two more factors that limit the efficiency and equitability of groundwater markets where renters could theoretically profit. First, the high land fragmentation increases coordination difficulties, as farmers need to arrange irrigation access in advance with several shallow tubewell owners. Second, farmers with limited financial resources experience financial illiquidity, as they have already invested their available cash in raising and transplanting rice seedlings. The latter situation in particular challenges the development of efficient water markets to overcome moisture constraints in the face of precipitation uncertainty.

Another issue that requires attention is male outmigration from rural areas. In our survey, this is mainly noticeable through the time delays reported by farmers in finding and hiring agricultural labourers in Rupandehi, the district with the largest migration rate (MOL, 2017). Since irrigation of field crops is predominantly a male task, households with migrated men rely on relatives or neighbours to assist, or they need to wait for a male household member to return home after work. More policy attention to the gender context is required as this trend intensifies. While there is support for expanding the role of women as decision makers in agriculture, service provision provides another approach to address this delay factor.

The first pathway requires improving the organizational components of informal water markets to address the prohibitive cost of irrigation. The provision of low-interest financial services to farmers, so they may overcome within-season cash constraints prior to harvest and the sale of rice grain, is likely to be important in efforts to move farmers to 'productivity-enhancing' shallow tubewell irrigation use (Bhandari & Pandey, 2006). Lastly, and perhaps most importantly, taking an anticipatory approach and agreeing on terms and conditions for pump rental and irrigation well before the season, instead of when large soil cracks appear, is also likely to be crucial, especially given the organizational difficulties posed by land fragmentation. To this end, seasonal precipitation forecasts deployed through meteorological and extension services could help 'trigger' irrigation arrangements and the provision of fuel for pumps well in advance of the months when rainfall deficits could occur. But such forecasts require much skill to be taken seriously by farming communities (Hewitt et al., 2012).

Support pathway 3: regional investment prioritization – selectively increasing infrastructure density

Turn-taking for shallow tubewells and pumpset rental are major delay factors and therewith inefficiency of the informal water markets in all three surveyed districts. This means that mere access to irrigation is not a sufficient condition for timely irrigation. Better organization at the community level can only reduce delays to a certain extent. For more substantial delay reductions, increasing the density of shallow tubewells becomes crucial in areas where infrastructure is present but insufficient. Targeting criteria can be developed from this perspective so that pumps are prioritized where they are most needed, increasing the return on public investment in irrigation infrastructure. This approach can be employed together with data on aquifer characteristics such that shallow tubewell infrastructure development is also prioritized in areas where higher levels of water abstraction can be sustained.

Initiatives to encourage better use of groundwater resources for irrigation are also likely to require policy action to address land ownership patterns. This is because there are fewer incentives for tenant farmers and landlords to invest in shallow tubewell infrastructure on rented land (Sugden et al., 2014a). Where higher pumpset penetration is desired, awareness raising and opportunities for the private sector to encourage market growth are likely to be crucial. For example, supporting spare-parts markets, assuring sufficient mechanic services and increasing commercial availability of pumpsets were prerequisites for the rapid and transformative growth of tubewell use in nearby Bangladesh (Qureshi et al., 2015). Convincing farmers that bigger pumpsets are not always better, e.g. by highlighting the fuel efficiency of small pumpsets, as well as identifying and promoting smaller pumpsets that require less frequent repair and maintenance, could be critical steps to increase pumpset ownership among smaller and marginal farmers.

Electric pumps: rural electrification and solar-powered irrigation

Given the large reductions in costs and CO_2 emissions achievable with electric pumpsets, rural electrification or solar-powered irrigation may be the best long-term solution for the sustainable intensification of kharif rice. Against the backdrop of groundwater overexploitation due to *de facto* free electricity in north-west India, it is important to keep in mind that metering electricity consumption can incentivize farmers to irrigate effectively (Mukherji et al., 2009). But the current rural electricity network in the Terai has significant problems, including frequent power cuts. Even when power is available, voltage fluctuations commonly damage pumpsets. And areas with relatively good access to electricity are especially vulnerable to power cuts and voltage fluctuations because irrigation pumping is often the largest consumer of irrigation during short periods, and often overloads the system. Besides the physical availability of electricity, access is often difficult to secure because the permit system in Nepal is highly political. And while the price of solar irrigation is falling, it remains prohibitive for many farmers.

The benefit of reliable agricultural electrification in the Terai is expected to be enormous for broader policy goals such as food security, poverty alleviation and climate change adaptation. But despite the potential benefits of expanding the grid to rural areas, officials in Nepal report that electricity for irrigation is not a development priority, as irrigation would only constitute 1–2% of potential new revenue sources, with very high installation costs required to reach widely scattered villages (NEA, 2017). Thus, improving the efficiency and reach of the diesel-based shallow tubewells continues to make sense as a near-term development priority.

Groundwater governance: reiterating the case for sustainable and evidence-based management

Groundwater depletion has become a global concern (Famiglietti, 2014), but the opposite is true in the Eastern Gangetic Plains, including Nepal's Terai. Nepal's government considers the

Terai's groundwater resources underdeveloped and estimates that 88% of the groundwater that could be abstracted on a sustainable basis (based on annual recharge) is not utilized, providing ample space for increased groundwater use for productivity-enhancing irrigation. In other words, encouraging productive use of water resources within regionally and locally defined sustainable abstraction boundaries will be a key element in reaching sustainable intensification targets in Nepal's Terai (Steffen et al., 2015).

Establishing a regional evidence base for groundwater governance in Nepal is difficult because the low-resource and low-technology environment poses great challenges for gathering recurrent monitoring data on the highly complex aquifer systems. But implementing a system that identifies persistent groundwater decline is a good first step; since groundwater dynamics are localized, local countermeasures such as managed aquifer recharge can be implemented. Regionally, such planning could leverage the Ganges Water Machine initiative, which is being used as a conceptual tool for managing the Indo-Gangetic Plain's complex and erratic hydrological cycle (Bharati et al., 2016; Shah et al., 2018c).

Conclusions

This study has established and ranked the importance of the key factors influencing the use of shallow tubewells for supplementary irrigation in kharif-season rice cultivation in the Terai region of Nepal. In areas where diesel pumps predominate, the factors most limiting shallow tubewell use are poor coordination among water users, delays in pump and tubewell availability, and financial constraints coupled with risk aversion towards cash investment. The electric grid permits the use of lower-cost pumps, and solar-powered irrigation systems could reduce operation costs. Electrification may overcome some of these delay factors, but the grid reaches only a small fraction of fields at present, and solar-powered irrigation is likely to remain beyond the financial means of most farmers in the Terai.

Our work indicates that a multi-scalar strategy to encourage diesel-pump-based shallow tubewell irrigation, to move Nepali rice farmers from 'life-saving' to 'productivity-enhancing' irrigation use, could contribute to climate resilience, higher yields, and higher profits. At the farm level, raising awareness of the importance of timely irrigation can be coupled with efforts to increase operational efficiency (e.g. pump maintenance, pump sizing, forecast-based irrigation scheduling) to overcome aversion to cash investments. At the community level, better preparation for irrigation events through organization of water markets before the start of the season could reduce transaction costs and delays during the season itself. At the regional level, government support programmes can target areas where tubewell and pumpset density is not yet high enough to ensure that all farmers have timely access to irrigation through water markets.

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Chapter 4

Harvesting the crops

Synchronizing rice planting with monsoon onset produces divergent agricultural productivity and resilience outcomes in the Indo-Gangetic Plains

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Abstract

It is broadly recognized that the timing of rice planting has a profound influence on the productivity, resilience, and resource use efficiency of the rice-wheat cropping system in the Indo-Gangetic Plains (IGP). Nevertheless, the advantages of different rice planting strategies such as using weather forecasts to synchronize crop planting with the anticipated onset of the monsoon are not well established. Here we show that optimal rice planting strategies significantly diverge across sub-regions of the IGP. The sustainability and resilience of the rice-wheat system can be boosted in the eastern IGP through synchronizing rice planting with the monsoon. Whereas this strategy is not effective in the northwestern IGP, because of later monsoon arrival, colder winters, and hotter summers than in the eastern IGP. We conclude that divergent climatic constraints imposed by sub-regional temperature and precipitation patterns will be critical for devising systems-specific and context-sensitive future research and development programs.

Introduction

Climate change, population growth, and persistent food insecurity require agricultural systems to become more productive and resilient (FAO et al., 2021), especially in smallholder-dominated cereal-based systems where adaptive capacity is low. These systems are projected to be worst hit by climatic change, while holding the highest potential for increasing yields (Rockstrom et al., 2017). The Indo-Gangetic Plains (IGP) that spans Pakistan, India, Nepal, and Bangladesh produce the majority of food grains for South Asia. An estimated 129 million people of the world's undernourished people live within their confines (Erenstein et al., 2010; Rawal et al., 2019). Development efforts face the challenge of increasing agricultural productivity, where it is low, while ensuring that resource use remains within an environmentally safe operating space (Rockstrom et al., 2009). Over 90% of the farmers in the Indian, Nepal, and northern Bangladesh parts of the IGP – on which this study focuses – grow a single, rainfed rice crop during the monsoon, typically from June to September. Wheat is sequenced after rice in the annual rotation (Singh et al., 2020). Late wheat planting following a late rice harvest pushes wheat maturation into hotter summer months reducing yields by >5% per °C increase in temperature during grain filling – rendering rice planting a key driver for the productivity and resilience of agricultural systems in the IGP (Asseng et al., 2015; Dubey et al., 2020; Mondal et al., 2013). However, early rice planting can increase water use at the start of the season when atmospheric demand is higher and rainfall less consistent (Singh et al., 2019b), while divergent socio-economic and climatic conditions, and water resource systems have created contrasting challenges in the northwestern and eastern IGP.

The northwestern IGP feature relatively high-yielding, input-intensive agricultural systems and electrically pumped irrigation water at a nominal cost (Shah et al., 2018b), but the sustainability of agricultural production is increasingly jeopardized by groundwater depletion and air pollution from crop residue burning (Balwinder et al., 2019b; Famiglietti, 2014). Farmers in the northwestern IGP use groundwater irrigation to plant rice before the onset of the monsoon to avoid terminal heat stress in wheat (Lobell & Gourdji, 2012; Rodell et al., 2009). Regardless of the current state policies that require farmers to delay rice planting to save water, further delaying rice planting to be in sync with the monsoon may bring crop water consumption within sustainable boundaries (Balwinder et al., 2019b). Its feasibility, however, remains unclear.

In the eastern IGP, agricultural systems are less productive, less input-intensive, and because of costly diesel-pump irrigation farmers tend to wait for the monsoon rains before starting to plant rice – often in late July and early August (Urfels et al., 2021). Late rice planting constitutes a prime reason for low cropping system productivity in the eastern IGP (Jain et al., 2017; Park et al., 2018; Urfels et al., 2021). State recommendations currently favour earlier planting, three weeks after the average monsoon onset – i.e. in the first week of July. We hypothesize that advancing rice planting to be in sync with the monsoon is key to improving agricultural productivity and resilience. Most government agencies, extension services, and research institutions provide recommended fixed planting dates for farmers to follow (ICAR, 2021). But these recommendations are often based on short term experiments under climate conditions that are no longer representative. And the spatio-temporal benefit of the existing and proposed planting strategies on agricultural productivity, resilience, and water use across the IGP remains unknown (Hunt et al., 2019; Lv et al., 2020; Mourtzinis et al., 2019; Nouri et al., 2017; Waha et al., 2013).Here, we show that tailoring rice planting strategies to sub-regional climatic variability in the IGP is a critical determinant of sustainable agricultural development pathways. We do so by assessing the advantages of different rice planting strategies across broad geographic and interannual domains and fill two additional gaps in the literature: first, the World Meteorological Organization aims to improve sub-seasonal to seasonal climate predictions for agricultural decision-making (Vitart & Robertson, 2018), but the suitability and potential value of a hypothetical, perfect forecast for agricultural productivity and resilience remains unknown. Second, most regional crop modelling studies for impact assessments treat each crop independently, failing to account for potential trade-offs and cascading effects between the crops grown in rotation on the same fields (Biemans & Siderius, 2019; Shah et al., 2021). Incorporating cropping sequence effects is necessary for *ex-ante* evaluations of planting date strategies.

We achieve this by deploying a gridded process-based crop model to explore the performance of rice planting strategies for the period 1982-2015 across the IGP (Allen et al., 2019) in terms of yield, yield stability, and adaptation to climate variability (Singh et al., 2019b; Urfels et al., 2021; Wang et al., 2015). We explore the influence of three different rice planting strategies: (i) planting dates based on farmers' practice, (ii) fixed planting dates based on current recommendations, and (iii) planting at monsoon onset. All scenarios were run under full irrigation and fertility treatments to assess performance for well-managed systems. We subsequently characterize agroecosystem resilience, defined as the capacity of the cropping system to continue its critical function of food provisioning despite external shocks (Allen et al., 2019), while investigating the water resource management implications of the three planting strategies. We conclude by providing tailored recommendations for future research, policy-making, and public and private efforts for agricultural development.

Results

Simulated yield patterns for different rice planting strategies

Average simulated rice yields range from 3.7 t/ha for planting in the northwestern IGP at monsoon onset to 7.0 t/ha for planting at fixed dates in the same region. In the eastern IGP simulated rice yields at fixed dates average at 4.9 t/ha and rise to 6.2 t/ha for planting with monsoon onset. The same pattern appears for combined rice-wheat system yields. For all scenarios except planting at monsoon onset in the eastern IGP, the simulated system yield exhibits a bi-modal distribution (Figure 4.1). The bi-modal distribution results from differential crop exposure to temperature stress in different years driven by a rapid decline of temperatures in autumn and a rapid rise in spring. Late rice planting leads to more exposure to low temperatures that slows phenological development of rice and decreases yields, but also delays the sowing of wheat, which increases exposure to terminal heat stress. The performance of each planting strategy therefore diverges across the IGP in response to a northwest to southeast climatic gradient (Figure 4.2, Supplementary Figure 4.2).

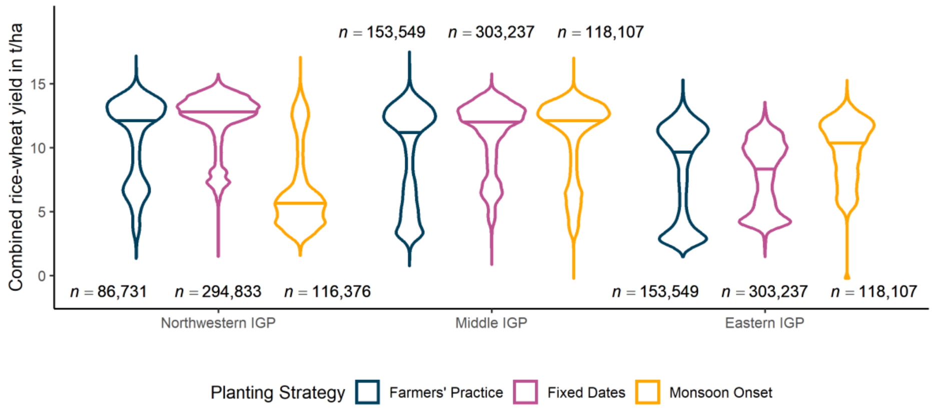

Figure 4.1 Violin plots of simulated historical (1982-2015) rice-wheat system yields in t/ha for the northwestern, middle, and eastern IGP. Horizontal lines show the median rice-wheat system yield. N refers to number of cell-year observations.

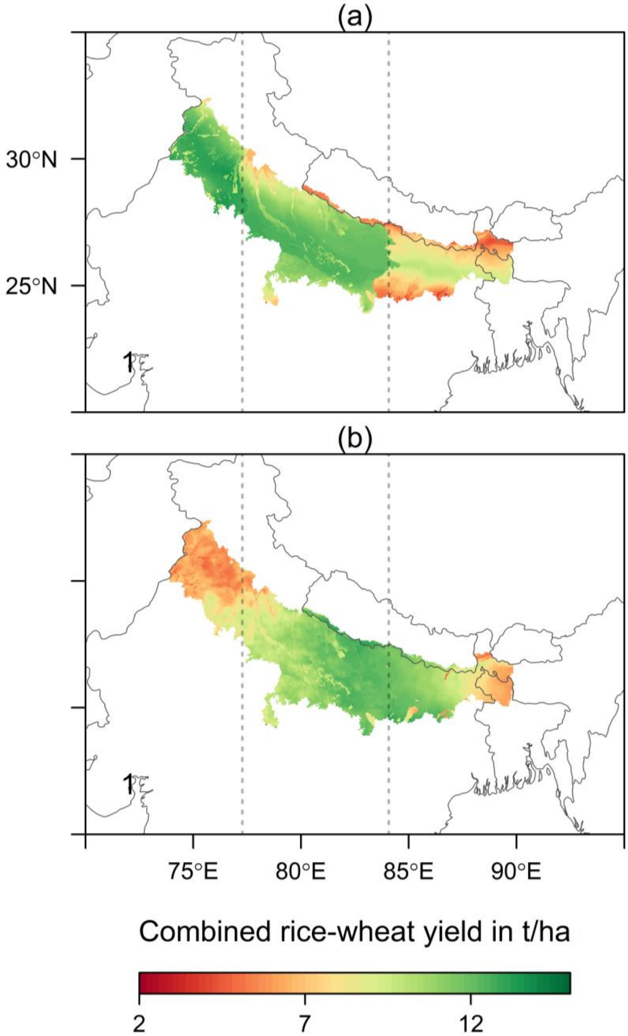

Figure 4.2 Average simulated historical (1982-2015) combined rice-wheat yield in t/ha for (a) fixed planting dates and (b) planting at monsoon onset. Dotted lines separate the region into northwestern, middle and eastern IGP.

In the northwestern IGP, farmers can achieve the highest average combined rice-wheat yield potential (11.7 t/ha) when planting on fixed dates according to state recommendation (Figure 4.2a). That is, on average, 15% higher than a typical farmers' practice. Areas with lower yield potential in the fixed date scenarios are concentrated in the north where autumn temperatures are generally lower (Figure 4.2, Supplementary Figure 4.2 and 4.3). Planting with monsoon onset is not a viable option for the northwestern IGP, because the monsoon arrives too late due to its east-west progression, compromising system yield potential to an average 6.5 t/ha.

In the eastern IGP, conversely, farmers can largely benefit from synchronizing rice planting with monsoon onset (Figure 4.2b), increasing the rice-wheat system yield potential by 21% above farmers' practice to 9.4 t/ha. Nevertheless, sub-regional differences remain. With monsoon onset planting, the easternmost area shows crop system level yield reductions caused by low wheat productivity due to low solar radiation (Supplementary Figures 4.2 and 4.3). Fixed planting dates perform overall worse than the prevailing farmers' practice (7.5 t/ha) as they increase exposure to temperature stresses for rice and wheat (Figure 2, Supplementary Figures 4.2 and 4.3).

Lastly, in the middle IGP, both planting on fixed dates and at monsoon onset outperform the farmers' practice scenario (24% higher). Farmers' practice results in an average system yield potential of 8.9 t/ha while fixed planting dates reach 10.6 t/ha and planting at monsoon onset 10.4 t/ha. However, for both alternative planting strategies parts of the region show low simulated yields. For the fixed planting dates these areas of low yield potential are found in the north of the middle IGP, where winters tend to be colder (Figure 4.2, Supplementary Figures 4.2 and 4.3). Planting at monsoon onset results in lower yield potential over the northwest of the middle IGP (Figure 4.2), where the monsoon arrives later (Supplementary Figures 4.2 and 4.3).

