Coping With Climate Risks in Crop Production in the Indus Basin, Pakistan

Hassnain Shah

Propositions

1. Farmers are more concerned with today's climate hazards than with future climate risks.
(this thesis)

2. Coping is no panacea; its effect is partial and it adds costs.
(this thesis)

3. Questioning one's own research questions leads to refined answers.

4. The transition towards sustainability starts with behavioural change.

5. The recent heatwaves are the beeps of the climate emergency siren.

6. The Sandwich PhD programme is like a multiflavoured spicy *biryani.*

Propositions belonging to the thesis, entitled

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Wageningen, 20 January 2023

Coping with Climate Risks in Crop Production in the Indus Basin, Pakistan

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The cover of this thesis shows crop production from the high mountains to the plains in the Indus Basin, depicting some of the effects of climate risks captured during field work by the author.

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Summary

Evidence is mounting of accelerated global warming and resultant changes in climate variability and extreme events. A main manifestation of this is increased risks for crop production. Indeed, sustaining crop production across diverse agro-ecologies and cropping systems is increasingly challenging, as in each, crops are exposed to a specific array of climate-related hazards throughout the production period. This thesis examines in-season climate hazards, farmers' current coping strategies and constraints to adopting coping strategies. Particularly, it analyses limitations to the adjustments farmers can make during growing periods to adapt to shifts in crop seasons under climate change. The central question of the thesis is "when, within a crop production cycle, are farming communities most vulnerable to climate hazards?"

First, the integrative concept of critical moments (CMs) is introduced, defined as "periods of risk during which livelihoods are vulnerable to specific climate hazards". The CM concept is explored through a review of the literature on climate modelling, agronomy and socio-economics. To structure evidence from that review, a conceptual framework is derived distinguishing three categories of CMs according to the "when" of their impact: immediate, compound and shifted (Chapter 2). Second, an empirical analysis of farm-level cross-sectional data (*n*=287) is presented, encompassing from four cropping systems (rice-wheat, groundnut-wheat, maize-wheat and potato-wheat) in different agro-ecological zones (high mountains, mountain valleys, mid-hills and irrigated plains) in the Pakistani part of the Indus Basin (Chapter 3). A step-wise methodology is presented and applied to identify important CMs, based on an in-depth cause-and-effect chain analysis by impact pathways, as well as the coping strategies farmers implemented to mitigate yield losses, their effectiveness, the costs involved, and the level of adoption. Third, farmers' recollections of shifts in seasons under climate change are explored, as well as changes that farmers instituted in growing periods and in sowing and harvesting dates over time, alongside the impacts of these and limitations to further adjustments of growing periods within the shifted seasons (Chapter 4). The results on shifts in seasons and changes in growing periods are substantiated using temperature and precipitation data and changes in growing degree days as obtained from meteorological stations near the study sites.

The concept of critical moments is novel as it considers direct and indirect impacts as well coping strategies and explicitly includes the total effects of individual and multiple hazards by crop stage and the cost of coping. Indeed, a weather hazard affects more than just the volumetric yield of a crop; often it also affects yield quality, which can render a crop unmarketable. From the literature, three types of CMs were identified: CMs resulting from hazards with immediate impact (iCM), CMs resulting from compound hazards (cCM) and CMs resulting from hazards in which the impact was shifted to the next period in the crop rotation cycle (sCM). The literature also provides examples of several workability issues and difficulties in crop management that affect cost, crop yield and quality. However, in-season coping strategies targeting crop stages and pathways to losses are seldom reported, as the climate change literature focuses mainly on adaptation (ex ante) and ex post livelihood adjustments.

Field evidence from this research shows that in-season climate hazards resulted in substantial losses without a coping strategy, though yield losses varied, being in the 10–30% range for 43% of the in-season hazards and in the 31–50% range for another 39% of reported cases. Application of in-season coping strategies resulted in a yield recovery of 40–95%. Both effectiveness in terms of the yield loss recovered and the cost of coping strategies affected farm profitability and income. The additional cost of coping varied from 4% to 34% of the recovered yield value, the average being 19%. There was no coping strategy possible for 22% to 45% of the events reported in the different study sites. For most of the hazards at later crop stages, which caused lodging, disturbed pollination, damaged spikes or shrivelled grains, farmers had

hardly any coping options available. In the rainfed ecology, foremost climate hazards included lodging, disturbed pollination, damaged spikes, shrivelled grains and wilting due to moisture stress. Farmers' possibilities to cope were constrained by multiple barriers, including a limited time window to respond; lack of the required resources; and land, labour or machinery conflicts due to overlaps in operations in multi-crop systems. Where coping options were available, the adoption rate varied from 60% in the mountain valley to 86% on the irrigated plains. The effectiveness of coping strategies varied by response time and level of inputs used. Coping became particularly difficult and costly when weather hazards disrupted farm management and field workability, giving rise to conflicts in the timing of crucial farm operations and labour allocation.

This thesis contributes to a contextual understanding of farmers' responses to shifts in crop seasons and the resulting changes in crop growing periods. Farmers' adjustments in sowing dates did not necessarily parallel shifts in seasons, as farm decision-making also had to consider risks linked to climate variability and management limitations. At higher altitudes (valleys and mountains), the frost period had shortened, producing a longer growing period that enhanced yields. At lower altitudes (irrigated plains and mid-hills), the summer crop season had lengthened and the winter season had shortened, but the growing period was shorter in both seasons, due to higher temperatures, which negatively impacted yields. As an adaptation strategy, changing sowing dates was only somewhat effective in preventing yield losses. Farmers adopted complementary strategies, but these brought additional costs.

For the future, farmers at lower altitudes indicated limited further scope to adjust sowing and harvesting dates for wheat. A better understanding of the differentiated risks and effectiveness of in-season coping strategies could support greater interdisciplinary engagement to identify risks, to develop and promote effective coping options, and to establish user-relevant support mechanisms to reduce vulnerabilities specific to places and moments in the crop production period under current and expected climate hazards.