Resilience: yield stability and sensitivity to shocks

Large differences in yield stability exist across the rice planting strategies (Figure 4.3 and 4.4). We defined shock years as any year in which the simulated yield in a grid cell drops below the long-term mean by more than one standard deviation. In the northwestern IGP, the system's sensitivity – i.e. mean reduction of simulated system yield in a shock year – averages at 1.5 t/ha for the fixed planting dates with a shock year occurring once every 10-11 years (exposure: 0.09; i.e. number of shock years per number of simulated years). The higher yield instability in the northern parts is largely induced by more frequent perturbations associated with cold waves. In the middle IGP, yield sensitivity for fixed planting dates (1.7 t/ha) is lower than when planting at monsoon onset (2.1 t/ha). These also show a lower exposure score (0.11). For the eastern IGP, we find that planting with monsoon onset displays the lowest sensitivity to shocks with a mean reduction of 0.9 t/ha in a shock year that occurs, on average, every 7-8 years. These results appear to be homogeneous across the eastern IGP. In summary, our results show that the fixed planting dates work better for the northwestern and middle IGP, in terms of yields and yield stability, while planting at monsoon onset works better in the eastern IGP.

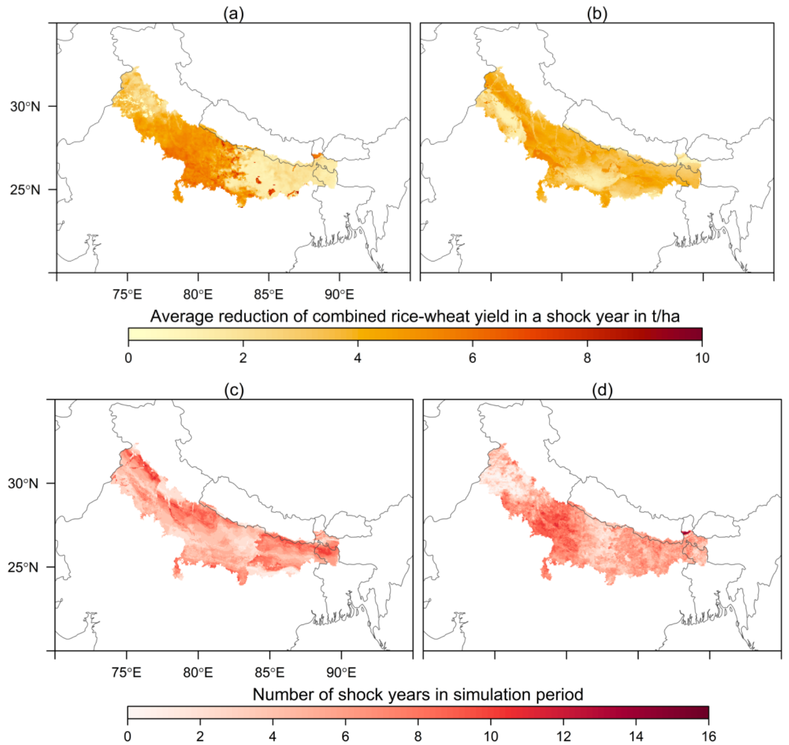

Figure 4.3 System sensitivity and exposure to shocks. Top: system sensitivity for (a) fixed planting dates and (b) planting at monsoon onset. Bottom: system exposure for (c) fixed planting dates and (d) planting at monsoon onset.

Environmental trade-offs? Irrigation and water productivity

Our results show that different planting strategies do not substantially affect simulated irrigation requirements, but significant differences in rice irrigation requirement exist between sub-regions of the IGP (Figure 4.4). The average irrigation requirements for rice are highest in the northwestern IGP (1088 mm) for fixed planting dates and lowest in the eastern IGP (381 mm) for planting at monsoon onset. Besides, different planting strategies' effects on yields result in large differences in water productivity (Figure 4.4). For instance, in the northwestern

IGP, the average water productivity for fixed planting dates (0.83 kg m^{-3}) is almost twice as much as when planting at monsoon onset (0.46 kg m^{-3}, Supplementary Table 4.2).

Due to ongoing groundwater depletion in the northwestern IGP, we also tested the use of medium duration rice varieties planted at monsoon onset with a low-input irrigation schedule (Supplementary Figures 4.5 and 4.6). This strategy largely avoided temperature induced yield penalties in the northwestern IGP. However, even if all runoff, drainage, and effective rainfall is captured, the difference between evapotranspiration (ET) and water availability – a crude indicator for irrigation requirements – remains at a substantial 687 mm. Late monsoon arrival and early retreat in the northwestern results in lower overall rainfall than in the eastern IGP, irrespective of planting strategy (Supplementary Figure 4.4).

In the eastern IGP, conversely, planting at monsoon onset allows, on average, to capture 227 mm more effective rainfall than for farmers' practice (Supplementary Figure 4.4). Irrigation requirements are, however, not reduced proportionately - most likely because captured rainwater is lost as percolation beyond the root zone and prolonged in-season dry spells continue to require supplementary irrigation. Planting at monsoon onset would likely also lead to higher irrigation losses in practice than simulated during transplanting due to high percolation losses during land preparation in practice (Bouman & Tuong, 2001).

Figure 4.4 Mean values of key system productivity, resilience, and sustainability indicators across sub-regions of the IGP and rice planting strategies.

Discussion

Building productive, climate resilient, and groundwater conserving agroecosystems: what is the scope for planting date adjustments?

In the northwestern and middle IGP, fixed planting dates provide higher productivity and resilience than farmers' practice and planting rice at monsoon onset. In this region, hotter summers and colder autumns and winters combined with shorter rainy seasons restrict the ability to synchronize planting dates with the monsoon onset without incurring yield losses or changing rice varieties. The water-saving potential of different planting strategies is equally limited as our results suggest only marginal changes in ET among different strategies. These findings align with studies indicating that large improvements in agricultural water productivity are mostly caused by changes in harvest index and yield potential and not water use (Perry et al., 2009). Considering ongoing groundwater depletion (Famiglietti, 2014), adaptation strategies to climatic change in the northwestern IGP should focus on further reducing actual agricultural water use through shorter duration rice varieties and switching to less water demanding crops like millet, sorghum, or maize. However, changing varieties or crops may incur yield or profit losses and requires changes in producer and consumer behaviour that are more difficult to achieve than shifting planting dates. But these more fundamental changes to the agricultural system would support goals of increasing agricultural and nutritional diversity (Willett et al., 2019).

In the eastern IGP, the current rice-wheat system still holds potential for improving yield potential and resilience within sustainable water use limits. This requires farmers to plant earlier and planting in sync with monsoon onset may reduce the risk of increasing irrigation requirements for land preparation. Advances in seasonal to sub-seasonal forecasting can reduce the risk of uncertain monsoon onsets for early planting and encourage farmers behaviours that enhance productivity and profits (Singh et al., 2019a). However, farmers are unlikely to adopt timely planting due to factors that delay planting and reduce yields, such as unavailability of pre-monsoon irrigation water, lack of reliable electricity access, timely availability of inputs, and lack of collective action to deter pest and disease pressures (Bouman & Tuong, 2001; Urfels et al., 2021). Therefore, monsoon forecast-based planting advisories should target areas with low physical or economic water scarcity and well-established input markets. Furthermore, given the growing rural electrification in the eastern IGP, monsoon forecast-based advisories should coordinate with irrigation expansion to target areas for more potential adoptions. In addition, science groups that develop sub-seasonal forecast should work together with local meteorological and agricultural extension agencies, to provide annual planting date recommendations based on the expected monsoon onset. Although better access to irrigation is likely to increase groundwater use, high recharge rates dilute the risks of depletion. Nevertheless, careful water use planning and local monitoring could detect unsustainable water use trends and avoid localized depletion that might affect surrounding water users and the environment (Bassi et al., 2014; Ramsar, 2021) – especially bio-diverse wetlands that produce a range of critical ecosystem services.

In the middle IGP, the current rice-wheat system has advantages in its eastern parts and in years with high rainfall, since earlier and heavier rains complicate cultivating short duration varieties and other crops. A combination of seasonal forecasts coupled to within season and longer-term crop choice advisories for this sub-region requires more research. A combination of options applied in the northwestern and eastern IGP would most adequately address the transition zone properties of the middle IGP and oversimplification through broad zonation.

Regional influences of low temperature on yield variability

The detrimental effect of low temperatures on rice-wheat system yield deserves special attention. Low temperatures reduce rice growth in some areas of the IGP in each scenario with marked spatial differences (Supplementary Figure 4.2). From a physiological perspective, varieties that are primed to flower in the early morning hours to avoid heat stress (Kadam et al., 2014) may be counterproductive in environments with low minimum temperature during anthesis such as in the IGP, so that flowering during the morning hours would increase exposure to cold stress. In addition, large-scale climatic anomalies induced by La Niña can cause widespread cold waves and increased rainfall and flooding, as was the case in 2020, when minimum temperature in October was below 15°C (Jin & Wang, 2017; Takaya et al., 2021). Our results also suggest that the yield response to planting dates and temperature stress exhibits critical thresholds beyond which potential yields decline rapidly. Better tools for communicating these risks to farmers are required (Tittonell & Giller, 2013).

Value of improved monsoon forecasting skill

The higher yields and water productivity of rice-wheat system with monsoon synchronized planting across the eastern IGP underscore the value in agriculture of generating actionable products for forecasting monsoon onset dates. The value of a perfect monsoon forecast provided as a climate service may be hypothetically considered as the average improvement of rice-wheat yield potential facilitated by monsoon synchronized planting compared to farmers' practice: 1.5 t/ha in the eastern IGP. This means, for instance, that with no other limiting factors, a rice growing area of around 3.3 million ha in Bihar, 3000 kcal/kg of grain, and 2500 kcal required per person per day, these improvements provide sufficient energy for an additional 16.3 million people a year from improved rice-wheat yields in the state of Bihar alone (D'Odorico et al., 2014).

Measuring resilience of crop production

Evaluation of farming systems productivity mostly focus on raising average productivity under ideal climatic conditions (Rockstrom et al., 2017). Resilience is normally regarded as an emergent property that characterizes productive farming systems without having to undergo radical transformations such as moving out of agriculture or changing crops (Perez et al., 2016). However, it has been reported that such radical transformation may only be required in 50 years or later and will not affect most crops and locations (Rippke et al., 2016). We contend that the resilience debate for farming systems should include the system's ability to handle shocks within current climatic conditions. This represents the best way to prepare for future stressors that are directionally aligned with contemporary stressors and helps to exploit current opportunities by informing contemporary action. We find measuring resilience (Grafton et al., 2019) helpful and recommend future studies to deploy crop models to better understand and characterize the performance of agricultural interventions. Moreover, including dynamical management decision induced by a shock year that carry over into the next year represents important steps for assessing resilience of crop production.

Conclusion

Our work fills a critical gap in studying food production systems between site-specific assessments and global simulations. We deployed a long-term, regional modelling study to assess the impact of rice planting strategies on resource-use trade-off and temperature stresses in the IGP. Firstly, our assessment demonstrates that the outcomes of different planting strategies diverge across the IGP. Synchronizing rice planting with monsoon onset improves system productivity and resilience over the eastern IGP, indicating that monsoon forecasting can be a promising service for farmers in this sub-region. However, the east-west progression of the monsoon and seasonality in temperatures restricts the application of this strategy to the northwestern IGP, with limited scope to improve both the productivity and sustainability of the rice-wheat system. Secondly, our study demonstrates the need to consider rice-wheat cultivation as an integrated multi-cropping system in which interventions, such as planting dates strategies, must be evaluated from a systems perspective that includes the full crop rotation. Future studies should assess other spatially explicit management factors and consider future climate scenarios to support programmatic targeting of interventions at the regional scale of mega-environments. In concert, strengthening the knowledge base on the spatio-temporal interplay of crop systems management and the climate system are critical for transforming food systems in the IGP and elsewhere.

Methods

Crop model simulations

The Agricultural Production Systems sIMulator (APSIM) was used to simulate crop growth of the rice-wheat system in each cell for the period 1982-2015. APSIM has been extensively calibrated, validated and evaluated for simulating major cereal cropping systems across Asia including the Indo-Gangetic Plains (Balwinder et al., 2011; Balwinder et al., 2016; Balwinder et al., 2019a; Gaydon et al., 2017; Singh et al., 2019a). The Parallel System for Integrating Impact Models and Sectors (pSIMS) was used to translate climate, soil, and spatially varying management input data into APSIM simulation files, execute the simulations, and combine the outputs into a geographically referenced gridded dataset (Elliott et al., 2014). Since some of the package versions for installing pSIMS were difficult to retrieve, we had to make some amendments to the code to work with package versions that were still available. A singularity container in which this model was installed can be obtained from the authors at reasonable request. The input and output files, and simulation system are available at https://git.wageningenur.nl/urfel001/igp-simulation-setup.

Phenology and yield

We focused on the most cultivated rice variety MTU7092 (also called Swarna) for which the APSIM model has been extensively calibrated (Balwinder et al., 2019a). In line with recent advances in knowledge on phenology, we removed delays in phenology for temperature above the optimal by setting the maximum development temperature to an arbitrarily high number (5,000,000) (van Oort & Zwart, 2018). These changes resulted in crop durations within 146 and 172 days for 90% of the results obtained, which compares well with expert estimates and published datasets (see Supplementary Figure 4.7) (Jat et al., 2014). For the supporting scenarios of medium duration varieties, we used parameters that we calibrated and validated in the IGP for the variety Arize 6444 which is popular among farmers (Dutta et al., 2020).

Planting date scenarios

For fixed planting dates, in the northwestern IGP we used the legal earliest planting date, June 20th, for Haryana and Punjab that has been enforced through policy to decrease groundwater abstraction due to earlier planting of rice (Singh et al., 2019b). For the middle and eastern IGP we used the commonly recommended planting date of 30th of June and 8th of July as also suggested by recent simulations (Singh et al., 2019a). Planting at monsoon onset was calculated based on rainfall data following a local agronomic onset definition (Marteau et al., 2009). This method defines the monsoon onset as the first rainy day (≥ 1 mm) of at least 20 mm rainfall and 7-day dry spell of precipitation less than 5 mm in the following 20 days. This implementation assumes that with a reliable monsoon forecast at hand farmers can establish nurseries in anticipation of monsoon onset and transplant at an ideal age of 20-day old seedlings, on the specified day of monsoon onset. As this scenario is primed to make best use of available rainfall, soils may not be sufficiently saturated for land preparation and irrigation likely required for this planting scenario in practice. Farmers' practice planting dates served as a baseline and were estimated using the TIMESAT Savitzky-Golay satellite time-series filter (Jönsson & Eklundh, 2004), applied to the Global Inventory Modelling and Mapping Studies (GIMMS) Advanced Very High Resolution Radiometer (AVHRR) NDVI3g product (Zhu et al., 2013) with transplanting assumed to take place 20 days in advance of NDVI reaching 20% of its seasonal peak value in each grid cell (Singh et al., 2019b). Cells where no planting date between May and August could be detected (10% of cells) were excluded. See Supplementary Figure 4.8 for the resulting average planting dates.

Crop management

Simulations were run without nitrogen limitation and irrigation input was provided on the 5th day after disappearance of ponded water for rice with sufficient water to fill the saturation deficit and add an additional 50 mm of ponding water. Irrigation for rice transplanting was calculated as the water needed to saturate the topsoil and it was assumed that puddling requirements were the same plus an additional 50% (Zhang et al., 2014). While this method may underestimate the actual water requirements at transplanting, it provides a conservative estimate that scales relative to soil moisture, thus accounting for increasing water requirements at planting before the start of monsoon rains. Wheat was always planted 25 days after rice harvest (Singh et al., 2020), allowing for sufficient time to manage harvesting and sowing preparations including burning of rice residue, three tillage operations and one starter irrigation of 75 mm. If wheat was not ripened by May 10th, it was harvested pre-maturely to allow for rice planting. Wheat was fully irrigated until the end of grain filling any time that the critical threshold for initiating the water stress routine in APSIM was passed. Further crop management parameters can be evaluated in the APSIM simulation file templates at https://git.wageningenur.nl/urfel001/igp-simulation-setup/-/tree/master/config/refdata.

Resilience metrics

We conceptualize resilience as the capacity of the agroecosystem to rebound and maintain its critical function despite external shocks (Allen et al., 2019). We focus specifically on the sensitivity and exposure of the system to shocks. Several alternative approaches for defining and measuring resilience and vulnerability – its counterpart – have been proposed across different disciplines, aiming to characterize a system's stability over time and its response to shocks (Füssel, 2010; Grafton et al., 2019). We focus on sensitivity and exposure to shocks that refer to (i) the impact of a shocks on yield and (ii) the number of shock years per number of simulated years.

Soil and meteorological data

The APSIM model was forced using multiple datasets. We used 0.05° × 0.05º spatial resolution daily rainfall from the satellite-derived Climate Hazards Group Infrared Precipitation with Station Data (CHIRPS) (Funk et al., 2015). Solar radiation and air temperature were extracted from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 global atmospheric reanalysis (Hersbach et al., 2020), provided at a horizontal resolution of 0.25º × 0.25º. ERA5 data were bilinearly interpolated to the CHIRPS resolution. Soil physical properties were extracted from the Global Soil Dataset for use in Earth System Models (GSDE) (Shangguan et al., 2014), from the SoilGrids products (Hengl et al., 2017), Jones et al.(Jones et al., 1991), and from the Harmonized World Soil Database (Nachtergaele et al., 2008). Soil albedo was derived from Carrer et al. (2014).

Data analysis

The analysis of output data was conducted in R Project for Statistical Computing using the raster package, and rasterViz for visualizations (Hijmans, 2021; Lamigueiro & Hijmans, 2021). The R code is available at https://git.wageningenur.nl/urfel001/igp-simulation-setup/-

/tree/master/analytics. The calculation of variables can be found in the APSIM documentation. Specifically, we used the variable sf1/2 to track temperature stress in rice and temp_stress_photo for tracking heat stress in wheat. We averaged all daily values across the growing season. Similarly, for water inputs such as irrigation and effective rainfall and outputs such as transpiration and evaporation we summed the daily values for the growing seasons. Water productivity was calculated as grain yield divided by the sum of evaporation and transpiration during crop growth. Irrigation use was calculated by APSIM based on the specified irrigation schedule and included irrigations for planting and in-season irrigation. We divided the landscape into northwestern, middle and eastern IGP by separating at 77.275º East and 84.075º East, which roughly aligns with Indian state boundaries as well as thresholds observed in the results.

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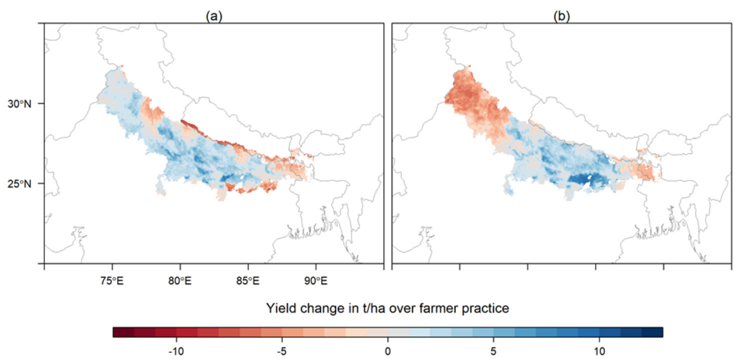
Supplementary Information

Supplementary Table 4.1 Rice-wheat system simulated yield potential in t ha^{-1} across three different rice planting strategies in the IGP, averaged across cells and years. Standard deviation provided in brackets. Within each column, all means are significantly different based on TukeyHSD test.

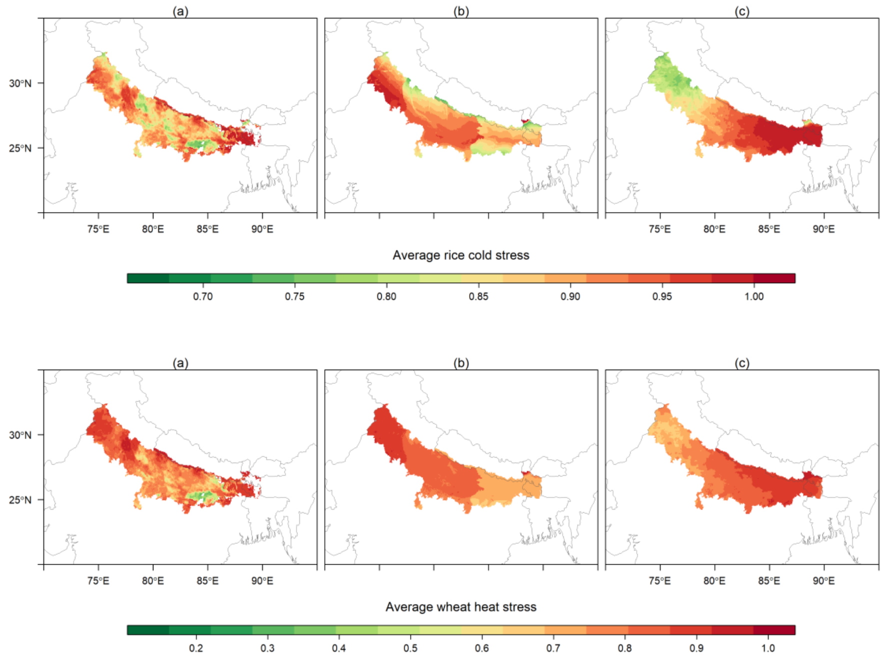
Planting Strategy	Northwestern IGP	Middle IGP	Eastern IGP
Farmers' Practice	10.2 (2.3)	8.9 (2.7)	7.7 (2.7)
Fixed Dates	11.7 (3.2)	10.6 (3.1)	7.5 (2.4)
Monsoon Onset	6.5 (2.1)	10.4 (1.2)	9.4 (1.1)

Supplementary Table 4.2 Water productivity as kg m^{-3} for different rice planting strategies and across sub-regions of the IGP. Averaged across cells and years. Standard deviation provided in brackets. Within each column, all means are significantly different based on TukeyHSD test.

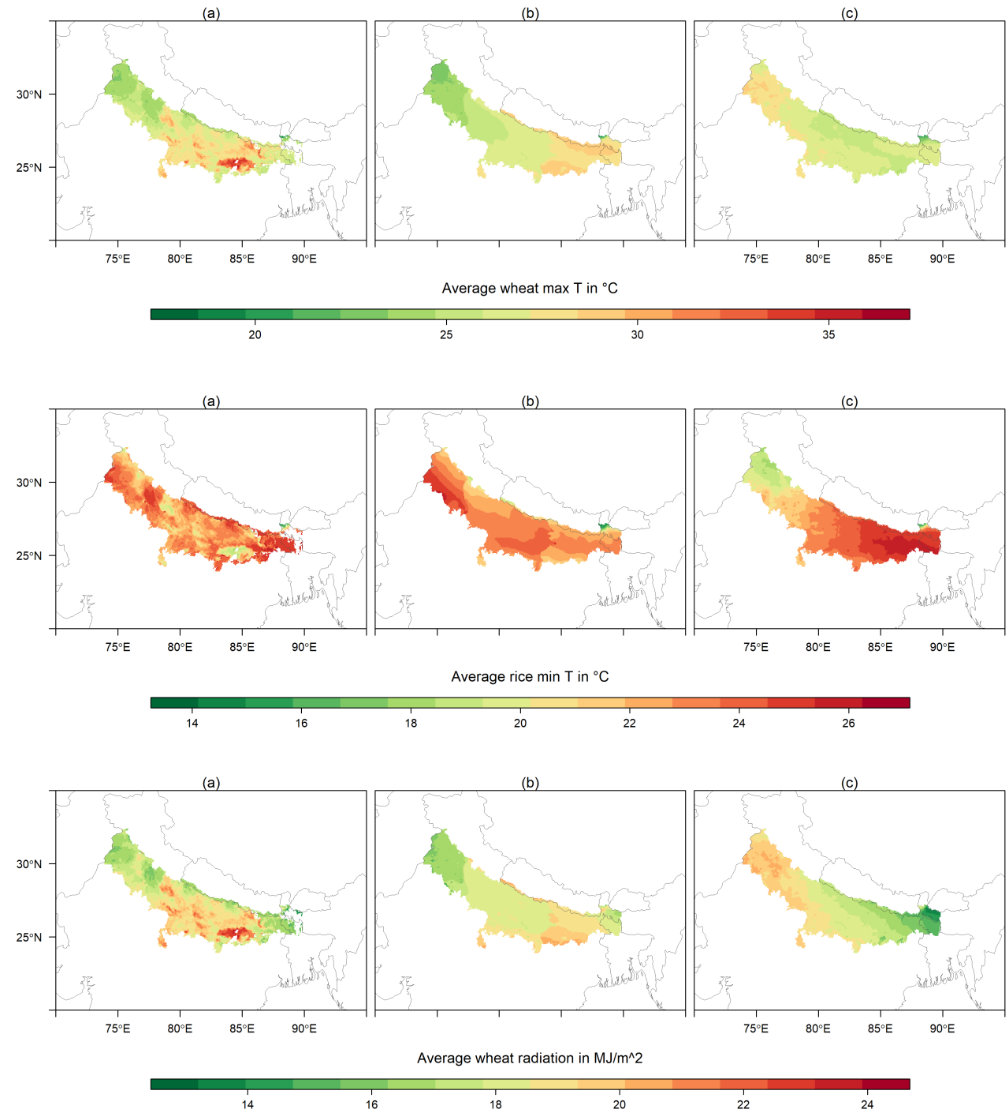
Planting Strategy	Northwestern IGP	Middle IGP	Eastern IGP
Farmers' Practice	0.73 (0.22)	1.05 (0.29)	1.07 (0.30)
Fixed Dates	0.83 (0.16)	1.27 (0.22)	1.16 (0.24)
Monsoon Onset	0.46 (0.22)	1.24 (0.25)	1.56 (0.15)



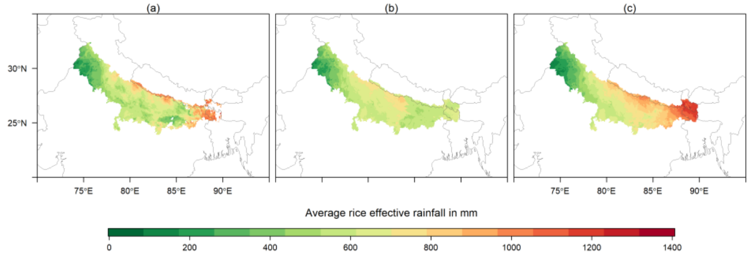
Supplementary Figure 4.1 Difference in simulated (1982-2015) yield potential of combined rice-wheat system yield between rice planting dates in the Indo-Gangetic Plains according to farmers' practice and (a) fixed rice planting dates, and (b) planting rice at monsoon onset.



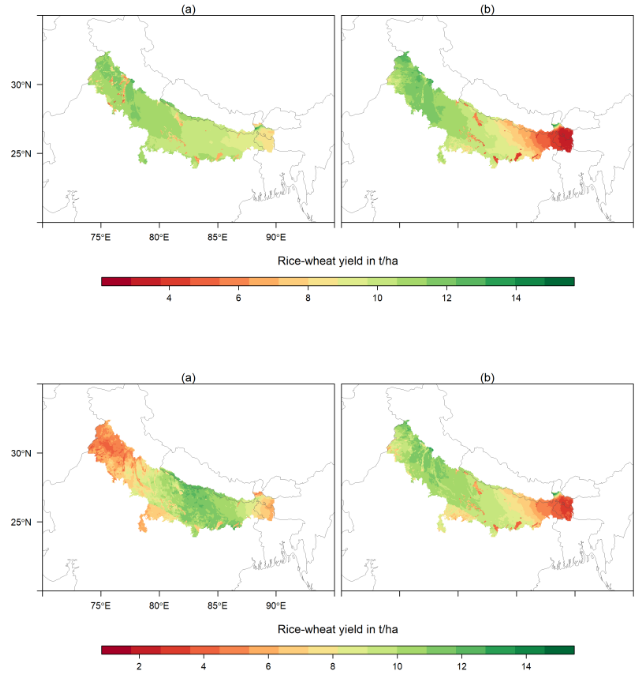
Supplementary Figure 4.2 Average temperature stress on rice-wheat production (1982-2015). Top: average heat stress during wheat season on a scale from 0 to 1, representing full to no impact. Bottom: average cold stress during rice season as recorded by APSIM variable sf1 on a scale from 0 to 1, representing full to no impact. (a) planting dates according to farmers' practice, (b) planting at fixed planting dates, (c) planting at monsoon onset.



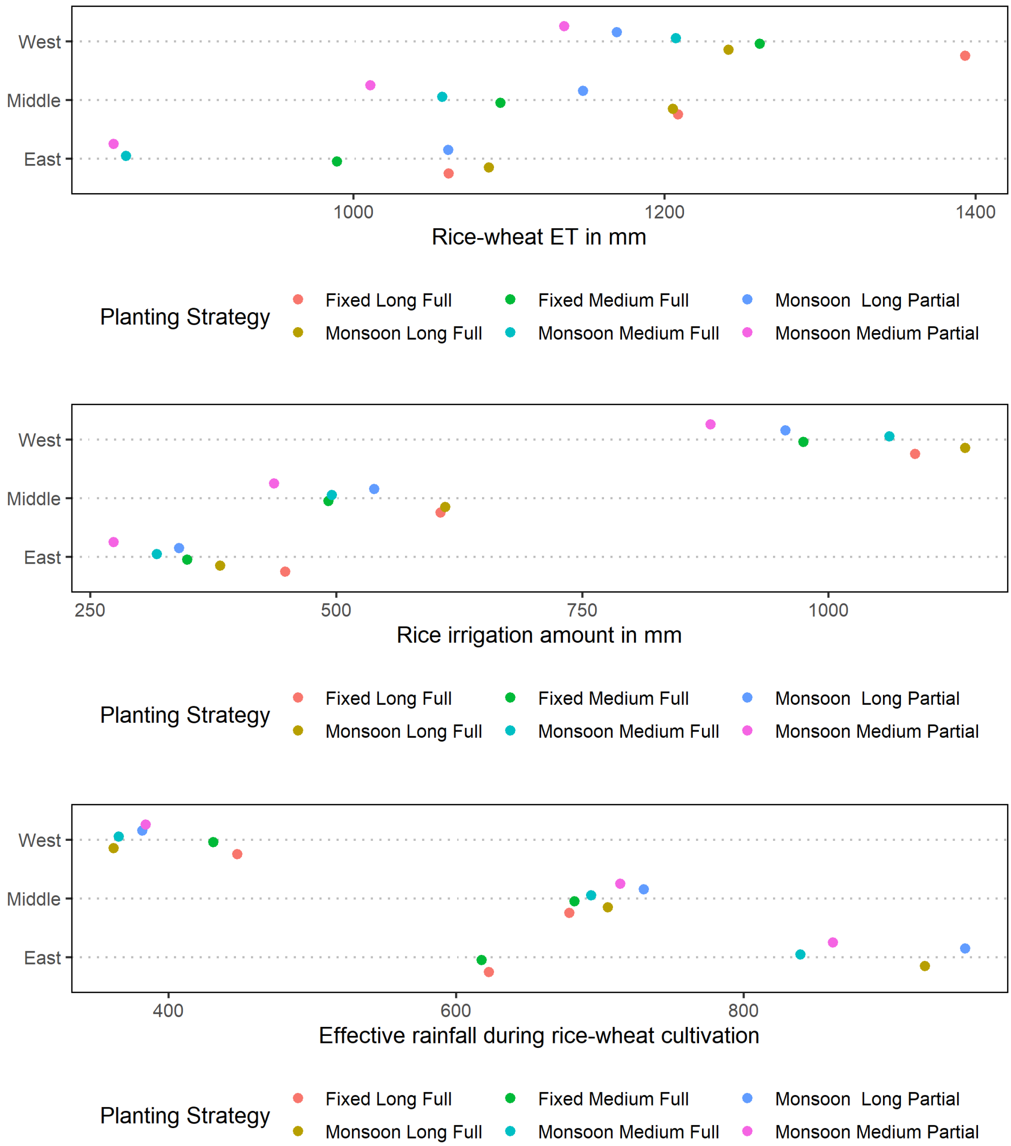
Supplementary Figure 4.3 Average climatic conditions during crop growth (1982-2015). Top: Average maximum temperature during wheat cultivation in the IGP. Middle: average minimum temperate during rice cultivation in the IGP. Bottom: average radiation during wheat cultivation in the IGP. (a) planting according to farmers' practice, (b) planting at fixed planting dates, (c) planting at monsoon onset.



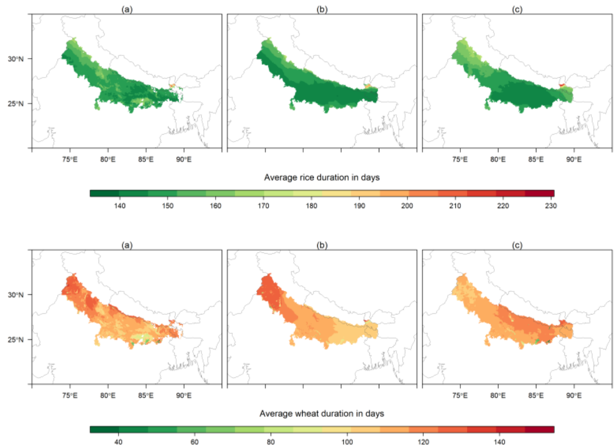
Supplementary Figure 4.4 Average effective rainfal captured during rice-wheat cultivation (1982-2015). (a) planting according to farmers' practice, (b) planting at fixed planting dates, (c) planting at monsoon onset.



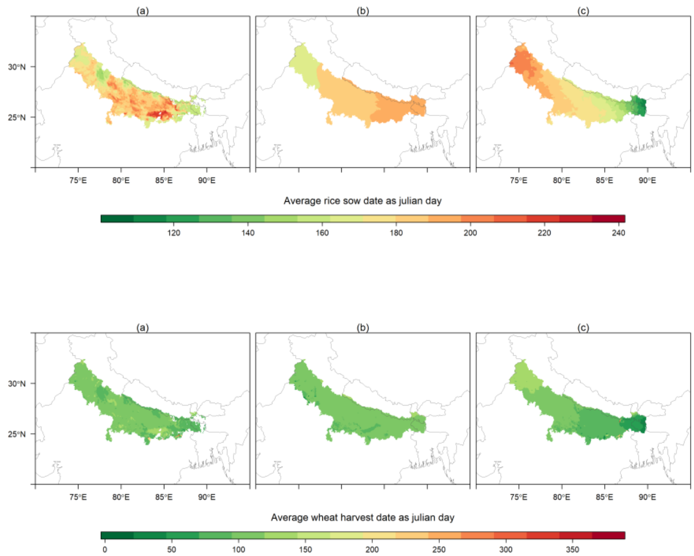
Supplementary Figure 4.5 Simulated rice-wheat system yields for additional supportive scenarios (1982-2015). Top: simulated yield potential for medium duration varieties (a) planted at fixed planting dates and (b) planted at monsoon onset. Bottom: simulated yield potential for partial irrigation schedules, for (a) long duration varieties planted at monsoon onset and (b) medium duration varieties planted at monsoon onset**.** Note: the medium duration rice varieties do not perform well when planting them at monsoon onset in the far eastern IGP, as monsoon onset is too early and higher temperatures shorten the growth period compared to the Western IGP.



Supplementary Figure 4.6 Water related indicators for core and supportive scenarios runs (1982-2015). Top: total rice-wheat system ET. Middle: total rice-wheat system irrigation water used. Bottom: total effective rainfall captured during rice-wheat cultivation. Planting strategy keys represent rice planting at fixed dates or monsoon onset, long or medium duration rice varieties, and full or partial irrigation of both rice and wheat.



Supplementary Figure 4.7 Crop growth duration in days (1982-2015). Top: average wheat growth duration in the IGP. Bottom: average rice growth duration in the IGP. (a) planting dates according to farmers' practice, (b) planting at fixed planting dates, (c) planting at monsoon onset.



Supplementary Figure 4.8 Average transplanting and harvest dates (1982-2015). Top: average transplanting date for rice cultivation in the IGP. Bottom: average harvest date of wheat in the IGP. (a) planting according to farmers' practice, (b) rice planting at fixed planting dates, (c) rice planting at monsoon onset.

Chapter 5

Selling the produce

Poverty reduction through irrigation intensification: unravelling the limited impact in Eastern India through a large-scale survey analysis

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Abstract

Many farmers in Asia already use groundwater to manage climate risks, enhance food security, and improve rural livelihoods. In the water-abundant Eastern Gangetic Plains (EGP) significant opportunities remain to intensify groundwater use. Policy makers target this pathway to address persistently high levels of poverty and food insecurity in the region. Nevertheless, evidence for poverty reduction by intensified irrigation remains largely anecdotal. To address this knowledge gap, we use a large household survey (n=15,572; 2017/18) to estimate the effects of increasing irrigation frequency on crop yields and personal daily incomes (PDI) in the rice-wheat system of Eastern India, the dominant cropping system of the region. We found that increased irrigation use falls short of transforming the poverty status of poorer farm households (median income of 66 cents/person/day with fully subsidized irrigation), when measured in 2018 Purchasing Power Parity dollars ($PPP) by the international poverty line of 210 cents/person/day. This value increases to 205 cents/person/day for households in the upper quartile of the Intensification Benefit Index (IBI) – a measure for how much a household gains in PDI from an increase in profits/ha; importantly, household dependence on agricultural income also varies widely. Irrigation-led intensification of the rice-wheat system in the EGP may provide substantial benefits for resilience to climatic change and food security. However, our results show that achieving meaningful reductions will require additional interventions beyond solely intensification of irrigation within the existing rice-wheat system. Developing diversified portfolios of rural on- and, especially, off-farm income opportunities can play an important role in helping to transform the poverty status of smallholder farmers in the EGP. Effective irrigation development should consider explicitly the heterogeneity amongst smallholder farmers when devising targeting strategies and consider household differences in current irrigation levels, IBI values, and dependence on agricultural income.

Introduction

Agricultural intensification and enhanced resilience to water stress through irrigation development is a widely discussed approach for achieving food security (Sustainable Development Goal 2; or SDG2), climate action (SDG13), and poverty reduction (SDG1) in smallholder dominated poverty hotspots such as the Eastern Gangetic Plains (EGP) of South Asia. From 1994 to 2012 poverty in the Indian state of Bihar, which encompasses a large part of the EGP, has been reduced from 61% to 34%, but still lags behind national averages in the region such as 21% in India, 15% in Nepal and 20% in Bangladesh as of 2010 (World Bank Group, 2016). Situated between the Himalayas and the Bay of Bengal, production risks in the Eastern Gangetic Plains' agroecological systems are increasing as they are affected by a progressively erratic monsoon cycle and high exposure to climate shocks such as droughts and floods (Sheth, 2015). These risks threaten to halt the progress that has been made in poverty reduction in the last decades. Consequently, policy initiatives in the EGP promise to drought-proof and transform agriculture by doubling farmers' incomes through irrigation-led intensification of agriculture (Lele, 2019).

Groundwater is already a key source of water for farmers in the EGP, but access to reliable irrigation and resulting irrigation intensities vary widely due to high diesel prices for the commonly used diesel pumps and the absence of reliable access to electricity (Foster et al., 2019; Shah et al., 2009; Urfels et al., 2020). However, while there is ample literature on the yield benefits of timely and adequate irrigation under controlled conditions (e.g. on research stations), there is less clarity about on-farm yield and income responses to increased irrigation use. As highlighted by Balasubramanya and Stifel (2020), the evidence on linkages between agricultural water use and poverty reduction remains limited although research has outlined the importance of cross-sectoral and indirect effects of irrigation development on poverty reduction (Namara et al., 2010). More recently, studies in Sub-Saharan Africa (Frelat et al., 2016; Harris, 2019) have shown that investing in agriculture may only provide modest improvements in livelihoods/poverty status and that increasingly cross-sectoral efforts are needed to reach SDG1. Although understanding the effects of agricultural intensification on personal daily incomes (PDI, the average daily income accruing to each family member assuming an equitable distribution and expressed in $PPP cents per person per day) are critical for understanding the livelihood implications of farm household, they have not been analysed in the EGP. Filling this knowledge gap will enable the formulation of effective policies and extension strategies by more accurately gauging the expected income effects of increasing irrigation frequency in these systems.