Samenvatting

Het bewijs voor een versnelde opwarming van de aarde en de daaraan gerelateerde veranderingen in klimaatvariabiliteit en extreme gebeurtenissen stapelt zich op. Dit uit zich in verhoogde risico's voor het verbouwen van gewassen. Het in stand houden van de huidige gewasproductie in verschillende agro-ecologieën en gewassystemen wordt steeds uitdagender, aangezien elk gewas gedurende de productieperiode wordt blootgesteld aan een hele reeks specifieke klimaatrisico's. Dit proefschrift onderzoekt de klimaatrisico's tijdens het groeiseizoen, de huidige coping-strategieën van boeren en de beperkingen aan verdere toepassing. Het richt zich daarbij met name op de aanpassingen gedurende de groeiperiode van gewassen als reactie op de verschuiving van seizoenen door klimaatverandering. De centrale vraag van het proefschrift is; "wanneer, binnen een gewasrotatie, zijn boeren het meest kwetsbaar voor klimaatrisico's?"

Eerst wordt het integrale concept van kritieke momenten (CM) geïntroduceerd, gedefinieerd als "risicoperiodes waarin activiteiten of levensonderhoud kwetsbaar zijn voor specifieke klimaatrisico's". Het CM-concept wordt onderzocht aan de hand van een literatuuronderzoek van gewas-gerelateerde studies uit de klimaatmodellering, de agronomie en sociaal-economische wetenschappen. Een conceptueel raamwerk is afgeleid waarin drie CM categorieën worden onderscheiden op basis van het 'wanneer' van de impact: 'instantaan', 'gecombineerd' en 'verschoven' (hoofdstuk 2). Ten tweede wordt een empirische analyse van cross-sectionele gegevens op boerderijniveau (n=287) gepresenteerd, bestaande uit vier teeltsystemen (rijst-tarwe, aardnoten-tarwe, maïs-tarwe en aardappel-tarwe) in verschillende agro-ecologische zones (hooggebergte, vallei, heuvels en geïrrigeerd laagland) in het Pakistaanse deel van het Indusstroomgebied (hoofdstuk 3). Een stapsgewijze methodologie is toegepast om belangrijke CMs te identificeren, gebaseerd op een diepgaande oorzaak-en-gevolg analyse van impact *pathways*. Ook worden de coping-strategieën die boeren hebben geïmplementeerd om opbrengstverliezen te beperken geïdentificeerd aan de hand van hun effectiviteit, de extra kosten die dit met zich meebrengt, en het adoptieniveau. Ten derde wordt de perceptie van boeren met betrekking tot verschuivingen in seizoenen onder klimaatverandering onderzocht, evenals de aanpassingen die boeren in de loop van de tijd hebben gedaan in zaai- en oogstmomenten, de gevolgen hiervan en eventuele beperkingen het verder opschuiven van de gewasperiode (hoofdstuk 4). De resultaten worden onderbouwd met temperatuur- en neerslaggegevens en veranderingen in graaddagen aan de hand van meteorologische data van weerstations nabij de onderzoekslocaties.

Het concept van kritieke momenten is nieuw omdat het zowel de directe en de indirecte effecten van zowel individuele alsook mogelijke combinaties van weersextremen meeneemt, en de kosten van coping-strategieën. Weersextremen hebben namelijk niet alleen invloed op de opbrengst van een gewas; vaak beïnvloedt het ook de kwaliteit, waardoor een gewas zelfs onverkoopbaar kan worden. Uit de literatuur zijn drie typen CMs te onderscheiden: CMs als gevolg van gevaren met instantane impact, CMs als gevolg van een combinatie van weersextremen en CMs als gevolg van extremen waarbij de impact is verschoven naar het volgende gewas in de gewasrotatie. De literatuur geeft ook voorbeelden van verschillende problemen in het gewasbeheer als gevolg van weersextremen, wat de kosten, de gewasopbrengst en de kwaliteit kan beïnvloeden. Er wordt relatief zelden melding gemaakt van coping-strategieën binnen het seizoen, aangezien de literatuur over klimaatverandering zich voornamelijk richt op adaptatie (ex ante) en aanpassingen in uitgaven en bezit om verliezen op te vangen (ex post).

Veldgegevens uit dit onderzoek tonen aan dat weersextremen in het groeiseizoen resulteerden in gevarieerde maar aanzienlijke verliezen bij het uitblijven van coping; 10-30% voor 43% van

de risico’s en 31-50% voor nog eens 39% van de gerapporteerde gevallen. Het toepassen van coping-strategieën resulteerde in een opbrengstherstel van 40-95%. Zowel de effectiviteit in termen van het herstelde opbrengstverlies als de kosten van coping-strategieën hadden invloed op de winstgevendheid van de gewasproductie en het inkomen van het boerenbedrijf. De meerkosten varieerden van 4% tot 34% van de teruggewonnen opbrengstwaarde, met een gemiddelde van 19%. Er was geen coping-strategie mogelijk voor 22% tot 45% van de gebeurtenissen die op de verschillende onderzoekslocaties werden gerapporteerd. Voor de meeste gevaren in de latere stadia van het gewas, die onderdak, verstoorde bestuiving, beschadigde stekels of verschrompelde granen veroorzaakten, hadden boeren nauwelijks mogelijkheden om het hoofd te bieden.