In this paper, we adopted a novel approach - the Intensification Benefit Index (IBI) (Harris, 2019) – to estimate the direct poverty impact of irrigation-led agricultural intensification on incomes of rice-wheat farmers in the EGP vis a vis the 2017 international poverty line (Atamanov et al., 2020). We focus on four core aspects: first, the distribution of IBI values and their implications for the median rice-wheat production characteristics in the region. Second, differences in PDIs and calorie provisioning for increased levels of irrigation frequency if irrigation is fully subsidized. Third, the impact of varying costs associated with different irrigation technologies on PDIs and energy provisioning. Fourth, home consumption and market participation patterns of irrigated rice-wheat production and their implications for overall livelihoods of farming households.

Materials and methods

Study area & data

The EGP encompasses parts of the Indian states of Uttar Pradesh and Bihar, the Terai region of Nepal and northwestern Bangladesh and contrasts with the drier Middle and Upper Gangetic Plains in Western India. The region generally receives between 1000 and 1500 mm of rainfall per year, of which more than 80% occurs in the monsoon months June-September. The soils and associated aquifers represent some of the world's most extensive alluvial plains formed by the meandering Ganges and its tributaries that carry sediments from the Himalayas. Smallholders predominantly grow rice (>90%) in the monsoon time followed by mainly wheat (>60%) but also other crops such as lentil, oilseeds or potato that are planted on residual moisture after the rice harvest in November and harvested in late March.

Household level production data for farmers' main rice and wheat plots in 2017-2018 (henceforth 'household data') were collected as part of a collaborative data collection effort between the Cereal Systems Initiative for South Asia (www.csisa.org) and the Indian Council of Agricultural Research (ICAR). Data were collected from 10 randomly selected villages per district and 10 randomly selected households per village. Although ca. 30% of the crop-year data records were collected from the same households (panel), we treated them as independent to retain the larger inference space from the original sample size.

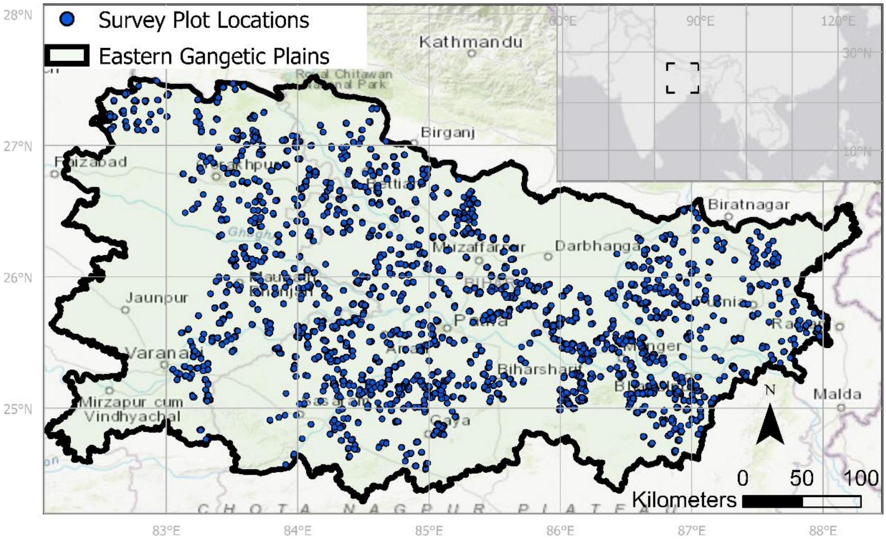

Figure 5.1 Map of study location and survey data points.

We analysed the household data from the 2017-2018 rice-wheat-rice season in the EGP with the following crop-year combination: rice-wheat=16,016; thereof rice: n=8589 and wheat: n=7427. Land fragmentation poses challenges to collecting production data from smallholder environments as management may vary from plot to plot. We simplify the analysis by assuming that farmers applied the same management practices, incurred the same costs, and obtained the same yields as on their largest plot for all rice-wheat cropped plots (Fraval et al., 2019; Niroula & Thapa, 2005). Furthermore, as is common with similar datasets, inaccurate estimates of landholding and plot sizes can cause large positive outliers, which we removed by trimming off households in the 99th percentile of affected variables (i.e. IBI, Personal daily income, landholding size and profits) which resulted in a total dataset of n=15,572 crop-year records.

Precipitation was average for the rice season 2017, with a Standardized Precipitation Index (SPI) ~0, and below average for the wheat 2018 and rice 2018 season, SPI ~ -1 to -3 (IRI, 2020). This means that our data only partially, but not fully, control for weather factors and therefore can only offer limited inference regarding resilience and robustness provided by increased irrigation intensities to the rice-wheat system of the EGP. Specifically, the data offer 'high side' estimates of irrigation advantages due to prevailing climate conditions.

Profit estimation for fully subsidized irrigation and Intensification Benefit Index

To analyse the effect of increased use of irrigation on household incomes, we first calculated the Intensification Benefit Index (IBI) that we adopted from Harris (2019). The IBI is defined as the return in cents/person/day that individuals in a given household receive from an improvement of 1 \$/ha/year in farm profitability when accounting for farm size and household size (Equation 4.1). Since both parts of this ratio are expressed in the same currency, the Index may be used to compare directly farming households in different countries in a unit of cents/dollar. That is, the IBI reflects the improvements of household income derived from intensification that go beyond profitability per hectare measurements to account for differences in crop area and household size to gauge benefits to individual household members (Harris, 2019).

$$IBI\ (\frac{cents}{dollar}) = \frac{\left(\frac{1\ \$/ha/year\ \ *100}{365\ days}\right)}{Household\ Size\ (persons)} * Cropped\ Area\ (ha) \qquad (5.1)$$

We then used the IBI approach to estimate personal daily income (PDI, in cents/person/day) and personal daily calorie (in kcal/person/day) values from the annual profitability and productivity values derived from rice-wheat production by households for each crop-year (Equation 4.2). To allow for international comparisons of income measures and comparison against the international poverty line, we converted the input and sales costs to purchasing power parity (PPP) by using a conversion factor of 18.10 INR-$PPP as reported by the World Bank for 2018. Subsequently, we calculated the value of total production by multiplying self-reported yields in t/ha with the reported farm gate price in ($PPP/t) and subtracting input costs in $PPP/ha. We treated the full net value of production as income since farmers would have to purchase grains for a similar price if home consumption were absent. We also calculated the crop specific calorie value of total production per ha using an average value of 2800 kcal/kg for rice and 3340 kcal/kg for wheat (D'Odorico et al., 2014). In addition, we compared the PDIs that account for the net value of production with cash incomes by multiplying PDIs with the self-reported marketed share of production and explored daily calories per capita retained by households. We further present the self-reported share of agricultural income in total household income as well as the surveyed crop's share of agricultural income.

$$PDI = [(Yield * Farm\ Gate\ Price) - Input\ Cost] * IBI \qquad (5.2)$$

For input cost, we used average fixed values as reported by the Indian Government for the state of Bihar for machinery (rice: 4,015 INR/ha, wheat: 5,936 INR/ha), seed (rice: 3,234 INR/ha, wheat: 3,234 INR/ha), and hired labour (wheat: 4,544 INR/ha, rice: 9,517 INR/ha) as our dataset did not include this information (CACP: Cost of Cultivation Report 2017) (Commission for Agricultural Costs and Prices 2017a, 2017b). For fertilizer, which accounts for around 15% of input cost, we multiplied the amounts of key fertilizer that farmers reported to have applied with its typical costs per kg (Urea \$PPP 0.9; DAP 1.06 \$PPP). For irrigation cost, we first treated irrigation as free (i.e. fully subsidized) and then conducted a sensitivity analysis that accounts for the different types of typical irrigation systems and associated costs as described below.

Secondly, we assess the effects of increased irrigation frequency on household benefits by modelling yields, personal daily incomes, and kcal as a function of the number of irrigations farmers apply. As this function is – in theory – non-linear, we first use a non-parametric general additive model with a smoothing spline and three knots to estimate the shape of the function in our dataset. Next, we use parametric, robust regressions (henceforth 'regression'), an alternative to ordinary least square regressions that perform better in the presence of outliers, to approximate a coefficient of change along the irrigation frequency continuum (Maronna et al., 2006). We checked whether these outputs were reliable by running multiple linear regressions and random forest algorithms with a larger number of predictors that tended to affect yield and profitability outcomes. While the wider models showed that benefits of irrigation varied regionally and with other factors and co-variates such as soil types, input intensity and farmers' education (which lie outside the scope of this paper), the sign and magnitude of yield and income responses to increasing irrigation frequency were confirmed even when other factors and co-variates were accounted for (see results and discussion section).

For the sensitivity analysis of irrigation costs, we assessed how the profitability of irrigation-based intensification changed with typical pumping costs. We used irrigation cost values based on field work data and secondary literature and included (rented) large diesel pumps, small diesel pumps, (rented) electric pumps and fully subsidized irrigation (Foster et al., 2019; Shah et al., 2009; Urfels et al., 2020). We assumed an irrigation of 60 mm, 65 INR/l of fuel, 22 INR/unit of electricity; Large pumps: 1.25 l/h fuel consumption and 12l/s discharge; Small pumps: 0.5 l/h fuel consumption and 10l/s discharge; Electric: 1 unit/h energy consumption and 8 l/s discharge. We further contrasted the profitability of the rice-wheat system for farms of low and high irrigation intensities by separating households into groups of low and high irrigation based on the range of irrigation intensities observed in the region (see Table 5.1). That is, < 3 irrigations in rice (28%) and wheat (63%) each for the low group and > 3 irrigations in rice (44%) and > 2 irrigations in wheat (36%) for the high irrigation group. Due to lack of sufficient panel data, we summed the rice and wheat distributions for each group to assess the overall system benefits.

Results and discussion

IBI distribution and the median household

The households in our dataset had a strongly right-skewed IBI distribution with a median of 0.02 cents/dollar (see Table 5.1 for crop-wise figures). This means that, for households with the median IBI value, 1000 $PPP per year provides 20 cents/person/day while10,500 $PPP/ha/year would provide the 210 cents/person/year that, in the absence of other income sources, are required to move above the 2017 international poverty line of 210 cents/person/day (Atamanov et al., 2020). The median number of household members in our dataset was 7.8 with 0.54 ha for a household's landholding (see Table 5.1 for crop-wise figures). Sample rounded landholding-household size combinations that produce the median are: 0.64 ha – 8 persons, 0.32 ha – 4 persons, 0.4 ha – 5 persons, and 0.81 – 10 persons. Consequently, the median household could cut the profit requirement to sustain incomes above the poverty line to 5,250 $PPP/ha/year if their landholdings could be doubled. Similarly, as the number of household members decreased, IBI values increased as relatively more land was available per person. For example, if a household member left the household, e.g. young adults to pursue work opportunities elsewhere, this would also decrease the profit requirements to lift the farming household above the poverty line. In general, households with higher IBI values tended to be more educated, derived a larger share of income from agriculture, applied more herbicides, attained higher yields, got higher farm gate prices, and spent less on fertilizer per ha (not shown). These findings are in line with other studies on efficiencies and dynamics among small farms (Deininger et al., 2017; Paul & Githinji, 2018).

We found that for rice-wheat farmers in the EGP, the full net value of production amounted to 2905 $PPP/ha/year and 56 cents/person/day for the median household (see Table 5.1 for crop-wise figures). Similarly, average yields of 3.9 t/ha (rice) and 2.8t/ha (wheat), provided 4,054 kcal/person/day at the median IBI of 0.02 (see Table 5.1). While not lifting households above the poverty line by themselves, the rice-wheat system did provide important contributions to household food security, especially when considering the cultural significance of home consumption of staple crops. When only considering the sold shares of production, profits for the median household amounted to 572 $PPP/ha/year and 11 cents/person/day (not shown). The value of self-consumed production stood at 45 cents/person/day for the median household (see end of results and discussion section). Furthermore, farmers

Table 5.1 Overview of descriptive summary statistics for key variables. Landholding, irrigation frequency, fertilizer cost, and yield are raw input data. Other variables were calculated for each household as described in the methods section before the summary statistics of each variable was calculated.

		Landholding size in ha	Number of household members	Irrigation frequency	Fertilizer cost in $PPP/ha /season	Yield in t/ha	Intensification Benefit Index in cents/dollar	Personal daily income in cents/person/day	Profit in $PPP/ha/year
Rice	Mean	0.85	7.91	3.90	270	4.06	0.031	59	1720
	SD	0.76	2.66	2.42	154	1.19	0.029	71	1045
	Min	0.01	1.00	0.00	0	0.52	0.000	-114	-3860
	Q1	0.33	6.00	2.00	167	3.25	0.012	13	996
	Median	0.63	8.00	3.00	242	4.00	0.022	36	1688
	Q3	1.10	10.00	5.00	358	4.80	0.041	78	2435
	Max	4.85	12.00	13.00	5114	13.54	0.196	472	4455
Wheat	Mean	0.69	7.92	2.27	342	2.98	0.025	32	1210
	SD	0.68	2.71	0.76	92	0.84	0.025	44	708
	Min	0.01	1.00	1.00	0	0.53	0.000	-103	-1119
	Q1	0.25	6.00	2.00	285	2.40	0.009	8	687
	Median	0.49	8.00	2.00	346	3.00	0.017	18	1161
	Q3	0.80	10.00	3.00	409	3.40	0.031	39	1629
	Max	4.98	12.00	5.00	794	6.50	0.196	424	4109

tended to substantially complement farm incomes with other income sources. Our data show that, for the median households, incomes from rice-wheat accounted for 20% median of total income and agriculture in general accounted for ca. 40% median (see end of results and discussion section). That is, the median household earned ca. 0.55 \$PPP/person/day from sources other than rice-wheat production. Together, these indicated that rice-wheat production contributed a significant share to household income, but also that the median household could not be lifted above the poverty line by increasing rice-wheat production alone.

Our results show that less than 30% of crop production was sold by the median household, less than 50% was sold by three-quarters of the households, and most households derived more than 50% of income from agriculture (Figure 5.2). When using the reported 5-year average estimate of the share of crop and agricultural income in total incomes in combination with the estimated income from crop sales in the surveyed year, the value of full household income sources for both rice and wheat data points showed very large variations (e.g. for rice Q1 = 52, Median = 162, Q3 = 402, and 95th percentile = 2581 cents/person/day; not shown). We suspect that this variation was largely due to recall bias and under-reporting of household incomes, but also simply huge variations in actual incomes from non-agricultural sources. With this very rough estimate, out of the rice farming households that did sell some share of their produce, 57.4% appeared to live below the poverty line of 210 cents/person/day (not shown). This is almost double when compared to the official figure for Bihar (2011). As rice-wheat profit values were in line with other reported values (World Bank Group, 2016) the discrepancies were likely caused by differences between rural farming and non-farming households as well as biases in the self-reported share of incomes and sales, e.g. by overestimating the importance of rice-wheat farming for income.

Most systems are irrigated with low frequency: 1-2 irrigations for wheat and 2-3 for rice. But several data points existed with higher irrigation intensities (see Table 5.1). Higher irrigation intensities were generally associated with the use of more affordable, electrically powered pumps, early planting, longer crop growth durations and higher market sale shares (CART, not shown). Better understanding the factors that drive adoption of higher irrigation frequencies remains outside the scope of this article, but preliminarily, our dataset indicates that differences in planting time, crop types and commercial orientation are tightly linked to differences in the numbers of irrigation.

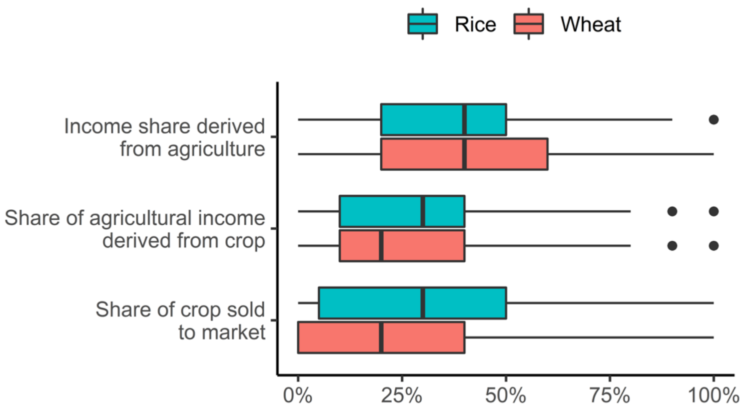

Figure 5.2 Distributions of income shares and marketed shares of crops for rice-wheat farmers in the EGP.

Income and productivity responses to increasing irrigation frequency at free irrigation rates

Our results confirm that increasing irrigation frequency is linked to increasing yields and personal daily incomes. For rice, 8% of farmers irrigated zero or one times, 20% irrigated two times, 27% irrigated three times, 16% irrigated four times 28% irrigated their rice crop five or more times. For wheat, 14% of farmers irrigated one time, 50% two times, 30% three times, 5% irrigated their wheat crop four times, and 13 farmers, less than 1%, reported to have irrigated their wheat crop five times. The difference, for rice, between average yields for low and high irrigation-frequency systems was 0.17 t/ha (see Figure 5.1, $p < 0.01$). For wheat, the yield difference between the median low and high irrigation frequency systems was 0.7 t/ha (see Figure 5.1, $p < 0.01$). For income, the difference between the medians of low and high irrigation frequency systems was 15 cents/person/day for rice and 10 cents/person/day for wheat, that is a 56% improvement in rice and 70% improvements in wheat (see Figure 4.1, $p < 0.01$). These results compare well to similar results reported for the improvements of net output from irrigated vs. non-irrigated crop production systems across Asia by (Hussain, 2007). The non-linear shape of the rice response to irrigation (see Figure 5.3) cannot be directly traced in this study. Other studies indicate that in low irrigation frequency systems farmers apply irrigation late to save the crop rather than to enhance productivity which may mute the yield response, or that water may not be the yield limiting factor in the lower input systems (Urfels et al., 2020; van Ittersum & Rabbinge, 1997). The regression results and partial dependency plots confirm the returns to increasing irrigation frequency in the rice-wheat system. In the regressions, the intercept (zero irrigations) is located at 3.57 t/ha (rice) and 2.07t/ha (wheat) and 29.5 cents PDI for rice and 7.3 cents PDI for wheat (see Table 5.2). Improvements per increase in irrigation frequency were 3.2 cents PDI for rice and 5.8 cents PDI for wheat per irrigation (see Table 5.2). Subsequently, at low irrigation frequency, the modelled rice-wheat system provided 36.8 cents/person/day, which is 19.3% of the poverty line.

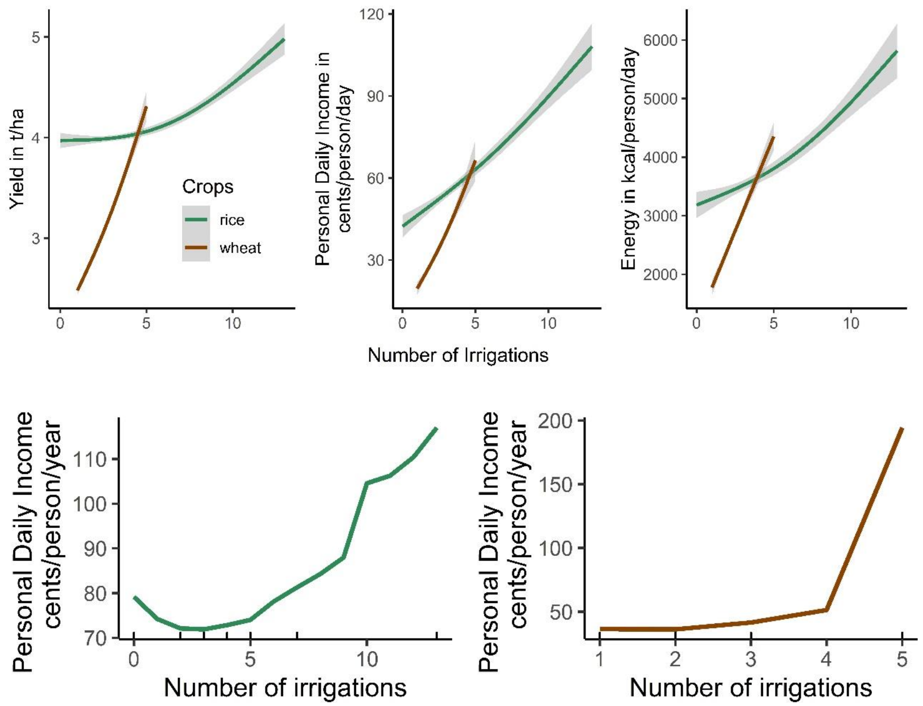

Figure 5.3 Top: GAM models showing non-parametric estimate of the relationship between yield, PDI and energy from the full net value of production for the increasingly frequently irrigated rice-wheat system. Bottom: partial dependency plots from a non-parametric model (randomForest) that was run on a wider set of predictors to address the potential confounding of other management factors that may change simultaneously with increased irrigation use. Note that observations for the highest irrigation frequencies are limited.

Table 5.2 Regression results with irrigation number as the independent variable. All parameters are statistically significant ($p < 0.01$)

Dependent variable	Term	estimate	std. error	statistic
rice yield in t/ha	intercept	3.785	0.025	151.1
rice yield in t/ha	number of irrigations	0.066	0.005	12.1
wheat yield in t/ha	intercept	2.055	0.029	70.6
wheat yield in t/ha	number of irrigations	0.392	0.012	32.4
rice personal daily income in cents/person/day	intercept	29.585	0.892	33.1
rice personal daily income in cents/person/day	number of irrigations	3.229	0.198	16.3
wheat personal daily income in cents/person/day	intercept	7.362	0.702	10.5
wheat personal daily income in cents/person/day	number of irrigations	5.885	0.295	20.0

Irrigation Cost and Minimum Support Price

Irrigation in the region often comes at a substantial price in the form of fuel cost for operating large diesel pumps or rental charges paid to pump owners. Previous research has identified that energy consumption per litre of water pumped varies greatly between small and large pumps and is significantly cheaper for electrically powered pumps (Bom et al., 2001; Foster et al., 2019). Although the region is currently being electrified, many smallholders still rely on diesel pumps to lift water from aquifers and are likely to continue to do so in the near future. Our sensitivity analysis on irrigation operating costs (see Figures 5.4 and 5.5, Table 5.3) confirms that, for most farmers, small diesel pumps can provide similar returns on investments as electric pumps, while large diesel pumps or rental rates diminish most economic benefits from increasing irrigation frequency in rice and return to investments turns negative for rental rates. Assuming all households use the same type of pumps, the median effect, on the full net value of production, for moving from low to high irrigation intensities amounts to 11 cents/person/day for rental, 34 cents/person/day for small diesel, and 38 cents/person/day for electric pump (Figure 5.4, Table 5.3). Again, the right-skewedness of the IBI distribution leads to significantly larger gains for household in the upper quartile of IBI values for which moving from low to high irrigation frequency has a median effect of 144 cents/person/day from rice-wheat production for electric irrigation (see Figure 5.5). With the right infrastructure, when accounting for the full net value of production, returns from increasing irrigation frequency in the rice-wheat system remain substantial, albeit not necessarily transformative in itself.

Returns to increasing irrigation frequency remain modest in absolute terms for all but the upper quartile of IBI values due to the strong right skewedness of the IBI distribution (Figure 5.5). This indicates that upper bounds of farm and family sizes rather than production practices, may limit poverty reduction through the direct impact of irrigation-led intensification of the rice-wheat system for the majority of farming households in the region. Two policy options are commonly invoked to strengthen food security and improve farmers' income: (a) diversified or integrated farming systems and (b) minimum support price policies. Profitability estimates for diversified or intensified farm systems in the region range between $PPP 4000 and $PPP 13000 per annum (i.e. 80-260 cents/person/day for the median household), with significant horticultural and/or livestock integration that replace rice and wheat at the higher levels (Khan & Verma, 2018; Sen et al., 2017). Diverse farming systems can significantly improve farmers' incomes and the most profitable ones may even lift the median household above the poverty line. But scalability of diversified systems may be limited by bio-physical constraints, the cultural and food security value of rice and wheat production and hinge on market integration, price fluctuations and farmers' ability to sustain capital investment costs. Minimum support prices (see Figure 5.5), the other major policy option, only has large effects on the highest IBI quartile. If the official minimum support price of 2020 were paid to farmers in our dataset, the personal daily incomes for the higher IBI quartile would amount to ca. 300 cents/person/day for low irrigation intensities and 400 cents/person/day for systems with high irrigation intensities (see Figure 5.5). The other 75% of farmers, however, see increases in farm-derived income, but no substantial transformative shift above the poverty line.

These results have two consequential implications: one, upgrading irrigation infrastructure in the region to technology that decreases operational costs to farmers, such as small diesel pumps, electric pumps, or solar pumps, is only likely to be attractive to farmers if these systems are very low cost because the small incremental increases in personal daily incomes from increasing irrigation frequency do not justify a large capital expenditure for most farming households. Solar powered irrigation systems, in particular, are receiving widespread attention from policymakers and development organizations with several business models to overcome the upfront capital costs being suggested for major investments (Shah et al., 2018b). While these models might have several impactful use cases, such as horticulture and households with high IBI values, their applicability to serve remote and small cereal farmers are not known. For these farmers, in the absence of workable models to overcome upfront capital cost, low-cost, portable easy to use and repair diesel pump sets are likely to continue to be the option of choice until reliable access to electricity has reached these plots.

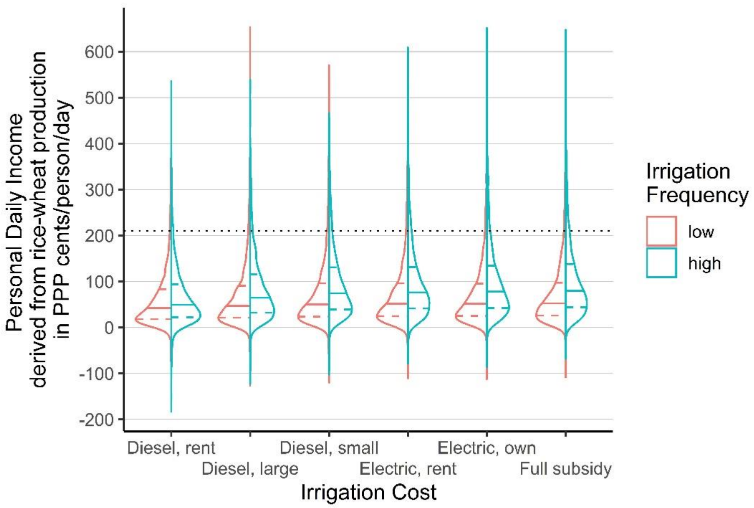

Figure 5.4 Violin plots of distribution of personal daily incomes from full net value of rice-wheat production for low vs. high irrigation frequency for varying irrigation costs. Coloured, vertical shapes show the density function of each group, the coloured and horizontal dashed lines show the 25th and 75th percentile and the solid ones the median. The dotted black horizontal line is poverty line of 210 cents/person/day.

More specifically, the Union Ministry of New and Renewable Energy (MNRE) has launched Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyaan (PM-KUSUM) scheme to install 1.75 million off-grid solar powered irrigation systems up to 7.5 HP capacity and solarization of 1 million grid-connected agriculture pumps with 60% capital subsidy to farmers (Government of India, 2019). Diesel pumps have low capital costs and high operating costs because the fuel is expensive. Solar pumps have the opposite cost structure: the capital investment required is very high while the fuel cost is zero. The lifecycle cost of solar pumps is lower than that of diesel pumps (Kolhe et al., 2002; Odeh et al., 2006). This is mainly because photovoltaic (PV) systems have long lifetimes, need minimal attendance and little maintenance, and have near zero operational cost while diesel is expensive and diesel pumps have low efficiencies. Despite lower lifecycle costs and high capital subsidies by state and central governments, there are still very few takers of solar pumps in India. Most states reported no demand for solar pumps in the first year of the implementation of the PM-KUSUM scheme (see the table on the schemes URL: http://164.100.94.214/pm-kusum-scheme). The initial capex requirement for solar pumps is very high even after the subsidy for most Indian farmers who are both asset poor and credit constrained. The expanding rural power grid with high subsidies on electricity use for irrigation in states like Bihar also makes investment in solar pumps less attractive to farmers.

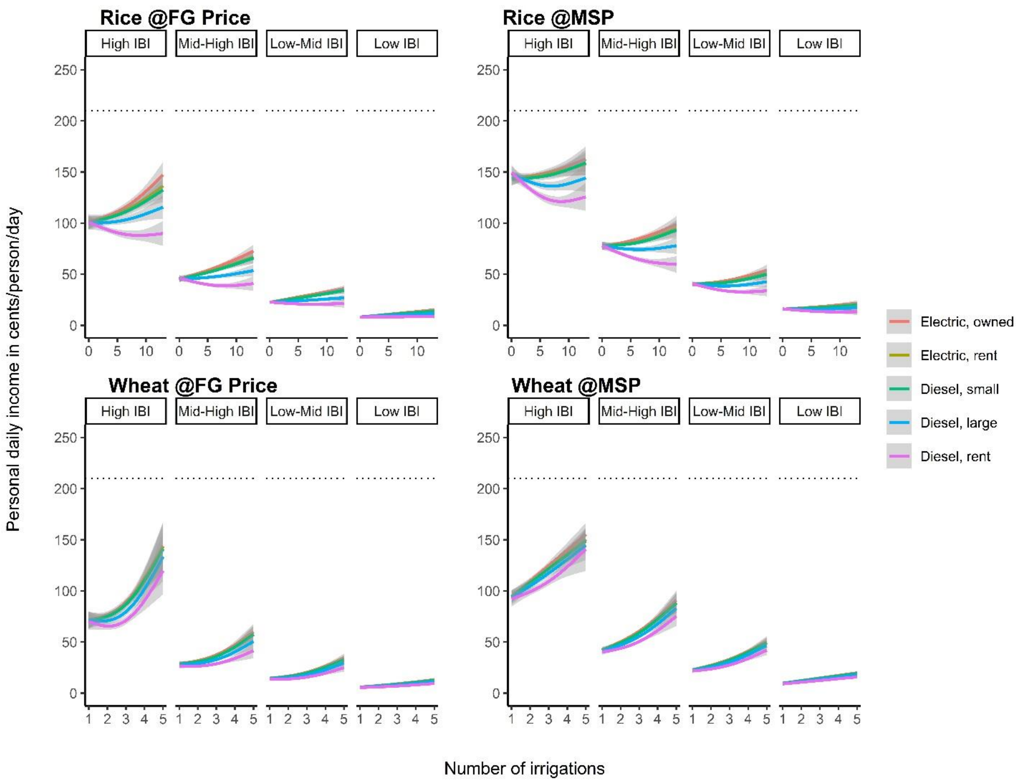

Figure 5.5 GAM models per IBI group for personal daily income as a function of increasing irrigation frequency. Incomes are derived from full net value of production for rice (top) and wheat (bottom) at the received farm gate prices (left) and most recent minimum support price of 2020 (right). Dashed line is the international poverty line of 210 cents/person/day. Non-linear features likely indicate influence of co-variates on yield response (e.g. limiting factors). Negative slopes indicate that irrigation is not profitable with the respective cost of irrigation of the associated irrigation technology.

Two, finding the right tariff policy for electrified farms – a heavily discussed policy lever – is unlikely to contribute to substantial transformations of rural economies (Sidhu et al., 2020). Even with flat tariffs, our results suggest, that farmers in the EGP are not likely to see vital changes to their income from crop production vis à vis the international poverty line. However, on a relative basis and with an eye to the policy goal of doubling farmers' incomes from to 2015-2016 levels by 2024, the median effect of moving from low to high irrigation frequency with owned electric pumps amounts to 40 cents/person/day, for Bihar, amounts to 32% of the 121 cents/person/day target (see Table 5.3; (Government of India, 2017; Lele, 2019). With low incomes to start with, however, it is a long way to go from doubling farm incomes to transforming farmers' poverty status. Policymakers need to invest in incremental and coordinated upgrading of agricultural input (including irrigation) and output chains, to create diversified job opportunities. Complementary investments in diversified farming system with scope for poverty reduction among the higher IBI quartiles may further generate rural off-farm income opportunities for smaller farmers.

Home consumption and market participation

While most farmers sell some produce, most crop production was consumed at home (see Figure 5.4). One may assume that increases in irrigation frequency may contribute to increases in income when home consumption is already above sufficiency levels of 2700/kcal/person/day. But multifaceted household, non-household and geographical factors influence smallholders' market participation (Barrett, 2008). When only considering sold shares of production, we find that PDIs for the median household approximately double with affordable irrigation, e.g. from 7.70 cents/person/day to 14.80 cents/person/day (not shown). Higher number of irrigations and yields are also associated with a higher number of kcal that are not sold to markets by the household, with households that have higher IBI values retaining an especially high number of kcal/person/day; ranging from an average of 546 (SD: 279) kcal/person/day (for the bottom 25% of IBI) to an average of 2624 (SD: 1277) kcal/person/day (for the upper 25% of IBI) in rice and from an average of 531 (SD: 251) kcal/person/day (for the bottom 25% of IBI) to an average of 2641 (SD: 1365) kcal/person/day (for the upper 25% of IBI) in wheat (not shown). Most households, including the bottom 25% of IBI values, did sell some rice to markets (see Figure 5.2). Intra-village insurance and exchanges are likely the source of these variations (Meghir et al., 2019; Townsend, 1994) and larger landowners may upgrade their consumption while poorer households need to sell to meet basic cash needs, better understanding the decisions involved in generating these sales shares can further improve the understanding of household's behaviour with regard to meeting household food security and cash needs when increasing yields would be informative for policymakers and program designers. Conversely, the relatively low sales shares of ca. 25% for the median household and indications for existence of informal exchanges between smaller and larger producers also means that the buffer to withstand climate shocks is relatively small. A 25% reduction in yield (the sold surplus) would not only impact farmers' incomes but also household and village level food sufficiency, highlighting the importance of irrigation for famine preventions by buffering against climate shocks.

Table 5.3 Results of two-sided paired t-test of personal daily incomes from systems with high and low irrigation frequencies for each irrigation price group. All tests are statistically significant ($p < 0.01$).

price group	estimate	statistic	conf.low	conf.high	method	alternative
Diesel rent	9.26	7.29	6.77	11.7	paired t-test	two.sided
Diesel large	24.03	17.72	21.37	26.7	paired t-test	two.sided
Diesel small	36.08	24.79	33.22	38.9	paired t-test	two.sided
Elec rent	35.04	24.15	32.19	37.9	paired t-test	two.sided
Elec own	39.94	26.41	36.97	42.9	paired t-test	two.sided
Full subsidy	40.64	26.27	37.60	43.7	paired t-test	two.sided

Non-agricultural income in our dataset accounts for at least 50% of household income for most households (Figure 5.2). The considerable share of non-agricultural income sources show that most households maintain non-agricultural jobs that complement agricultural income streams. These non-farm income streams can provide fallback options for climate shocks to agricultural production and thus form critical parts of farmers' livelihoods and climate resilience (Meghir et al., 2019). Our data, however, do not support sufficient inference on the impact of shocks in the rice-wheat system or incomes not derived from rice-wheat production including off-farm incomes. Further research is required to better understand how households respond to shocks under different levels of reliable irrigation and how they (re)arrange their income portfolios when they gain access to reliable irrigation.

These findings are in line with the general notion of non-farm income sources becoming an increasingly important source for household food security (Pingali et al., 2019; Sugden et al., 2014a). That is, the rural economy of the region is currently undergoing critical aspects of structural transformation, where home consumption and in-kind trading is being replaced by an increasing commodification, non-farm employment and purchasing of food crops. A large literature exists on the dynamics of structural transformations and its effects on the allocation of resources as well as household food security dynamics (Pingali & Sunder, 2017; Tomich et al., 2019; Webb & Block, 2012). Specifically, this body of research shows that increases in staple crop productivity and farm income do not necessarily go in hand with positive impact on poverty reductions and food and nutrition security. For example, supply and price levels of non-staple food sources may not keep up with increasing demand. Investing in non-staple value chains and production support is one potential way to increase the benefits of irrigation by maintaining low price levels that allow households with increasing earnings to purchase more diverse diets and by supporting households in lower IBI quartiles through enabling home consumption of a more diverse diet while they seek for increasing employments in non-farming activities.

Policy implications and recommendations

Our results show that while irrigation-led intensification has potential to improve productivity of the rice-wheat system and will likely become more important with climate change, most farms are too small to substantially increase income and home food production through increased irrigation use. These findings align with studies on ex-ante simulations of the effects of climate shocks to different farm types and the adoption of conservation agriculture in the region (Keil et al., 2019; Lopez-Ridaura et al., 2018). One may suggest that the consequence is a structural transformation that goes in hand with most smallholders stepping out of agriculture (Dorward et al., 2009). However, economic development in other land scarce rice producers in Asia, such as Japan or Thailand, did not lead to an increase in farm sizes as it did in Europe or North America, and part-time and family farm rice-cultivation with scale-appropriate mechanization has prevailed as a common mode of rice cultivation, albeit with ageing farmers, high levels of subsidies and often inefficient farm management (Doner & Schneider, 2016; Faysse et al., 2020; Veldhuizen et al., 2020). Achieving higher levels of productivity and irrigation use therefore requires irrigation-led intensification to cater to the needs of both small and large farmers with varying investments preferences that take into account not only the cost of irrigation but also changes in mobility, off-farm wage rates, family labour and drudgery required to apply water to the fields (Keil et al., 2019; Khatri-Chhetri et al., 2020). Developing an improved understanding of what works where, for whom, and why is required to bring reliable irrigation to the farmers of the EGP.

For example, larger and well-connected farmers can derive substantial improvements in households incomes from upgrading their irrigation systems to electrically powered ones; while subsidized solar systems targeted for group use may also provide some additional benefits for small farmers that have horticultural plots close to homesteads with market linkages and transportation infrastructure (Agrawal & Jain, 2019). Many small farmers, however, are remote farmers that occasionally rent pumps for irrigation on broadacre plots away from their homesteads (Deininger et al., 2017). For them, electrification can bring reductions in rental fees and thus drought risk, but the small profits that can be derived from their small plots, unreliable market linkages and variable non-farm income streams to generate capital to invest in part-time agriculture are unlikely to spur a rural transformation (de Bont et al., 2019; Keil et al., 2019). For small farmers, rice-wheat may not be the poverty alleviation strategy for the future, as profit margins are simply too low for farm-household size. But intensification of rice-wheat farming has a clear role to play in famine prevention among the poor. Therefore, policymakers and practitioners should encourage equitable distribution of irrigation infrastructure and incrementally build a rural knowledge base around sustainable and effective water management at the field level.

Increasing land productivity through irrigation-led intensification of rice-wheat production does not stand at odds with poverty reduction – but achieving both requires a multi-faceted approach that encompasses farmers' broader livelihoods strategies as well as strengthening and upgrading agricultural input and output chains (Hanjra et al., 2009; Namara et al., 2010). Upgrading value chains requires institutional capacity and coordination among line ministries and local governments to foster trust among upstream and downstream stakeholders, avoid technological lock-ins, and invest in critical and reliable infrastructure (Doner & Schneider, 2016; Veldhuizen et al., 2020). Farmers may play a key role in this process. For example, investments in training and education may teach both valuable on- and off-farm skills, counteract the notion of agricultural jobs being unattractive, and allow farming households to become not only productive farmers but also off-farm workers and entrepreneurs that form an integral part of the coordination and feedback mechanisms required for effective upgrading of rural economies (Hanjra et al., 2009; Ogundari, 2014; Reimers & Klasen, 2013). For instance, supporting the pump and well-drilling sector to incrementally develop a sustainable, equitable, safe, and efficient infrastructure base should be considered as an entry point to create attractive jobs.