In de regenafhankelijke open teeltsystemen waren de belangrijkste klimaatrisico’s legering van het gewas, verstoorde bestuiving, beschadigde stekels, verschrompeling van graan en verwelking als gevolg van vochttekort. De mogelijkheden van boeren om deze risico’s het hoofd te bieden werden beperkt door meerdere barrières, waaronder de responstijd; gebrek aan de benodigde middelen; en land-, arbeids- of machineconflicten als gevolg van overlap in landbewerking in systemen met meerdere gewassen. Daar waar coping-opties beschikbaar waren, varieerde het adoptiepercentage van 60% in de vallei tot 86% op het geïrrigeerde laagland. De effectiviteit van coping-strategieën varieerde aan de hand van de responstijd en de hoeveelheid input. Coping werd gezien als bijzonder moeilijk en kostbaar in gevallen waarbij weersomstandigheden het management van de boerderij en de werkbaarheid op het land verstoorden, wat leidde tot conflicten in de timing van cruciale landbouwactiviteiten en de toewijzing van arbeid. Dit proefschrift draagt bij aan een contextueel begrip van de aanpassingen die boeren doorvoeren in reactie op verschuivingen in seizoenen en de daaruit voortvloeiende veranderingen in groeiperiodes van gewassen. Aanpassingen in de zaaidata volgden niet noodzakelijkerwijs de verschuivingen in seizoenen, aangezien bij de besluitvorming ook rekening moest worden gehouden met het risico op verschillende weersextremen en de beperking die het managen van een boerenbedrijf met zich meebrengt. Op grotere hoogten (valleien en bergen) werd een kortere vorstperiode waargenomen, wat leidde tot een langere groeiperiode en hogere opbrengsten. Op lagere hoogten (heuvels en geïrrigeerd laagland) was het zomerseizoen langer en het winterseizoen korter, maar de groeiperiode was in beide seizoenen korter vanwege de hogere temperaturen, wat opbrengsten negatief beïnvloedde. Als coping-strategie was het veranderen van zaaidata slechts in beperkte mate effectief om opbrengstverliezen te voorkomen. Boeren kozen voor aanvullende strategieën, maar die brachten extra kosten met zich mee.

Voor de toekomst gaven boeren op lagere hoogten aan dat verdere mogelijkheden om de zaai- en oogstdata voor tarwe aan te passen beperkt zijn. Een beter begrip van de gedifferentieerde risico's en effectiviteit van coping-strategieën binnen het groeiseizoen, zou interdisciplinaire samenwerking kunnen bevorderen om risico's te identificeren, effectieve coping-opties te ontwikkelen, en om gebruikersrelevante toepassingen te ontwikkelen om plaats- en tijd-specifieke kwetsbaarheid te verminderen, zowel in een huidige als toekomstig klimaat.

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Chapter 1

1. Introduction

1.1 Background

Evidence is mounting of accelerated global warming and resultant changes in climate variability and extreme events (Cheng, Abraham, Hausfather, & Trenberth, 2019; IPCC, 2021; NOAA, 2017; Zhang, Li, Luo, & Huang, 2019). The Intergovernmental Panel on Climate Change (IPCC) has particularly highlighted the risk that climate extremes pose for crop production (IPCC, 2014). Many consider climate extremes to be a greater risk to crop production than changes in mean climate (Haasnoot, Middelkoop, Offermans, Van Beek, & van Deursen, 2012). Yet, a focus on the most severe climate extremes, such as large-scale flooding and extended drought periods, has tended to overshadow the cumulative effects of smaller, intra-annual climate hazards that impact yields and erode farm income.

Climate events that are not statistically extreme in themselves can have extreme impacts if they cross critical thresholds (Seneviratne et al., 2012); for instance, when one or multiple weather hazards coincide with a critical crop stage at a time when farmers have limited capacity to cope. Crops are sensitive to varying degrees at different crop stages, and climate hazards that impact crop production affect food supplies (Ashok & Sasikala, 2012; Cyr, Kusy, & Shaw, 2010; Katz & Brown, 1992; Panday, Thibeault, & Frey, 2015; Schär et al., 2004). Food security can be compromised via multiple pathways (IPCC, 2022). Unlike extreme events, that cause immediate widespread damage and loss of life, low intensity but higher frequency events erode household income gradually, undermining sustainable crop production and food security. Susceptibility to climate variability is a strong determinant of people's livelihood vulnerability overall (Jain, Naeem, Orlove, Modi, & DeFries, 2015; Pelling, 2010).

Climate change and variability bring increased crop production risks (World Bank, 2015). Growing seasons, minimum and maximum temperatures and rainfall patterns are all changing, along with concomitant changes in crop water requirements and pest and disease infestations (P. K. Aggarwal & Mall, 2002; Munir Ahmad, Siftain, & Iqbal, 2014; Chakraborty & Newton, 2011; Hundal & Kaur, 1996; Juroszek & von Tiedemann, 2013; Ludwig & Asseng, 2006; R. Matthews, M. Kropff, T. Horie, & D. Bachelet, 1997; MoE, 2003; Ortiz et al., 2008; Peng et al., 2004; G Rasul, Mahmood, Sadiq, & Khan, 2012; Rosenzweig, Iglesias, Yang, Epstein, & Chivian, 2001; F. Shah et al., 2011; M. V. Sivakumar & Stefanski, 2011; Wassmann, Jagadish, Sumfleth, et al., 2009; Yoshida, 1981). Changes in seasonality have the potential to alter regional agricultural systems, with far-reaching consequences for crop production and food security alike (Nienaber, Hahn, & Eigenberg, 1999; Parmesan, 2006; M. L. Parry, Rosenzweig, Iglesias, Livermore, & Fischer, 2004). Emerging evidence and projections of negative impacts on agricultural production are not restricted to any single region or farming system. Serious losses and threats to food security are expected to occur both in low-income countries of Asia, Africa and Latin America (M. L. Parry et al., 2004; Philip K Thornton, Ericksen, Herrero, & Challinor, 2014), and in regions characterized by high-yielding varieties and advanced technology (Kang, Khan, & Ma, 2009).

A growing body of literature supports a categorization of climate hazards according to their time of incidence, intensity and pathways to losses, in order to explore potential adaptation interventions (Füssel, 2007; Heltberg, Siegel, & Jorgensen, 2009; IPCC, 2012; Wilby & Dessai, 2010; World Bank, 2015). Quantification of climate risk by crop and crop development stage at the regional level is thus an important avenue of research (Luo, 2011). Climate impact modelling has targeted ever smaller spatial scales and more specific periods of risk during the crop production cycle, to identify measures to mitigate negative impacts (Adger et al., 2007; Mechler, Hochrainer, Aaheim, Salen, & Wreford, 2010; Schaap, Reidsma, Verhagen, Wolf, & van Ittersum, 2013). Less is known about farmers' capacity to implement adaptation measures, especially in intensive multi-crop systems in which timing is crucial. Adaptive capacity is strongly dependent on prevailing socioeconomic and biophysical conditions, perceptions of farm-level risks by those involved and barriers to coping (Lopes & Aguiar, 2008; White, Hoogenboom, Kimball, & Wall, 2011). Such barriers can include extra costs associated with coping measures, as well as operational and workability issues. This again points to the importance of categorizing climate hazards by type of impacts, the possibility to cope and the costs involved, in order to understand farm-level vulnerability.