Next, sustainability concerns need to be taken more seriously. In the short to mid-term, the EGP faces less risk of groundwater depletion as groundwater recharge is high (>300mm) (Mukherji, 2018; Shah et al., 2018b). Aquifers are large and the electrification of groundwater in West Bengal has not led to any widespread decline in groundwater tables even with intensive Boro rice irrigation (Sarkar, 2020). In the long-term, however, growing water demands from non-agricultural sectors and the impact of increasingly frequent coupled climate shocks imposes additional sustainability concerns and further research is required on the linkages with intensified groundwater use (Raymond et al., 2020). For example, dry spells that are coupled to heat waves may affect crop growth beyond the sum of individual stresses and changes in crop choice or new, resistant cultivars may be required to fulfil food production needs (Kadam et al., 2014). Likewise, the impact of successive droughts and decreased recharge from increasingly erratic precipitation events pose further concerns to the sustainability of irrigation in the EGP in the long-term and new methods to assess the impact of climate change on groundwater recharge should inform policy making (Dillon et al., 2019; Kirby et al., 2016).

Lastly, intensified rice-wheat farming may not transform the poverty status of small farmers – but securely irrigated rice-wheat farming has a critical capacity for ensuring food security, especially given the prevalence of poverty in the region. Strengthening this capacity requires further understanding of the non-homogeneous productivity and profitability response to increasing irrigation frequency as it may be constrained and vary across IBI, bio-physical, socio-economic, and socio-technical factors and gradients (Molden et al., 2010; Suhardiman et al., 2018; Zewdie et al., 2020). A better understanding is needed on how the complexity that emerges from variability among these interacting factors shapes important sustainability outcomes (Rockström et al., 2017). For example, soil and drainage types of the plots interact with weather conditions, crop types and the timeliness and amount of irrigation, a management factor that is further conditioned by farmers' knowledge and experience. Socio-technical requirements of use for different irrigation systems add another layer of complexity as timeliness, for example, may be constrained by the design and capabilities of the irrigation systems in place (Westling et al., 2019). Understanding these factors and their interactions can pinpoint potential avenues for increasing land productivity and system profitability that are anchored in context- and place-specific development trajectories and informed by patterns of spatial inter-village and intra-village heterogeneity (Lambe et al., 2020). Understanding these patterns can then inform policymakers on where investments would pay off most in future research. Expanding irrigation features high on the political agenda in the region, and a new wave of irrigation research is needed to extend our understanding about effective utilization of irrigation infrastructure to foster targeted systemic change in a rapidly changing food system.

Conclusions

We studied the effect of irrigation-led intensification of the rice-wheat system on personal daily incomes of smallholder farmers in the Eastern Gangetic Plains. We find that increasing irrigation use significantly increases productivity and income. But for most farmers, except the largest ones, rice-wheat production alone may not lift the household above the poverty line. But irrigation provides substantial benefits for productivity that play a key role in preventing famine and strengthening food security. Therefore, we argue that irrigation development should be considered as part of cross-sectoral efforts and coordinated upgrading of the rural economy that creates both agricultural and non-agricultural jobs and skills. As such, policymakers should develop targeted investments in the private sector that can directly support irrigation (e.g. pump vendors and mechanics, tubewell drillers, spare part traders and manufacturers), capacity building on sustainable and cost-effective water management at the field scale, and consolidation of the knowledge base around groundwater dynamics, especially in light of increasingly erratic rainfall patterns. Further research is required to fill the following knowledge gaps: (a) effective use cases of different irrigation technologies in varying contexts, (b) spatial distribution of factors limiting the yield response to increased irrigation, (c) effects of connected extreme climate events on groundwater flows and recharge, and (d) suitability of irrigated agroecosystems to withstand connected climatic as well as socio-economic shocks.

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Chapter 6

General discussion

Chapter 6

A social-ecological perspective on managing water and time in agricultural systems

This chapter reflects on and discusses the overall research aims and findings of this thesis and their implications. After revisiting the context of this thesis, the first section of this Chapter 6 restates the research questions, followed by the second section where findings are summarized per research question and thus per Chapter 2 to 5, thereby mirroring the overall structure as presented in Chapter 1. The third section of this Chapter then critically engages with the scientific literature and reflects on the policy, theoretical and methodological implications of this thesis in light of the research objective. The fourth section places the thesis's research results within a broader scientific and societal context and discusses the implications of its findings regarding four relevant cross-cutting themes, namely water systems, climate shocks, the monsoon, and social science for targeting policies and interventions. Future research needs are also stated here. Lastly, the fifth section of this Chapter 6 concludes and briefly summarizes the key findings and their implications.

This thesis set out to advance:

(i) the scientific understanding on building resilient farming systems amidst global change impacts and processes through a social ecological systems' perspective on managing water and time in smallholder farming systems; and
(ii) a mixed methods approach that combines the use of big data and participatory approaches to develop a contextualized but largely generalizable understanding of social-ecological interactions in agricultural systems.

More specifically, this thesis investigates how social and ecological aspects affect the management of water and time in rice-wheat cultivation in the Eastern Gangetic Plains of South Asia (Figure 1.1). The aim is to provide a basis for the development of context-specific and targeted interventions for planting date adjustments and irrigation that support the sustainable intensification of agricultural production. Due to the complexity of the challenge, agronomic and water related interventions cannot be treated in separation, but require a holistic, interdisciplinary, and pluralistic approach that can elucidate the constituents and dynamics of change processes from various angles (see Figures 1.2 and 1.3). In doing so, this thesis offers a novel approach that combines the use of statistical tools to analyse large datasets, computational simulation tools, and community engagement for an integrated analysis of the social-ecological diversity and performance of agricultural systems.

Research questions: from planting the crops to selling the produce

The social-ecological systems' perspective structures the rice-wheat system into sub-systems that are connected through activities and flows of resources (Figures 1.2 and 1.3). This thesis unpacked these flows and activities to characterize key variables of the different sub-systems and how these variables shape the performance of the rice-wheat system with special attention to the activities of crop planting and irrigation (Figure 1.4). The performance of the rice-wheat system was then assessed against its contribution to the development objectives of food security and poverty reduction. From this social-ecological systems' perspective the overarching research question and the sub-research questions were formulated (see also Figure 1.4).

Overarching research question:

"How can water and time be managed successfully to sustainably intensify the rice-wheat system in the Eastern Gangetic Plains?"

Sub-research questions:

1. **Planting the crop:**
   "How do farmers perceive constraints and opportunities for planting the rice-wheat system in the Eastern Gangetic Plains?"
2. **Irrigating the crop:**
   "How do farmers perceive constraints and opportunities for irrigating the rice-wheat system in the Eastern Gangetic Plains?"
3. **Harvesting the crop:**
   "To what extent can improved planting and irrigation of the rice-wheat system contribute to food security in the Eastern Gangetic Plains?"
4. **Selling the produce:**
   "To what extent can improved planting and irrigation of the rice-wheat system contribute to poverty reduction in the Eastern Gangetic Plains?"

Chapter 6

Overview of findings: how social heterogeneity and ecological thresholds affect the management of water and time

The overall findings of this thesis show that improving the management of water and time for increased productivity and resilience of the rice-wheat system in the Eastern Gangetic Plains is possible – but it is not a panacea. That is, adjusting planting dates and improving irrigation are not universally able to substantially improve productivity and incomes. Figure 6.1 presents an overview of the key findings of the study per sub-research question. The ability of farmers to adjust planting dates is delimited in space by the climatic system and requires irrigation and the timely availability of other inputs, both of which depend on the conditions of the water system and social system (Figure 1.2). Numerous factors inhibit farmers from applying adequate and timely irrigation for crop planting (and during dry spells) as the social sub-system and the water sub-system impair farmers in their capacity to irrigate their crops adequately and timely. This means that the adjustment of planting dates and irrigation development requires accompanying investments to improve input markets, to facilitate local coordination, and to raise awareness about the benefits of the interventions. The social-ecological diversity within the rice-wheat system requires solutions to be tailored to the heterogeneity in the climatic, water, socio-economic, and ecological sub-systems. However, these interventions are limited in scope to increase agricultural production across the landscape, while they provide little monetary benefit to most farmers. Agronomic improvements in the farming system cannot lift most farmers out of poverty. Besides, the ability of aquifers to sustain increased groundwater pumping also remains unknown.

More specifically, this thesis shows that farmers are generally aware of the benefits of timely planting, but less aware of the benefits of timely irrigation (Chapters 2 and 3). While high irrigation costs act as a deterrent to use irrigation for planting crops or buffer against drought, this thesis shows that different sub-systems such as the water system and the social system further restrain farmers from irrigating their crops. Importantly, management of water and time are shown to interact with critical ecological thresholds, such as for the ability to pump groundwater from depth of below 4.5 m below ground level (Chapter 3) and the detrimental, partially cascading effects of exposing rice crops to low temperatures after the monsoon season on rice-wheat system productivity (Chapter 4). This thesis further finds that availability constraints of inputs in the form of capital goods (e.g. tractors, pumps) creates local queuing. Farmers at the end of the queue, who tend to be more vulnerable, have less control over planting dates or water management as they partially depend on the activity of the farmers with earlier access to these capital goods. Insufficient availability of supporting sectors, such as spares and repair, further delays farmers' timely access to machinery. Consumable inputs (e.g. seed and fertilizer), on the other hand, do not create queues but their often-subsidized nature and the limited timely access to these subsidies often deter farmers from acting in an anticipatory manner (Chapter 2). Since the limited farm size of most households translates only into modest income gains derived from improved productivity, coordinated efforts to address the entirety of the delay factors in any locality is likely required to precipitate behavioural change that results in landscape level productivity improvements (Chapter 5). More detailed summaries of each chapter are provided below:

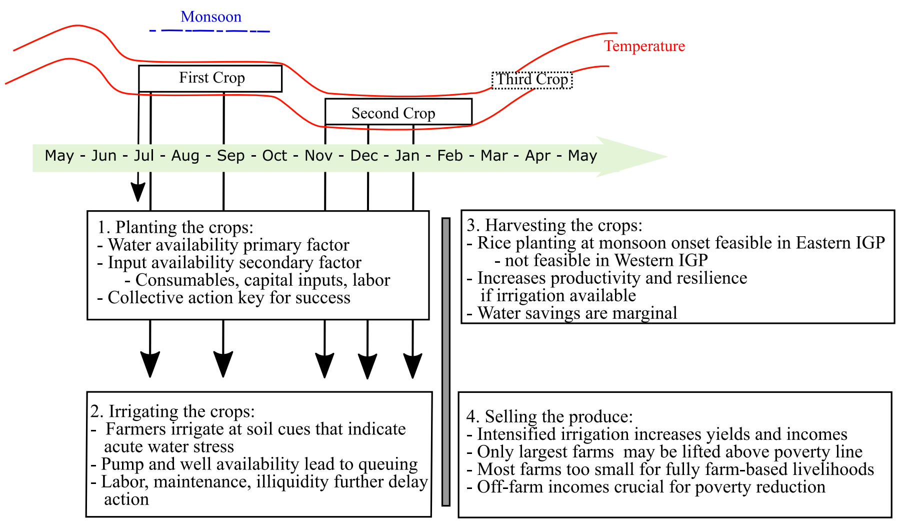

Figure 6.1 Overview crop system interactions with temperature and precipitation over time and summary of key findings for each research chapter.

In **Chapter 2**, this thesis uses a novel mixed-methods approach to reveal that farmers' capacity for timely planting is primarily predicated on the timely availability of pre-monsoonal irrigation, while social factors such as timely access to farm inputs and machinery act as secondary constraints for timely planting. In addition, absence of collective action for rice planting increases pressure from pests, diseases, and grazing animals on individually early planted plots. This lack of collective actions for timely planting emerged as an additional constraint but could not be quantified. Addressing these issues, will require new data collection efforts that quantify the spatial structure of these barriers. In addition, finding arrangements that can solve collective action problems, at times perhaps through creation of new service models in the private sector will also enhance farmers' capacity for timely planting. The sustainability of some of these interventions also depends on the resilience and sustainability of the water system as well as input, machinery, and labour markets. Understanding these will require research beyond the agroecosystem, e.g. on the food system, on how these system components behave amidst global environmental change.

In **Chapter 3**, this thesis establishes and ranks the importance of key factors influencing the use of groundwater for supplementary irrigation in the Eastern Gangetic Plains. In diesel pump dominated areas, factors most limiting for water use include poor coordination among water users, delays in pump and tubewell availability, and financial constraints coupled with risk aversion towards cash investment. Presence of the electric grid permits the use of lower cost pumps while solar powered irrigation systems could reduce operation costs. Electrification may overcome some of these delay factors, but the grid reaches a small fraction of fields at present and solar powered irrigation is likely to remain beyond the financial means of most farmers in the region. A multi-scalar strategy is required to move farmers from 'crop saving' to 'productivity enhancing' irrigation use. At the farm level, increasing awareness of the importance of timely irrigation can be coupled with efforts to increase operational efficiencies (e.g. pump maintenance, pump sizing, forecast-based irrigation scheduling) in order to overcome aversion to cash investments. At the community level, improved preparation for irrigation events through organization of water markets before the start of the seasons can reduce transaction costs and avoidable delays during the season itself. At the regional level, government support programs can target areas where tubewell and pumpset density is not yet high enough to ensure all farmers have timely access to irrigation through water markets.

In **Chapter 4**, this thesis uses gridded crop simulations to analyse intra-regional variability in the rice-wheat system's response to different planting strategies. The results showed that rice planting at the onset of the rainy season improves crop systems productivity and resilience over the eastern Indo-Gangetic Plains (IGP), indicating that monsoon forecasting can be a promising service for farmers. However, the spatiotemporal structure of monsoon progression and temperature stresses restricts the possibility to synchronise rice planting with the monsoon in wider parts of the IGP. In addition, the sensitivity to shocks varies across systems and the IGP depending on the planting strategies that is followed. This indicates that recommended planting dates are preferred in the middle IGP as they are more resilient although average productivity when planting at the monsoon onset is comparable. Whereas, in the western IGP there is less scope to adjust planting dates and irrigation interventions, hence adaptation pathways must focus on other response options.

In **Chapter 5**, this thesis studies the effect of irrigation-led intensification of the rice-wheat system on personal daily incomes of smallholder farmers in the Eastern Gangetic Plains. This Chapter finds that increasing irrigation use significantly increases productivity and income. But for most farmers, except the largest ones, rice-wheat production alone may not lift the household above the poverty line. However, irrigation provides substantial benefits for productivity that play a key role in preventing famine and strengthening food security. Therefore, this Chapter argues that irrigation development should be considered as part of a cross-sectoral effort and coordinated upgrading of the rural economy that creates both agricultural and non-agricultural jobs and skills. As such, policymakers should develop targeted investments in the private sector that can directly support irrigation (e.g. pump vendors and mechanics, tubewell drillers, spare part traders and manufacturers), capacity building on sustainable and cost-effective water management at the field scale, and consolidation of the knowledge base around groundwater dynamics, especially in light of increasingly erratic rainfall patterns.

Reflections on theory and methods

This section reflects on the policy, theoretical, and methodological implications of this thesis in light of its objective. The objective of this thesis is "to produce knowledge that can guide farmers and policy makers in adequately managing water and time for sustainable agriculture in the Eastern Gangetic Plains". The subsequent overarching research question is formulated as:

"How can water and time be managed successfully to sustainably intensify the rice-wheat system in the Eastern Gangetic Plains?"

The findings of this thesis showed that the performance of the rice-wheat system is of limited scope to contribute to food security and poverty reduction. Even seemingly simple interventions, such as planting date adjustments and irrigation, are not of universal validity due to their dependence on other social-ecological sub-systems. In Eastern Gangetic Plains, planting date adjustments and irrigation can increase food production, but constraints imposed by the social system, ecological, and water system limit their feasibility. Potential productivity increases from adjusted planting dates in the Western Gangetic Plains are limited by constraints imposed by the climatic systems. The systems perspective shows that the social-ecological diversity of the rice-wheat system requires interventions to be tailored to specific subsets of farmers in the Eastern Gangetic Plains. Analysing the constraints and opportunities of management options to contribute to system productivity, resilience, and sustainability needs to incorporate the full rice-wheat rotation, and the different subs-systems that interact with the cropping system. Nevertheless, recent advances in statistical methods and computational simulations increasingly enable researchers to study the social-ecological diversity and tailor interventions to the specific needs of farmers. But a better theoretical underpinning and integration with participatory research is required to effectively coordinate different methodological approaches to the study of agricultural systems.

Given these overall findings and reflections, this section will address the following three domains in more detail:

(i) rice-wheat system capacity to contribute to development objectives,
(ii) insights from social-ecological perspective into the rice-wheat system, and
(iii) integrated methodologies for the study of social-ecological systems facilitated by clearer theoretical underpinning.

Capacity of the rice-wheat system to contribute to development objectives

The systems approach of this thesis shows that a one size fits all approach does not work and an intervention may not universally improve the agricultural production or farmers' incomes in the rice-wheat system of the Eastern Gangetic Plains. Even technically relatively simple interventions such as the adjustment of planting dates or intensified irrigation face limitations imposed by the social and ecological subs-system (Figure 1.2). This issue aligns with several other studies that point out the shortcomings of silver bullet solutions for addressing complex development issues (Ramalingan, 2013). The COVID-19 pandemic has impacted the state of food security in the world during the last two years of this thesis project. The number of food insecure people in Southern Asia dramatically increased by ca. 50 million to a total of 305.7 million in 2020 (FAO et al., 2021). Our results suggest that, with no other limiting factors, adjustments in planting dates of the rice-wheat system may increase the capacity of the state of Bihar in the Eastern Gangetic Plains to produce sufficient food to meet the dietary energy needs for more than 15 million people a year (Chapter 4). Combined with yield gap closure through better fertility, pest, and disease management, these agronomic interventions can make substantial contributions to food security in the region. Their adoption, however, remains strongly limited by the social and ecological diversity of the rice-wheat system that impedes full and ready uptake of these interventions.

The poverty alleviation effect of the rice-wheat system remains more limited as only the largest landowners are set to benefit directly from increased profits. With the size of landholdings predicted to further decline in South Asia (Erenstein et al., 2021), incomes that can lift farmers out of poverty must come from other sources than tending the land. Our results show that only the upper 25% of farming households may have a chance to be lifted above the international poverty line with intensively irrigated rice-wheat system. And only a small percentage may derive much higher levels of income than the poverty line. Most households own too little land to farm themselves out of poverty, even if profit margins from agriculture were to increase dramatically. Nevertheless, India sees more than 100 million people in poverty with more than 30% of the population in the Eastern Gangetic Plains in poverty, mostly concentrated in rural areas (World Bank, 2020). Efforts to improve rural livelihoods must find solutions that can both address smallholders' income needs and cultivation practices. That is, rural development pathways must aim to provide rural jobs for farming households as well as sufficient and nutritious diets. The future challenge will be to tailor agricultural interventions to the social and ecological diversity of agroecological landscapes, while creating rural jobs, social protection, and reducing inequality in an effort to meet people's livelihood needs and aspirations. Adopting a systems perspective will be critical to achieve these goals.