The IPCC has pointed to the persistent lack of preparedness for increased climate variability and associated risks (IPCC, 2014). Effective coping is considered the first step towards adaptation (P. J. M. Cooper et al., 2008; Murray, 2012). Farmers' adaptive capacity is rooted in past events and experiences (Pelling, 2010). Adaptation starts with farmers' responses to hazards at the production level. For example, farmers may adopt risk-spreading and impact-mitigation strategies during the crop production period (P. J. M. Cooper et al., 2008). These so-called "in-season coping strategies", however, have tended to be seen as a given, meaning their cost effectiveness has been ignored, while research has focused mainly on ex ante or ex post coping strategies. In-season coping strategies are often complex due to the need for rapid responses and the extra costs these bring, leading to considerable trade-offs between cost and an often uncertain yield recovery. To help farmers navigate these trade-offs, scientific exploration and provision of advice needs to resonate with farmers' coping experiences and adaptive capacity.

Considerable socioeconomic and biophysical diversity exists across agro-ecologies and production systems, even within a single country or region. Climate risks and the way these can be managed vary as well. To make sense of this diversity we need a systematic categorization of climate risks in crop production at the sub-system level, to help identify suitable coping strategies for particular climate hazards according to the particular crop stages in which they occur and appropriate adaptations to changes happening during crop growing periods – to improve farmers' resilience to current and future crop production risks (Füssel, 2007; Heltberg et al., 2009; IPCC, 2012; Wilby & Dessai, 2010; World Bank, 2015).

While climate change affects the whole world (IPCC, 2018; Ortiz-Bobea, Ault, Carrillo, Chambers, & Lobell, 2021), developing countries are most vulnerable (Rahman & Lateh, 2017), largely due to their limited adaptive capacity at the community and institutional level (Ullah, Nafees, Khurshid, & Nihei, 2019). Within developing countries, Pakistan, with its burgeoning population and lagging economic growth, is particularly vulnerable to climate change impacts, due to its geographic location, low adaptive capacity and high dependence on agriculture for livelihoods, food security and exports (Abbas et al., 2018; A. Q. Aslam, Ahmad, Ahmad, Hussain, & Hussain, 2017; Sajjad & Ghaffar, 2019). Pakistan is already regularly exposed to climate extremes, including large-scale flooding, seasonal droughts and heat waves (Abbas et al., 2018; K. Ahmed, Shahid, & Nawaz, 2018; Nasim et al., 2018). These affect the poorest farmers most (M. Hussain et al., 2020). Climate change is also a threat to the Pakistan government's aim to further develop agriculture and its agro-based industry – to tap opportunities for export-led growth (Mahmood Ahmad, 2020).

In Pakistan, agriculture employs 37.4% of the labour force and contributes 22.7% of GDP (Government of Pakistan, 2022). Most of Pakistan's agricultural land area is located in the Indus Basin, where the combination of climate change, population growth, limited investment in agriculture and water stress pose severe challenges; indeed, threatening the food security of more than 200 million people (H. Biemans, Siderius, Mishra, & Ahmad, 2016; K. Malik, 2013; J.-E. Parry, Keller, & Murphy, 2013; World Bank, 2011). Increasing climate variability puts crop production here further at risk, undermining the sustainability of agriculture-based livelihoods (Lutz et al., 2022). To identify and assess potential losses and farmers' coping strategies and constraints, we need to better understand hazards due to climate variability, especially crop vulnerabilities in particular periods of the year, when farm households may be less able to cope. This thesis therefore focuses on the question of "*when*, within a crop production cycle, are farming communities most vulnerable to climate hazards". Climate change affects the timing and length of crop seasons, and crops are subject to different climate hazards under these shifting seasons. The current research therefore investigates the compatibility of current coping measures with shifts in growing seasons, and the limitations farmers face in adjusting crop growing periods.

1.2 Objectives and research questions

This study seeks to enhance understanding of the ways farmers cope with climate risks to crop production. It has two objectives:

- to identify the climate risks and assess strategies and barriers to coping with in-season climate hazards in different agro-ecologies and cropping systems in the Indus Basin
- to explore the limits of coping strategies in a changing climate

To meet these objectives, four research questions are addressed: (i) What types of climate risks can be differentiated? (ii) How effective are strategies to cope with in-season climate hazards? (iii) What barriers prevent farmers from coping with in-season climate hazards? (iv) What scope is there to further adapt to changing climate conditions?

1.2.1 Types of climate risks that can be differentiated

The current research categorizes the types of risks that crops are exposed to during different time periods within the crop production cycle by hazard occurrence, coping possibility and impact. The aim is to derive distinct critical moments (CMs), defined in this study as "periods of risk during which livelihoods are vulnerable to specific climate hazards". The classification of hazards' impacts and pathways to losses by time window can support the identification of appropriate coping interventions to improve farm-level resilience.

1.2.2 Effectiveness of strategies to cope with in-season climate hazards

To assess the effectiveness of strategies to cope with in-season climate hazards, this study examines what hazards affect crops at different growth stages, by what pathways these hazards lead to losses, the coping options that farmers adopt and the level of effectiveness of those options in terms of yield loss recovery and the cost of the coping strategy.

Farmers' choices in adopting coping strategies are shaped by hazard pathways; that is, how a hazard leads to impact, with or without coping. A categorization of hazards by pathways to losses, with quantification of the yield loss averted through coping, can inform effective in-season risk management. Yet, coping brings costs as well, which can differ considerably between different agro-ecological regions, land use patterns and farm typologies (Dono et al., 2013; Kaushik & Sharma, 2015; McCarthy, Lipper, & Branca, 2011). The location and farm-specific cost of coping must therefore be considered in quantifying yield loss recovery.

1.2.3 Barriers to coping with in-season climate hazards

Barriers hinder farmers' attempts at coping with in-season climate hazards. A barrier might be the unavailability of a coping option, or a too-short time window to implement it. Or, the required resources may be unavailable during the time window, or some other operational conflict may hamper coping; for instance, overlapping needs for land, labour or machinery, especially in multi-crop systems.

1.2.4 Scope to further adapt to changing climate conditions

Whether scope remains for further adaptation to changing climate conditions depends on the degree that farmers have already adjusted their crop growing patterns in the face of shifts in seasons, and the extent to which farmers expect to be able to adapt further. This scope can be evaluated by investigating gains and losses in crop yields related to changes in growing periods in response to shifts in seasons in different agro-ecologies, as well as differences in farmers' adjustments of the growing periods and limitations relative to perceived shifts in seasons.

1.3 Methodology

To answer these questions, the current research explores the concept of "critical moments" through a review of the literature combined with empirical analysis of farm-level cross-sectional data collected by means of a formal survey. The literature review and farm-level survey sought to identify CMs by crop stages, as well as coping strategies and the effectiveness of these. In a stepwise fashion, the research examines changes in crop growing periods according to shifts in sowing and harvesting stages, the impacts of such shifts, farmers' adaptations to shifts in seasons, and the limitations farmers face in adjusting growing periods within shifting seasons.

1.3.1 The concept of critical moments and existing evidence

To answer the first research question, regarding what hazards affect crops at different growth stages, this study introduces the concept of critical moments (CMs), defined as periods of risk when livelihoods are vulnerable to specific climate hazards. CMs underscore the time dimension of climate variability, which is expected to increase in the coming years and decades, bringing greater impacts on agricultural livelihoods.

Here, the question of "when" with respect to risk does not relate to a single hazard incidence or crop phenology. Rather, it is multifaceted, encompassing a time window in which a climate hazard may occur, alongside the extent of crop exposure and the possibility for a farmer to implement a coping strategy. The CM concept thus encompasses the hazard occurrence, pathways to losses and coping at different stages in the crop growing period. As such, it allows us to better understand hazards due to climate variability, especially their time dimension, enabling investigation of associated potential losses and farm-level coping and adaptation measures.

To structure existing evidence on CMs, a conceptual framework was developed distinguishing three categories of CMs according to the "when" of their impact: immediate, compound and shifted (see Chapter 2, Figure 1). This was accompanied by a review of relevant literature to garner evidence on the CM concept and compile examples of different types of CMs and factors that can lead to losses, in order to answer the first research question. Specifically, the CM concept was developed through a review of three streams of literature: climate modelling, agronomy and socioeconomic research. Risk was defined as the product of the probability of a hazard and its adverse consequences (IPCC, 2012). The hazards included in the review are similar to the simple extremes referenced by the IPCC (2001) and described in terms of individual local weather variables exceeding critical thresholds, like high or low temperatures, high or low rainfall and extreme winds (Seneviratne et al., 2012). Evidence on hazard frequencies for critical time periods relevant to crop production is synthesized through a review of climate modelling research. For the causal relationship between a weather hazard and yield considering threshold levels for the different crop growth stages, CM-relevant examples from agronomy research are included, while socioeconomic studies were reviewed to link these effects to farm incomes. Where reported, examples of indirect impacts, including weed growth, disease incidence, quality or workability issues and recommended coping and adaptation strategies were also included. The CM concept explicitly includes the total effects (direct and indirect) of individual and multiple hazards by crop stage covering possible coping options and the cost of coping, integrating these dimensions to assess the vulnerability of crop production-based livelihood systems.

Vulnerability to extreme events occurring over a larger area, like large-scale flooding, drought and cyclones, has been extensively studied and is therefore not included in this review. Typically, the return period for CMs is shorter than for extreme events; that is, once in five to ten years instead of once in 100 years or more (though these latter return periods tend to shorten with climate change).

1.3.2 Field evidence on CMs

Field research was conducted to answer the second, third and fourth research questions. Specifically, a field survey instrument was developed to collect cross-sectional data with which to investigate full pathways of cause and effect, over complete crop production cycles in a given year. Considering the importance of cropping systems, especially in regions where sequential cropping is performed (Claas Nendel, Rötter, Thorburn, Boote, & Ewert, 2018; Reidsma et al., 2015; Toffolini, Jeuffroy, Mischler, Pernel, & Prost, 2017), limitations to coping were identified from a system perspective rather than for crops individually. The full pathways of cause and effect were thus captured, starting from incidence of hazards by crop stage to identification of pathways by which a hazard causes loss, farmers coping responses to mitigate yield loss, barriers to coping with in-season hazards and limitations to adapting to changing climate conditions. In addition to the combined impact of simultaneous hazards, cascading effects were addressed; that is, situations whereby an overlap in harvesting and planting might have led to conflicts in the utilization of land, labour or capital, adversely affecting growing conditions and yield of a subsequent crop.

The research conceptual design and findings from the literature review fed into the strategy for field data collection. To this end, an extensive survey was conducted among farmers (n=287) representing four cropping systems in different agro-ecological zones within the Indus Basin of Pakistan. A multi-stage stratified random sampling framework was employed to achieve a representative sample of farmers, using a climate- and physiography-based agro-ecological zone classification of the country to stratify the study population.

With the aim of gathering evidence on CMs, a detailed questionnaire was developed in line with findings from the literature on CMs. The questionnaire covered full pathways of cause and effect, farmers' coping strategies and limitations in coping in sequential cropping systems (Chapter 3, Annex I). Before finalization, the survey design was refined in consultation with agricultural scientists working in each of the target agro-ecological zones/cropping systems. The final survey instrument incorporated their feedback, alongside outcomes from pretesting, field observations and insights from focus group discussions with farmers in each study area.