Social-ecological diversity of the rice-wheat system

For reaching the goal of increased food production, improvements in productivity need to occur across the entire agroecological landscape. This thesis shows that a social-ecological systems perspective can provide a holistic assessment of the constraints and opportunities regarding the potential impact of agricultural interventions and technologies. First, this thesis shows how the agro-climatic constraints imposed by the climate system on the rice-wheat system vary spatially and restrict the possibility of intervention, such as adjustment of planting dates, to specific areas (Chapter 4). For example, the later monsoon arrival, harsher winters, and warmer summers limit the flexibility to adjust planting dates in the Western Gangetic Plains. Furthermore, resource-system variability such as land types and water availability further restrict the options for interventions (Chapters 2 and 3). For example, the constraints imposed by the water system on the rice-wheat system limit the applicability of planting adjustments to specific sub-regions of the agroecological landscape where water tables before the monsoon season are within reach of centrifugal pumps. Variation in the social sub-system further increases the complexity regarding which intervention works where and for whom (Chapters 2, 3 and 5). For example, labour constraints and inaccessibility of inputs constrain the ability of farmers to adjust planting dates or irrigate on time. Concurrently, addressing constraints and intervening in one sub-system, e.g. planting date adjustments in the cropping system, may be further limited by sustainability concerns imposed by another sub-system – for instance, the resource-system through groundwater depletion, or ecological systems of pests and diseases (Chapter 4). A system perspective is critical to ensure that these interactions are fully considered during the design of future development pathways.

Second, this thesis shows that the temporal aspect of activities in the social-ecological system is critical to the performance of the whole system. This requires treating interventions as non-binary decision-processes with a temporal component. Doing so allowed this thesis to unpack the interdependencies of the different sub-systems within the agroecological landscape in more detail. Conversely, existing studies of managing the planting time of crops have largely looked at the ecological and economic effects of time management on crop production (Ding et al., 2020; Kim et al., 2021; Waha et al., 2013). While adoption studies often look at predictors for individual management decision such has wealth, farm size, or position in a social network (Takahashi et al., 2020). But the decision-processes that shapes the social and ecological inter-dependencies at the field, community and landscape levels have received less attention (Makate, 2019; Mwangi & Kariuki, 2015; Schut et al., 2020). Future studies can build on the findings of this thesis to guide hypotheses creation, data collection, and analytics of cropping system performance.

For a more general framework, managing time can be regarded as a problem of synchronization; that is, temporal mismatches between subsystems. This lens can, for example, be applied to the alignment of crop growth with temperature regimes, or crop water demand with soil moisture. Alignment of the bio-physical sub-systems shapes the ecological flexibility of the cropping systems (Figure 6.2). But this lens can also be applied to the alignment of water distribution or subsidy distribution systems to individual farmers' needs. That is, the temporal nature of farmers' demands to the social system. Together, the management of time can be considered as one of synchronizing the demands to the social system to align with the ecological flexibility of the cropping system (Figure 6.2). A mismatch between the two increases the risk of farmers to not manage the timing of their activities effectively. Fixes on the ecological side include varietal improvement for stress tolerance, shortening of growth duration to avoid sub-optimal temperature regimes or creating micro-climates that align with crop needs (Chapter 4). Increasing biological diversity at the landscape level would also impact the ecological flexibility if the different cultivated crops would have varying moments of optimal planting time. On the social system side, potential options are fourfold. First, the decision point can be advanced within the limits of the ecological flexibility. Second, delays caused by unavailability of consumable inputs can be reduced through improvements in markets and subsidy schemes. Third, the delay reduction caused by capital inputs can be addressed by increasing organizational effectiveness for deploying machinery at (i) the community level including their supporting industry such as mechanics and spares and repairs, (ii) operating efficiency at the field level, or (iii) infrastructure density as to increase the land to capital input availability ratio. Besides, climate change stands to increase extremes events and climatic variability that disrupt the synchronization of the rice-wheat system (Raymond et al., 2020). These impacts of climatic change will continuously challenge farmers' ability to adapt and keep their systems in synchrony. Future studies should investigate more deeply on the impact of each decision-points, delay factors, and ecological flexibility and the impact of interventions on improving each of these aspects now and under future climates. Many of these variables, such as infrastructure density, are increasingly available as spatially explicit datasets across larger regions and would help to test and understand the impacts of their variability on timely crop management in future studies. Such research efforts could directly inform advances in developing targeted policies and advisories.

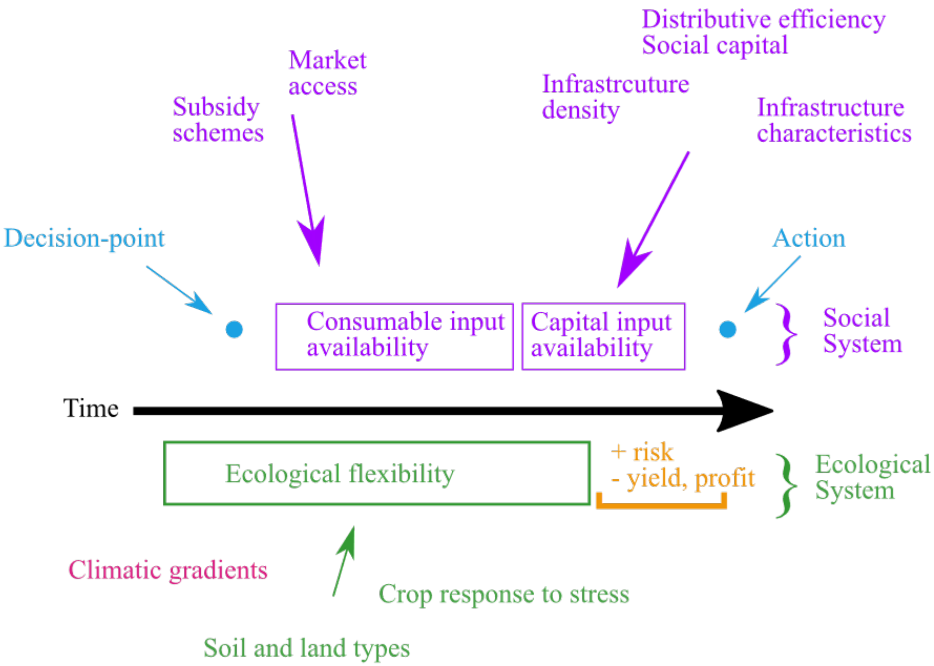

Figure 6.2 Managing time in agricultural systems as a matter of system synchronization.

Methodological and theoretical advances to address social-ecological diversity: critical reflections and future pathways

Capturing the social-ecological diversity of the agroecological landscape has become increasingly possible through methodological and computational advances such as machine learning and high-performance cluster computing. Statistical learning techniques can assist researchers in studying non-linear relationships in very large and messy datasets, while high computing power to run large-scale simulations provides the tools for impact assessments at the landscape level. Hence, it becomes increasingly feasible to tailor technologies to households, communities and regions that face very specific social-ecological configuration of the rice-wheat system. These tools can overcome some of the challenges that complex systems pose to traditional methods of analysis. For example, they can help to rank variable importance and identify the shape non-linear relationships between predictor variables and outcomes (Chapters 2 and 4). In doing so, these methods can help researchers to characterize the systems' tipping points that, if crossed, can switch the rice-wheat system into a different mode of management or production. For instance, late rice planting due to pre-monsoon season groundwater levels exceeding a depth of 4.5 m below ground level or plummeting yields if planting after a certain date in a certain place and year. Ongoing programs for providing farmers with planting date advisories and modernization of irrigation infrastructures and management can benefit from the increased precision for providing relevant management strategies. However, large-scale data analyses such as survey analytics or simulations should not be conducted in isolation but supported by data collected from community engagement and ground level observations. These developments across disciplines should fruitfully cross-fertilize and feed off each other to develop targeted insights and advisories and push forward institutional innovation. They will need to prioritise smallholder farmers (Hounkonnou et al., 2012), and facilitate continuous dialogue with stakeholders (Klerkx et al., 2010; Klerkx & Rose, 2020). Such interdisciplinary collaboration for sustainable intensification will become increasingly important, especially in low-income countries. But how can this be achieved?

Better integration of three dominant interdisciplinary scientific communities within the field of sustainable agriculture can provide the methods and tools. These three communities are the following: first, the participatory approach supported by Robert Chambers and others. These also had a significant impact on development practice, contributing significantly to the development of rapid rural appraisals and community-based development initiatives. Theoretically, the focus of the participatory research community is the empowerment of local communities with an emphasis on outcomes of pro-poor development and the unpredictability of emergent phenomena (Chambers, 2015). Second, the social-ecological systems community informed by Elinor Ostrom’s work aims to study institutions and their governance. This community uses quantitative methods to identify generalizable mechanism and conclusions about systems’ behaviour aided by non-linear models and network approaches that study feedbacks and non-linear relationships between social and ecological system components and processes (Bodin, 2017; Ostrom, 2009b). Third, the earth systems science community is increasingly contributing insights for agroecological systems from the large-scale gridded simulation bio-physical earth system models. These approaches produce large spatial-temporal datasets that can be used to understand bio-physical variability within a region and linkages with other regions and have increasingly focused on sustainable agriculture (Rockström et al., 2017). Sustainability science can develop a streamlined portfolio of participatory methods, statistical models, and simulation models that strengthens the interdisciplinary teams in co-producing knowledge for sustainable agriculture. These methodologies should also link to institutional innovation processes in support of adaptive management. For example, future research could couple these integrative methodological developments to online platforms and dashboards that allow for a wide range of user inputs and comments. Such a participatory database could broaden the access and inclusion of stakeholder engagement that is necessary for a more pluralistic effort for navigating the values-based, cultural, and ethical decisions that are required along sustainable intensification trajectories (Leeuwis et al., 2021; Struik & Kuyper, 2017).

In addition, better integration of the tools and methodologies of the participatory, social-ecological systems, and earth system sciences communities requires conceptual and theoretical clarity. Social-ecological systems studies often do not define their systems or theoretical background in much detail (Colding & Barthel, 2019). While scientific pluralisms is an important characteristics of scientific advancement (Chang, 2012), the explosion of sub-disciplines and new fields in sustainability sciences without theoretical clarity might obscure knowledge and knowledge gaps. Developing a handful of defensible competing conceptualizations and competing theories, within which scientists increasingly adhere to specific definitions and concepts, might be useful for advancing the study of sustainable agriculture (Clark & Harley, 2020). Arguably, efforts to study sustainable agriculture and food systems may learn a lot from the history of economics as a discipline. The founders of economics have been frequently engaged in very pluralistic arguments and there is a strong sense of different schools (Chang, 2009; Phelps, 1990), but subsequently the field turned to perhaps too strict dogmas to achieve mathematical rigor (Lawson, 2019). Sustainability science offers an umbrella term that encompasses a pluralist set of sub-fields and schools of thought about systems within which social and ecological, humans and nature are theorized about and studied empirically (Clark & Harley, 2020). Consistent ontologies with clear epistemological guidelines will need to be developed. These theoretical and methodological developments will require social scientists and natural scientists to work together ("Calling all economists," 2020; Ji & Luo, 2020), while philosophers of science could perhaps provide some guidance for this process (Eigenbrode et al., 2007). With a theoretical framework and an integrated methodological toolset at hand, knowledge gaps within the system can be prioritized and explored through community engagement to inform the construction of key research questions. The research questions can then drive quantitative analytics where, for example, earth system models, statistical learning from survey data, and agent-based models can be deployed to gain initial insights and conduct ex-ante assessments. These assessments can then be returned to the communities to verify their salience and applicability and co-identify new research frontiers.

Besides, logistical limitation deserve consideration as they presented crucial impediments for fully unpacking the integrative approach of this thesis and should be considered in future work. For example, the developed models have not yet been taken back to the field to discuss the results with farmers themselves. Doing so, provides an important avenue for gaining further knowledge and validation of the research, instigating change processes, and empowering communities. Similarly, due to logistical constraints in the research deign, several of the findings of the participatory approaches were not taken up in the large-scale quantitative surveys and proxy indicators had to be used. At the same time, the decision heuristics and connections between social and ecological system have not yet been formalized into computational models – opening promising opportunities for future research. This would allow for further and more detailed testing of general hypotheses of how the rice-wheat system work, why and where. Nevertheless, the collaborative efforts with the Consultative Group of Agricultural Research Centres (CGIAR) system and regional development projects ensured that the findings informed ongoing development programming and initiatives, showing the strengths of participatory research for informing action on the ground.

Discussion on the water system, climatic shocks, the monsoon, and social science

The findings also have implications for broader scientific issues that are mentioned in the theoretical framework but not specifically investigated within the research chapters (i.e. various sub-system components and relationships in Figures 1.2 and 1.3). This section discusses the implications of the overall findings of this thesis on these additional issues by identifying gaps and future research needs considering the current literature. This discussion section hence zooms out from the specific concerns that are discussed in the research chapters and previous reflection section and focuses on the sub-systems and their linkages that were not previously discussed. It discusses the findings through four cross-cutting themes that are crucial for the sustainable development trajectories of the rice-wheat system.

These cross-cutting themes are:

(i) water for food and challenges of water scarcity,

(ii) system stresses, climatic shocks, and resilience,
(iii) the monsoon and its relationship with society, and
(iv) the role of social science for the development of targeted intervention and policies.

Water for food – implications and issues

How many people can the world's water resources feed sustainably despite climate change and growing cross-sectoral demands? Several integrated assessments and modelling exercises have addressed this question over the last two decades and generally agree that, theoretically, feeding an expected 9-10 billion people is possible without compromising the environment (Gerten et al., 2020; Molden, 2007). However, the challenge lies in the implementation. Especially areas with high yield gaps and abundant water resources, such as the Eastern Gangetic Plains, have the potential to contribute substantially to food security. Managing water and managing time are intricately linked and a focus on the stepwise decision-logics at the centre of these management activities outlines the procedural space in which cross-sectoral efforts must meet to drive successful implementation. At the same time, this thesis shows that the spatial heterogeneity in the water cycle requires context-specific solutions that reconcile place-based development concerns with the natural resource base. Managing water at the landscape level requires an integrated approach, that has long been acknowledged, but rarely been utilized in agricultural planning. For example, this thesis shows that intra-annual water table fluctuations and canal management have a significant impact on the ability of farmers for timely planting – often jeopardizing system productivity. Integrating these practical agronomic concerns into the ongoing initiatives on irrigation expansion and irrigation modernization provide actionable entry-point for ensuring that returns on investments materialize. Concurrently, coupling irrigation development to targeted mechanization programs has the potential to significantly enhance the uptake of improved water management practices where high levels of investment risks, induced by untimely machinery availability, might deter anticipatory use of irrigation technologies. Thinking of (access to) irrigation as a binary variable that is enabled or disabled by a set of conditions will not suffice to guide policymakers and practitioners in steering sustainable water resources development and management. All in all, investigating the temporal component of irrigation performance deserves further attention in building capacity to overcome future water scarcity in the Eastern Gangetic Plains and elsewhere.

Progress on three dimensions is required to steer water management in the Eastern Gangetic Plains into a sustainable and growth promoting enterprise:

(i) A better understanding of the characteristics and spatial structure of the aquifers that sustain groundwater irrigation including their response to increased pumping and climatic change are required. These will require investment in empirical data collection and multi-year analyses of representative locations across the Eastern Gangetic Plains coupled to an improved mapping of aquifer potential zones guided by recent advances in paleochannel identification, participatory mapping, and remote sensing. Ideally, these research efforts should be coupled to the development of an early warning system for depletion and unintended consequences of increased groundwater use that is critical for the sustainable scaling of irrigation use in the region.

(ii) Mapping the social system that supports irrigation development including the educational knowledge base around improved irrigation management at the field level, level of technology penetration of irrigation equipment and other machineries and inputs, and the supporting capital goods sector including spares and repairs. Targeted support to spur private sector development where it is most needed and is likely to contribute significantly to enhancing the productivity of existing irrigation infrastructure.

(iii) Empowering local communities to build coordination mechanisms, through private or public means, that allow for a more anticipatory and thus effective distribution and utilization of existing water resources and irrigation technologies in times of large water demand. Focusing on solutions that are just, with tangible benefits for the resource-poor farmers normally at the tail-end of the distribution queue, are critical to ensure pro-poor growth and landscape level improvements in water productivity.

Similar efforts have been called for and conceptualized by proponents of the farmer-led irrigation development and solar irrigation communities. Farmer-led irrigation is increasingly gaining traction and, after being a critique of institutionalized practices (Woodhouse et al., 2017), has become the flagship irrigation development program for major international development and research organisations such as the World Bank, Food and Agriculture Organization of the United Nations (FAO), and International Water Management Institute (IWMI) (Lefore et al., 2021). At the same time, alongside diesel-based irrigation, solar irrigation systems have become a key technology at the centre of sustainable irrigation development promotion owing to its promise to substitute fossil fuels in irrigation with clean energy (Ringler, 2021). These initiatives are generally comprehensive in scope but lack specificity in their articulation of key challenges and are mute on temporal qualities of irrigation management and its supporting sectors. Our study suggests that, in addition to the usually proposed lenses, adding a temporal lens that intersects with other aspects such as input markets, knowledge etc., would greatly increase the precision of irrigation development diagnostics. After all, a wealth of canal irrigation literature showcases how managing flexibility and time of water delivery is among the most critical aspects of successful irrigation management (Chambers, 1988; FAO, 2018; Horst, 1998). Being specific about input requirements and separating between consumables, machinery, labour and spares and repairs – may provide further clarity on the bottlenecks of irrigation development. The same accounts for the temporal aspects of resource availability. Much of farmer-led irrigation takes place in countries with a pronounced rainy season where much of the proposed irrigation takes place with water from either alluvial aquifers or rivers with large intra-annual fluctuations in water levels and availability. These natural cycles largely drive the key decision points for water demands and the input systems need to be synchronized with them to be effective. At the same time, environmental concerns need to be guarded through a focus on recharge capture and aquifer discharge patterns (Gleeson et al., 2020) that can evaluate the effects of increased abstraction on sub-seasonal water table dynamics and interactions with other water users' needs. Focusing on estimates of annual recharge does not suffice. Most farmer-led irrigation initiatives remain largely silent on details about these key issues. In the Eastern Gangetic Plains, interest in the prospects of the potential groundwater use and their ramifications for the risks of depletion and impacts on other water users have accelerated while the work for this thesis was being conducted. Research and development programs are now required to develop adaptive water management systems and their underpinning monitoring and data collection needs.

In times of stress: crop production, climatic shocks, and agricultural development pathways

Some of the impacts of climatic variability on crop production can be addressed through irrigation, and temperature stresses may be addressed by managing the timing of crop growth by choice of planting times. Modifying micro-climates through large-scale irrigation or the integration of water bodies or forests may provide some relief but is outside of the control of local stakeholders, poorly understood, and ultimately limited in scope. Regarding rice cultivation, our results on climatic stresses on crop production are in line with reports by Espe et al. (2017) and van Oort and Zwart (2018) who found that in temperate climates and in Sub-Saharan Africa the cold stresses in rice tend to dominate the yield response to temperature –

not high temperature stresses as one might expect from general global warming. With rising temperature, these dynamics might change in the future and the impact of cold stress may become less important. Heat stress in rice would likely require an improved understanding of monsoonal behaviour. Wetter monsoon with longer and more frequent breaks may lead to an increase in short-term heat stress during drought periods, which would need to consider different mechanisms for rice crops to cope with these (Shi, 2017). Future studies should investigate these concerns for South Asia. However, current regional and global climate models may not be very well suited for predicting these localized and sub-seasonal dynamics (Lloyd & Winsberg, 2018; Müller et al., 2021) and crop models may not represent the effect these stresses very well (Asseng et al., 2013; Wang et al., 2017a). In-field monitoring of climatic change process is therefore required, while suitable simulation solutions to investigate probable future weather patterns and their potential impact are being developed. Relatively novel process-based crop models, such as Genotype-by-Environment interaction on CROp growth Simulator (GECROS), improve the simulation of crop response to stresses, and they may be used in future studies to increase confidence in simulation results (Ingwersen et al., 2018; Kadam, 2018). Global change is also likely to impact wheat production, although the climatology of the wheat season is arguably simpler, and global change processes are generally expected to increase temperatures during the wheat season so that timely rice planting and harvest as well as short duration varieties continue to be the major entry-points (Liu et al., 2016).