The farm-level data encompassed farmers' experiences of climate variability and pathways to losses for the most common hazards, focusing on the 2008–2018 period, as well as coping responses and their effectiveness. First, the impact on crop yield of individual hazards was differentiated for various loss-causing pathways by crop stage, considering cause-and-effect chain analysis (Kiprutto, Rotich, & Riungu, 2015; Kuster et al., 2015), as well as the coping strategies that farmers adopted to mitigate yield losses. Second, the effectiveness and cost of coping options were assessed for each loss-causing pathway, in terms of yield loss recovery. Third, the changes in growing period over the long run were investigated, considering changes in farm practices related to sowing and harvesting, in lieu of changes in start and end points of the summer and winter seasons.

Data on farmers' perceptions of changes in the local climate were also collected. Perceptions of changes in temperature and precipitation were based on memory recollection, spanning a 30-year time period. Data was obtained by interviewing older farmers, mostly household heads still involved in day-to-day crop management and farm decisions. To check the consistency between the climate changes reported by farmers and those observed at meteorological stations, data from stations nearest the study sites were obtained from the Pakistan Meteorological Department (PMD).

Shifts in crop seasons were traced based on farmers' estimates of changes in both the start and end dates of seasons, considering changes in temperatures and frost periods at the study sites. The "growing period" was defined as the actual period in which farmers grew a crop in their given agro-ecological setting, as distinct from the "crop season", which is based on meteorological conditions in which crop growth and development is possible.

1.3.3 Study location

The study area, shown in Figure 1, lies in Pakistan, a country highly vulnerable to climate change (Dehlavi, Gorst, Groom, & Zaman, 2015; Government of Pakistan, 2012, 2013; Kreft, Eckstein, Junghans, Kerestan, & Hagen, 2014). Pakistan is situated between latitudes 24° and 37° North and longitudes 61° to 75° East, stretching over 1,600 kilometres from north to south and 885 kilometres from east to west, with a total area of 796,095 square kilometres. Annual rainfall ranges from 125 mm in the extreme southern plains, to 500–900 mm in the sub-mountainous and northern plains. A seminal work by the Pakistan Agricultural Research Council (PARC) divides the country into ten agro-ecological zones based on variation in climate, geography, soil composition, agricultural land uses and water availability (PARC, 1980). Pakistan is an agro-ecologically diverse country with large variation in topography, landscape, altitude, geography, climate, seasons, soils and cultures (Haider & Adnan, 2014; Haider & Ullah, 2020; Kazmi et al., 2015; Sajjad & Ghaffar, 2019). Climate zones range from arid to humid, with four precipitation seasons (pre-monsoon, monsoon, post-monsoon and winter) and two main cropping seasons (summer and winter), allowing multi-cropping in many locations. Winters are long and cold in the northern mountains while hot summers characterize the plains (S. Khan, 2019). Such diversity provides opportunities for growing a large variety of crops across Pakistan. Each agro-ecological zone offers a distinct environment for agriculture and crop farming, but is also subject to singular environmental and socio-economic challenges (Mahmood et al., 2019).

An agro-ecological zone-centred approach can be helpful in identifying suitable technology options and appropriate incentives and economic stimulus to optimize production potential and farmers adaptive capacity in the face of the threat of climate change (Vosti & Reardon, 1997). An understanding of agro-ecological characteristics can provide a basis for design of adapted agricultural systems (Altieri, Nicholls, Henao, & Lana, 2015). Maladaptation can lead to agricultural land degradation (Waldon et al., 1998), undesirable changes in ecosystems (Lambert et al., 1990) and depletion of natural resources (de Molenaar, 1990; Lambert, Brubacher, & Arnason, 1990; Waldon, Gliessman, & Buchanan, 1998). The concept of food sovereignty, which emphasizes local food economies and ecologically sustainable production, further sets off agro-ecological considerations and the need for comparative advantage-based production systems (Altieri, Letourneau, & Davis, 1983; Altieri & Nicholls, 2008).

To explore and evaluate the impact of CMs on crop production, the current research selected study sites in three of Pakistan's ten agro-ecological zones; namely, the Northern Irrigated Plains (IVa), the Barani Lands (V) and the Northern Dry Mountains (VII). Each represents a distinct but important cropping system. Together, the three span from Pakistan's high mountains to the rainfed mid-hills and irrigated plains. The traditional farming systems within these agro-ecological zones offer historical insight into the factors underlying the longevity of these systems – knowledge that can support modern agricultural systems' resilience to climate extremes (Altieri et al., 2015). These agro-ecological zones are distinct in cropping patterns, irrigation regimes, farming systems, gender participation and other characteristics, while at the same time having similarities with other domains in and beyond Pakistan, in other South-Asian countries.

In each zone, the dominant cropping system was selected for study, and was considered one stratum. In the Northern Dry Mountains, there was a clear distinction in cropping systems between the main valleys and areas higher up, so a fourth stratum was added to include the higher altitude cropping system here. Multiple cropping with two major crops was practiced in all four of the studied cropping systems. Wheat *(Triticum aestivum)* was grown as the staple food crop in all of the systems, with the second food crop grown mostly for commercial purposes. Wheat was grown in a multi-crop rotation system with potato (*Solanum tuberosum*) in the high mountains (HM), with maize (*Zea mays*) in the mountain valleys (MV), with groundnut (*Arachis hypogaea*) under the rainfed conditions in the mid-hills (MH) and with rice (*Oryza sativa*) on the irrigated plains (IP). Hence, within the boundaries of each agro-ecological zone important cropping systems were selected wherein winter wheat was the focal crop in rotation with one other major summer crop, which differed per location (further detailed in Chapter 3).

The selected agro-ecological zones and cropping systems are briefly described below.

1.3.3.1 Northern Dry Mountains

The Northern Dry Mountains are found in the upper Indus Basin and high mountains and mountain valleys. This zone comprises Gilgit, Baltistan, Chitral and Dir valleys, which are irrigated by glacier-fed streams and include the Chitral, Dir, Swat and Tribal areas of Peshawar and Kohat, the Karakorum Mountains and spurs of the Hindu Kush, which border the syntaxial bends of the Himalayas. The climate is undifferentiated. The tops of the high mountains are covered with snow most of the year. Mean monthly rainfall is 25–75 mm in winter and 10–20 mm in summer. The valleys are extremely arid, with mild summers and cold winters. Soils in the valleys are deep and clayey. Soils on the mountain slopes are shallow and non-calcareous acid (pH 5.5–6.5) above 2,100 m altitude and calcareous at lower altitudes. The Northern Dry Mountains zone is rich in crops, fruits and nuts. Most of the area is used for grazing, in part under scrub forest. Characteristic crops include potato, maize, wheat, rice, finger millet, barley, buckwheat and several kinds of temperate fruits and nuts.