The impacts of social shocks and feedback loops as well as connected events, be these social or ecological or both, deserve further attention as they have not been considered in this study. Such feedback loops are likely to rise in importance over the next years as recently describe by Raymond et al. (2020). To better understand these social-ecological feedbacks it is crucial to gain further insight into their impact on crop growth and farmers' decision making-processes (Pande & Sivapalan, 2017). For example, how do farmers change their investment preferences after a year of late monsoon onset? A late monsoon year is likely to lead to diminished returns from farming and might act as an anchor event that changes baseline expectations for the next year (Wens et al., 2019). From a simulation perspective, integrating such legacy effects requires two additional advances: coupling decision-making to bio-physical events across social ecological gradient and incorporating influence of decisions on future decisions. With increasing computational power, regional gridded and high-resolution crop models that integrate contextual knowledge of production drivers and constraints in the agroecological landscape provide a promising way forward as they allow flexible programming of behavioural dynamics (Silva & Giller, 2021). However, one key constraint is that the current models, even if they are of high resolution (e.g. 5 × 5 km) would not be able to simulate community dynamics. To address this, one approach would be to use empirical data on management constraints to impose these constraints on a series of crop model simulation runs, where the distribution of these constraints and shifts therein could provide insights into the effect of interventions. Another approach would be to deploy agent-based models that use the outputs of the crop models as inputs and may provide an innovative coupled environment to experiment with and bring together various aspects of technology adoption, management, and ecological gradients and thresholds.

Lastly, the shape of future rural economies in developing countries will strongly influence the behavioural response of farmers to major shock events such as large-scale droughts. A better understanding of these interdependencies is necessary to ensure that policy making and decision support systems are adaptive to the ongoing evolution of rural livelihoods (Gassner et al., 2019; Mausch et al., 2021; Sumberg & Thompson, 2012). One way to achieve a better integration of these cross-cutting issues is to set up interdisciplinary and cross-sectoral research teams to work out sensible theories of change; i.e. definitions of future system states and how to potentially get there (Thornton et al., 2017). However, current efforts for developing theories of change often lack an integrated vision and are often strongly driven towards the epistemic and ontological concerns of a specific sub-discipline (Allen et al., 2017; Gupta et al., 2021). Researchers and development programs need to engage in pluralistic exercises that bring together different actors, analytical lenses, and scenarios of regional development pathways. Such exercises can support a deeper engagement and exchange between scientists and practitioners who work at different scales and in different fields that cover the breadth of possible land use future (Popp et al., 2017).

The monsoon – need for an interdisciplinary systems perspective

Another key aspect of this thesis is the relationship between the monsoon, people, and agriculture. Being one of the largest annually reoccurring climatic phenomena, distributing up to and more than 2 m of water across large swaths of land in a matter of only 4 months, the Indian monsoon has fascinated scientists for centuries (Sunil, 2018). Other Asian, African, and American monsoons also play important functions for global food production (Zhisheng et al., 2015). Due to the importance of the monsoons, several scientific endeavours to better study, understand, and predict monsoons have been launched recently; such as the Global Monsoon Intercomparison Project (Zhou et al., 2016), the International Workshops on Monsoons supported by the World Meteorological Organization (Chang et al., 2021), and the PAGES Working Group on Global Monsoons (Wang et al., 2017b). But more progress remains to be made in connecting the climatological study of monsoons to the social-ecological systems that monsoons drive in the biosphere. That is, in addition to advances about understanding and predicting monsoon patterns, there is an increasing need for developing indicators for aspects of the monsoon that are key to agricultural management practices. Initial progress has recently been made by aiming to synthesize definitions of the agronomic monsoon onset that was used in Chapter 3 (Fitzpatrick et al., 2015; Lisonbee et al., 2020; Stiller-Reeve et al., 2014). A better understanding of how onset, breaks, withdrawal, and the duration of the monsoon can be captured locally could inform agronomic decision-making and breeding efforts. Evaluating these in relation to tele-coupled phenomena, for example El Niño Southern Oscillation (ENSO), would provide valuable information for adaptive climate advisories. A more participatory development of climate service indicators that capture not only expert opinions but also local needs should further inform the study of the monsoon (Gbangou et al., 2021; Kumar et al., 2020).

Elucidating the connectivity between the monsoons and the biosphere would benefit from using a systems perspective that starts from analysing monsoon progression and associated temperature effects and their interaction with agriculture. These initial insights would provide actionable perspectives to orient the design of sub-regional development pathways and provide guidance for structuring investments and innovation spaces for climate adaptation while clarifying existing knowledge gaps. A systems thinking perspective would further help to bring scientists working across different regions together to develop a common language, exchange their findings and insight, and corroborate these into more general understandings of how to manage monsoonal agriculture in an era of rapid social and ecological change across multiple scales (Scholz & Steiner, 2015). In fact, points about irrigation development, temperature stresses on crop growth and shocks to food production might be generalizable depending on a fields' location within the monsoon progression gradient of a region. Such a perspective effectively adds a temporal lens to climatic categorization that can support the conceptualization of adaptation pathways at the landscape level. In areas of late monsoon arrival, for example, higher variability might be expected as shown for the Western IGP in this study. Another benefit would be contributions to current efforts to develop global to local datasets for improved integrated assessment (Müller et al., 2020). Furthermore, lack of spatially explicit agricultural management data at global scale represents a major limitation for more context specific global modelling efforts. To address this, the global modelling community would benefit from understanding how management decisions can be characterized in light of climate data that are more readily available and provide tangible, dynamic reference points for generating management input datasets (Minoli et al., 2019; Waha et al., 2012).

Targeting interventions: social science to inform policies and decision-support systems

Turning towards the more practical side of designing targeted policies and development interventions, a better understanding of the decision process involved in agricultural activities is required (Krishna et al., 2020). Brown et al. (2017) for example take a sequenced decision-making perspective to disentangle the adoption process to identify entry points for modifying and improving interventions and technologies. Decision-processes critically interact with farmers aspirations and future livelihood perspectives (Mausch et al., 2018; Salaisook et al., 2020), and align with recent calls for more social science (Buyalskaya et al., 2021). Social science is increasingly gaining prominence in the field of climate change where understanding the social and political aspects of transitions between different networks of production are moving into central focus (Barnes et al., 2020). Network science and complex systems thinking have been increasingly used to study these phenomena in agriculture (Labeyrie et al., 2021; Lansing, 2006). But qualitative and social science methods that are readily deployed for targeted investigations in different aspects of agricultural systems remain elusive (Cumming et al., 2020; Magliocca et al., 2018). Building such a method stack would allow researchers to investigate not only the social aspects more effectively, but also their relationship with climatic, technological, and ecological ideas and artifacts in a way that is comparable across cases (Bodin et al., 2019). Their rapid deployment through interaction with innovation systems should be a key focus. Combining such methodological advances with progress on spatial analytics arguably represents a core research frontier to support targeted development policies and programming. After all, path-dependency features strongly in the evolution of economies (Hidalgo et al., 2007) and the better policies can capture these path dependencies, the more effective the policies can be.

Final conclusion

This thesis assesses the constraints and opportunities of planting date adjustments and irrigation to improve the performance of the rice-wheat system in the Eastern Gangetic Plains. The main finding of this thesis is that improving the performance of the rice-wheat system through planting date adjustments and irrigation is not universally possible. Constraints imposed by the ecological, climatic, and social sub-systems limit the overall feasibility and impact of these interventions. Planting date adjustments and irrigation can increase the productivity and resilience only in parts of the Eastern Gangetic Plains. The applicability of planting date adjustments and irrigation as a strategy to improve rice-wheat system performance and sustainability in the Western Gangetic Plains is limited by the spatial-temporal variability of temperature and precipitation in the climate system. Genetic changes to different crops or varieties will be required in the Western Gangetic Plains to further improve the cropping system. In the Eastern Gangetic Plains, the social-ecological diversity of the rice-wheat system further constrains identification of areas where implementing planting date adjustments and improved irrigation use are feasible. The water system, land types, the availability and distribution of inputs, and collective action problems constrain the uptake of these interventions. Development programs need to address these issues in concert, and tailor technologies and interventions to the social-ecological diversity of households, communities, and landscapes. This thesis shows that a social-ecological characterization of agricultural systems at the regional scale can be achieved by deploying a combination of participatory approaches, large survey analytics, and regional, high-resolution gridded modelling studies. However, this thesis also shows that agronomic interventions in the Indo-Gangetic Plains will only contribute to poverty reduction of the largest farmers, as most farms are too small to substantially increase incomes from farming. Creating off-farm jobs through integrated rural development programs will be required to address the income needs of the poor in the Indo-Gangetic Plains. Lastly, the capacity of aquifers to sustain increased groundwater use remains unknown and must be addressed.

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Summary

Global hunger, food insecurity, and poverty have been rising for more than five consecutive years, thwarting the progress that has been made over the last decades. Efforts to meet the Sustainable Development Goals in 2030 are off-track. And the intensifying climate crisis further challenges the sustainable development of societies, including the food system. Climate change impacts constitute one of the major driving forces of food system disruptions and it is through changes in the water cycle and temperature regimes that the impacts materialize. Understanding how these climatic factors affect the performance of agricultural management decisions constitutes an essential bedrock for delivering progress in sustainable food production. At the same time, increasing amounts of data collection in the form of surveys, earth observation and simulation model outputs (big data) provide opportunities for making significant gains in developing a contextualized understanding of agricultural system dynamics at the landscape level. These big and spatial data promises to enable the development of spatially bounded interventions and policies that are targeted to specific household types, even in areas that have been and continue to be relatively data scarce. The development of such novel and integrated research approaches constitutes a promising area for scientific advancement.

South Asia is experiencing some of the strongest impacts of climate change while it is among the most vulnerable regions across the globe. High levels of poverty and food insecurity prevail, especially in the Eastern parts of the Indo-Gangetic Plains – the region's breadbasket. In the Eastern-Gangetic Plains, rice is cultivated by more than 90% of farmers during the summer monsoon season and mostly followed by wheat as a second crop that is grown during the mild winter months between October and March. However, crop yields for both rice and wheat in the Eastern Gangetic Plains remain relatively low at around 2-3 t/ha as compared with 5-7 t/ha for both crops in the Western Gangetic Plains. Besides, progressively erratic monsoon patterns threaten the ability of the rice-wheat system in South Asia's Eastern Gangetic Plains to provide food and livelihoods for their food insecure and impoverished people. Sustainably intensifying – i.e. raising agricultural production without comprising the environment – the rice-wheat system in the Eastern Gangetic Plains to provide high and stable yields is therefore regarded as a centrepiece of development pathways in the region.

Previous research has identified timely crop planting and improved irrigation use as key entry-points to sustainably intensify the rice-wheat system. The cropping season in the Eastern Gangetic Plains starts with the challenge of aligning the following activities with the increasingly erratic monsoon onset: rice nursery establishment, water-intensive puddling operations, and labour-intensive transplanting of rice nurseries. Delayed rice planting not only leads to a late rice crop, but also complicate subsequent wheat cultivation by increasingly exposing wheat to high summer temperatures that cause large production losses (due to terminal heat stress). Similarly, more frequent monsoon breaks and less reliable winter precipitation events further challenge crop production.

However, there are critical knowledge gaps on the complex feedback mechanisms involved in these activities resulting in their low and incomplete adoption. These feedback mechanisms comprise of intertwined factors beyond classic water challenges in the rice-wheat system, including temperature rise, pest and disease pressure, value chains, and policy discrepancies between household and national scales. To unpack these factors, this thesis investigates and evaluates farmers' planting and irrigation activities in the rice-wheat system through a socio-ecological systems framework – thus identifying constraints and opportunities to overcome water-related challenges for food security and poverty reduction. The main contribution of this thesis is the use of a social-ecological systems framework and a novel mixed-methods approach. With this approach, this thesis investigates the rice-wheat system at landscape level to gain better insights into critical decision-making processes and social-ecological constraints and opportunities for timely rice crop planting and irrigation activities in the Eastern Gangetic Plains. This methodological approach is premised on the assumption that a context-specific understanding can be gained by using mixed-methods that combine advances of the last decades in participatory and computational approaches for data collection and analysis. Building on the knowledge that has been generated across different relevant disciplines, this thesis aims to show that such an approach can bring together different fields and ideas to contextualize and characterize key system dynamics – allowing for the development of contributions to science as well as timely, practical, and context-specific recommendations to guide development programming.

In essence, within the agro-ecological landscape farmers (1) plant crops, (2) irrigate, (3) harvest and (4) sell crop produce in interaction with environmental factors of the landscape. This sequence of activities forms the basis of the organization of the research chapters (Chapters 2-5) each focusing on one activity. Broadly, activities (1) and (2) correspond to the activities

identified as crucial to manage water (irrigation) and time (crop planting) and form the basis for building farm typologies and modelling scenarios; activities (3) and (4) correspond to the system states (development objectives) of interest.

Chapter 1 introduces the context, theoretical framework, and methodology in detail and provides an outline of the overall thesis. **Chapter 2** sets the scene and deploys a detailed survey in which scored causal diagrams were used to guide focus group discussions across three agro-ecological zones, where farmers discussed and ranked the factors that shape their decision on when to plant their rice crops. The Chapter shows that farmers are generally aware of the benefits of early rice planting. The Chapter further finds that sociological factors are the primary factors that shape the timing of rice planting – with water availability being the most important one. Social factors, however, play an important secondary role as the unavailability of inputs for planting frequently delays rice planting of farming households. In addition, heightened pest and diseases pressure for individual early planters deters farmers from early planting of rice in the absence of collective rice planting that disperses these pressures across the landscape.

Chapter 3 subsequently focuses on how farmers deploy irrigation. Irrigation is critical for rice planting but also, as survey data show, to buffer against drought and maintain high system productivity. This Chapter shows that the cues that farmers use to start organizing for irrigating their fields, large soil cracks, already indicate severe drought stress. Moreover, after deciding to irrigate, insufficient infrastructure development led to queuing for pumps and borewells that delay water applications. Unavailability of cash, lack of labour, and sparsity of mechanics to repair broken pumps in times of high irrigation demand further extend the delay period. These delay factors, however, differ across locations allowing targeted interventions that, together with earlier cues to irrigate, may boost productivity enhancing irrigation use.

After investigating the decision processes and factors that influence them, **Chapter 4** turns towards the impact of changing management practices and how these changes may be bound by climatic and ecological gradients. This Chapter zooms out and compares rice planting date strategies using a gridded crop model across the Indo-Gangetic Plains. This Chapter shows that regional temperature and monsoon onset progression patterns shape the effectiveness of the analysed rice planting strategies. Synchronizing planting dates with the monsoon onset is an effective strategy for increasing productivity and resilience in the Eastern Gangetic Plains – where the monsoon starts earliest, and temperatures are milder - while currently recommended fixed dates already work best in the Western IGP. The impacts of the planting strategies on overall water use remain marginal.

Lastly, **Chapter 5** assesses what role improvements in the farming system may play in the portfolio of income generating activities of smallholders. This Chapter estimates farmer profits from intensifying irrigation of the rice-wheat system on a dollar per day basis. Using the large-scale production practices survey already deployed in Chapter 2, this Chapter 5 finds that only for the largest farms does increased productivity translate into incomes that can lift the households above the poverty line. For most households, the income response to improved intensified irrigation and associated production practices is relatively flat. The Chapter then discusses the implications of these findings for targeting interventions and reflect on the importance of creating rural off-farm jobs to support poverty reduction.

Chapter 6 provides a general discussion that extends beyond the specific concerns discussed in the research chapters and focuses on the linkages between sub-systems of the social-ecological system. After summarizing the objectives, research questions and key findings, this Chapter 6 reflects on the implications of the findings for theory, methodology, policy, and society in light of the overall research objective. Specifically, these relate to (i) the capacity of the rice-wheat system to contribute to overall development objectives, (ii) the value of systems thinking and the social-ecological diversity of the rice-wheat system, and (iii) the role of transdisciplinary and mixed-methods approaches that combine social science and computational approaches. Subsequently, this Chapter zooms out further and discusses the implications of the findings on themes that were not in the focus of the overall thesis objective and research questions. This discussion is organized across four cross-cutting themes that are crucial for the sustainable development trajectories and performance of the rice-wheat system, namely (i) water for food and challenges of water scarcity, (ii) system stresses, shocks, and resilience, (iii) the monsoon and its relationship with society, and (iv) the development of targeted intervention and policies. This Chapter ends with a final conclusion.

Altogether, this thesis assesses the constraints and opportunities of planting date adjustments and irrigation to improve the performance of the rice-wheat system in the Eastern Gangetic Plains. The main finding of this thesis is that improving the performance of the rice-wheat system through planting date adjustments and irrigation is not universally possible. Constraints imposed by the ecological, climatic, and social sub-systems limit the overall feasibility and impact of these interventions. Planting date adjustments and irrigation can increase the

productivity and resilience only in parts of the Eastern Gangetic Plains. The applicability of planting date adjustments and irrigation as a strategy to improve rice-wheat system performance and sustainability in the Western Gangetic Plains is limited by the spatial-temporal variability of temperature and precipitation in the climate system. Genetic changes to different crops or varieties will be required there to further improve the cropping system. In the Eastern Gangetic Plains, the social-ecological diversity of the rice-wheat system further constrains identification of areas where implementing planting date adjustments and improved irrigation use are feasible. The water system, land types, the availability and distribution of inputs, and collective action problems constrain the uptake of these interventions. Development programs need to address these issues in concert, and tailor technologies and interventions to the social-ecological diversity of households, communities, and landscapes. This thesis shows that such social-ecological characterization at the regional scale can be achieved by deploying a combination of participatory approaches, large survey analytics, and regional, high-resolution gridded modelling studies. However, this thesis also shows that agronomic interventions will only contribute to poverty reduction of the largest farmers, as most farms are too small to substantially increase incomes from farming. Creating off-farm jobs through integrated rural development programs will be required to address the income needs of the poor in the Indo-Gangetic Plains. Lastly, the capacity of aquifers to sustain increased groundwater use remains unknown and must be addressed.

Curriculum Vitae

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SUMMARY

Anton Urfels is Systems Agronomist at CIMMYT International Maize and Wheat Improvement Center. Anton has been working with CIMMYT on water and climate related challenges in Nepal and India for several years. His research uses a systems perspective and deploys mixed methods approaches including participatory methods, survey analysis, and crop modelling to bridge scales and disciplinary boundaries in food systems research. Anton has also been involved in fostering innovation and policy networks and partnerships in the region. When he is not working, Anton enjoys spending time in the outdoors, meditation, food, and learning about history.

PROFESSIONAL EXPERIENCE

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KEY PUBLICATIONS

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- Foster, T., Adhikari, R., Adhikari, S., Justice, S., Tiwari, B., Urfels, A., & Krupnik, T. J. (2021). Improving pumpset selection to support intensification of groundwater irrigation in the Eastern Indo-Gangetic Plains. *Agricultural Water Management*, 256, 107070.
- Urfels, A., McDonald, A.J., van Halsema, G. et al. Social-ecological analysis of timely rice planting in Eastern India. *Agron. Sustain. Dev.* 41, 14 (2021). https://doi.org/10.1007/s13593-021-00668-1
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Netherlands Research School for the
Socio-Economic and Natural Sciences of the Environment

D I P L O M A

for specialised PhD training

The Netherlands research school for the
Socio-Economic and Natural Sciences of the Environment
(SENSE) declares that

Anton Urfels

born on 28 September 1992 Berlin, Germany

has successfully fulfilled all requirements of the
educational PhD programme of SENSE.

Wageningen, 2 November 2021

Chair of the SENSE board

Prof. dr. Martin Wassen

The SENSE Director

Prof. Philipp Pattberg

The SENSE Research School has been accredited by the Royal Netherlands Academy of Arts and Sciences (KNAW)

KONINKLIJKE NEDERLANDSE
AKADEMIE VAN WETENSCHAPPEN

The SENSE Research School declares that **Anton Urfels** has successfully fulfilled all requirements of the educational PhD programme of SENSE with a work load of 37.2 EC, including the following activities:

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- Managing CSISA project water workstream (2018-2021)
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- Organizing workshops on "Managing water and time for sustainable intensification of the rice-wheat system in the Eastern Gangetic Plains" at (i) The University of Manchester, (ii) Potsdam Institute for Climate Impact Research (PIK) and (iii) Cornell University (2020-2021)

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