Due to substantial variation in altitude, cropping systems and crop seasons vary within the zone. To cover this diversity, two study sites were selected. The first, in the Gilgit region, represents lower altitude farming with a maize-wheat cropping system. It is termed here mountain valley (MV). The second, in the higher altitude, upper Hunza region, is termed high mountain (HM) and represents a potato-wheat cropping system. This system was identified in collaboration with local agricultural experts. The maize-wheat cropping system in the MV region was practiced in two seasons, with each crop grown in sequence on the same land parcels. The potato-wheat cropping system in HM was practiced in a single crop season, with the crops planted in parallel on different land parcels during the same crop season. Snow melt and rainfall/stream flow were the main water sources for both cropping systems in this zone.

1.3.3.2 Barani (rainfed) lands

Barani, or "rainfed" lands were representative of agriculture in the mid-hills (MH). The barani zone spanned a salt range, the Pothowar Plateau and the Himalayan Piedmont Plain. A small, narrow belt along the foot of the mountains is nearly humid, with hot summers and cold winters.

In the north, mean monthly rainfall was 200 mm in summer and 35–50 mm in winter. The southern areas, however, were hot and semi-arid. The mean monthly rainfall was 85 mm in summer and 30–45 mm in winter. A large proportion of the zone was comprised of gullied lands. Key crops here included groundnut, wheat, millet, sorghum, oilseeds and pulses, and fodder. Maize was grown in high rainfall areas or where groundwater could be extracted by tube wells for irrigation purposes. Wheat was the main winter crop. The barani zone contributed 90% of Pakistan's groundnut production. The groundnut-wheat cropping system was therefore selected for study in this zone.

1.3.3.3 Northern Irrigated Plain

The Northern Irrigated Plain encompasses the flood plains and Bar uplands covering most of the province of Punjab and is the main breadbasket and principal area of agricultural production in Pakistan. Termed here the irrigated plains (IP), the climate is semi-arid to arid, with mean annual rainfall 300–500 mm in the east and 200–300 mm in the southwest. The soils are sandy, loam-clay and loam. The canal-irrigated crops are wheat, rice, sugar cane, oilseeds and millet in the north and wheat, cotton, sugarcane, maize, citrus and mangoes in the central and southern areas.

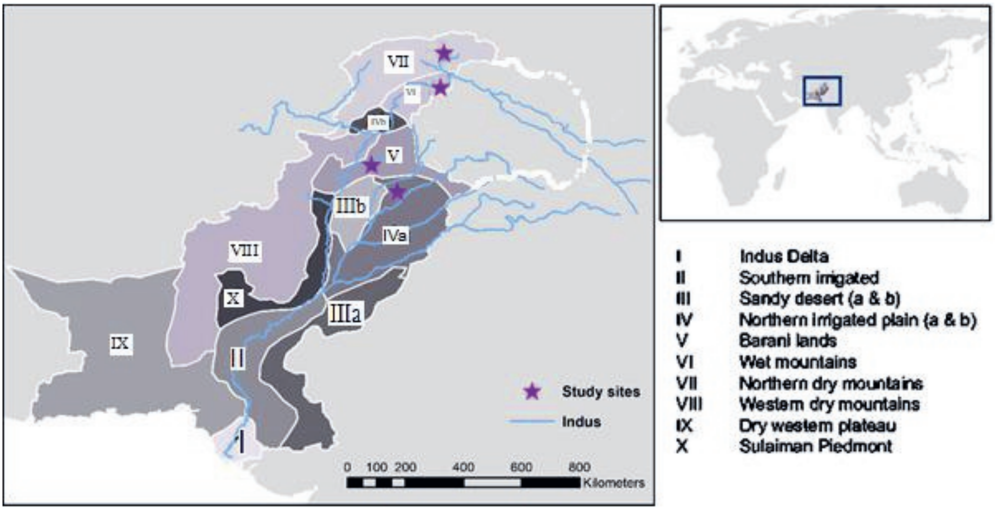

Figure 1. Case study sites and agro-ecological zones within the Indus Basin *(Source: Pakistan Agricultural Research Council, 1980)*

1.4 Outline

Figure 2 presents the structure of the rest of this thesis. Chapter 2 presents evidence related to CMs gathered from the literature. Chapter 3 presents field evidence for categorizing the impacts of hazards by pathways, farmers' coping strategies, cost of coping and effectiveness of coping. Chapter 4 then addresses farm-level adjustments to sowing and harvesting dates (i.e., the growing period) in response to shifts in meteorological crop seasons, as well as their impacts on yields and farmers' complementary adaptation strategies. Chapter 5, summarizes the research, synthesizing policy implications and deriving conclusions.

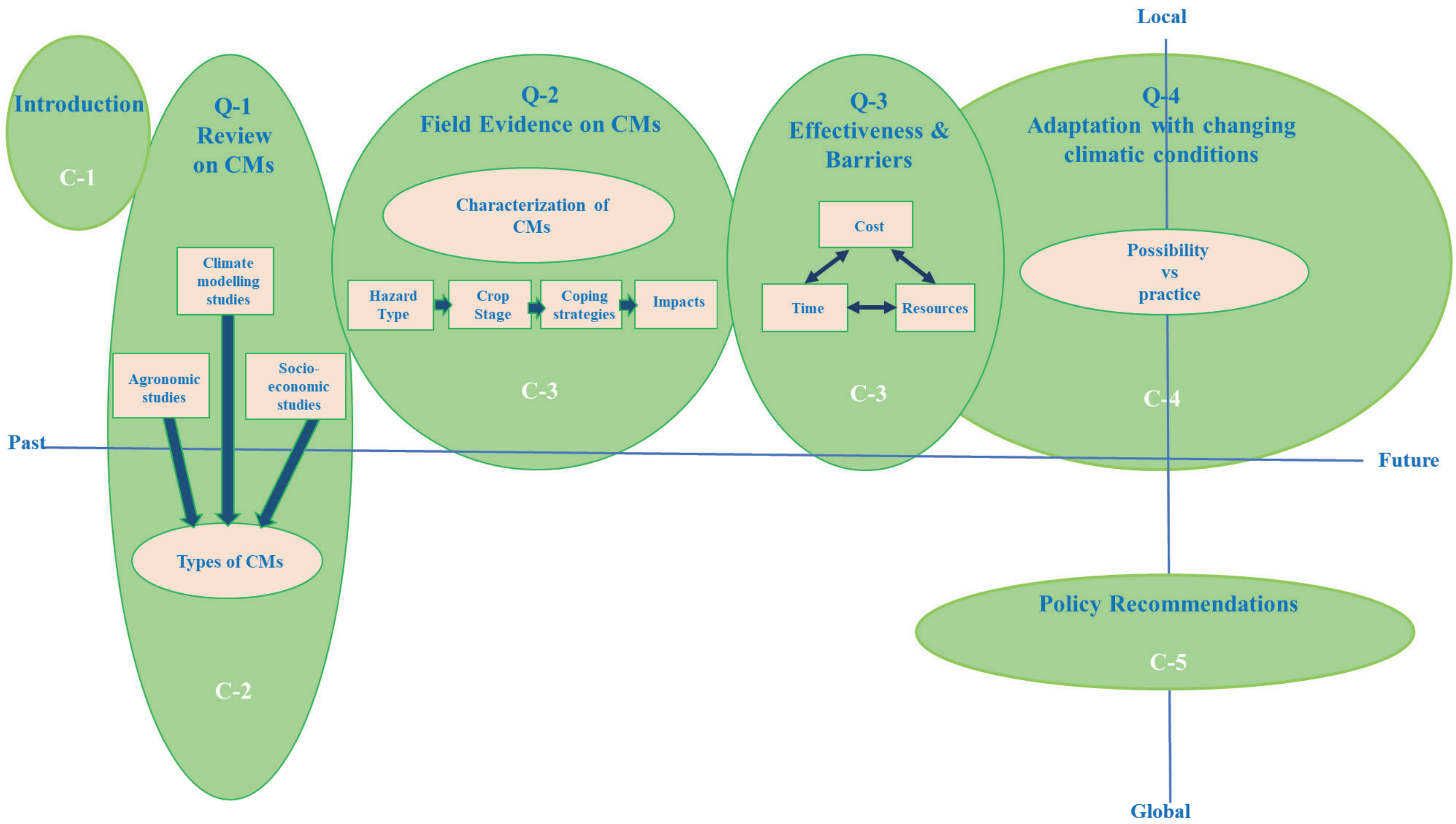

Figure 2. Structure of the thesis

Note: 'Q' refers to research questions presented in sub-section 1.2.

Chapter 2

This chapter is based on: Shah, H., Hellegers, P., & Siderius, C. (2021). Climate risk to agriculture: A synthesis to define different types of critical moments. *Climate Risk Management*, *34*, 100378. https://doi.org/10.1016/j.crm.2021.100378

2. Climate risks to agriculture: A synthesis to define different types of critical moments

Increasing climate variability will put crop production at risk, undermining the sustainability of agriculture-based livelihoods. Much effort has gone into assessing differential vulnerability – or who is at risk. However, the time dimension of increased risk – the when – is often only implicitly included in modelling, statistical and empirical studies. We define and explore the concept of "critical moments" (CMs); that is, periods of heightened risk during the year when farm households are vulnerable to specific climate hazards. The climate modelling, agronomy and socio-economics literature is reviewed to define different types of critical moments. Climate modelling emphasizes hazards but is less specific about the time window of risks in relation to crop cycles. Agronomy research develops cause-and-effect relationships between weather variables and yields by crop stage but generally does not consider hazard frequency and associated vulnerability. Socio-economic research analyses associations between hazards, yields and farm income, but often lacks full process knowledge, neglecting other pathways that contribute to vulnerability. Our synthesis aims to bridge disciplinary silos, and proposes an integrated concept towards risk. In this study, three types of CM are identified: CM's with immediate, compound and shifted impact. The concept of critical moments is novel as it considers direct and indirect impacts as well coping strategies. Viewing climate risk to agriculture through a CM lens can support greater interdisciplinary engagement to identify vulnerabilities and develop and promote effective coping options and user-relevant support mechanisms to reduce vulnerabilities specific to particular places and moments.

2.1 Introduction

Global warming changes not only the climate's mean state but also its variability, which is projected to increase in most areas (Panday et al., 2015; Schär et al., 2004). Climate variability and extremes are a key driver behind rises in global hunger and one of the leading causes of severe food crises, particularly in the most food insecure regions (Richardson et al., 2018; World Health Organization, 2018). A vast literature addresses the negative impacts of climate variability on agricultural production. Throughout the production season, crops are sensitive in varying degrees to different weather events. Both inter- and intra-annual rainfall variability, affects the outcome of cropping systems during any particular season (IPCC, 2012; Nippert, Knapp, & Briggs, 2006). A sudden change in temperature at particular times in the growing season (Tripathi, Tripathi, Chauhan, Kumar, & Singh, 2016), or out-of-season spikes in humidity (Hall, 2017), hail (Singh, Rajat, Akhilesh, Neetu, & Ray, 2017) and wind (Gardiner, Berry, & Moulia, 2016) are examples of weather events that can impact crop development, yields, and farm income.

Academic and popular reporting on extreme weather and large-scale climate events – the disasters – tends to overwhelm the impacts of smaller intra-annual and localized hazards. Shifts in seasonal runoff, precipitation, humidity, and temperature regimes can be just as disruptive as larger, more dramatic weather events such as large scale floods (IPCC, 2012). Similarly, a weather event that is not statistically extreme in itself may have extreme impacts if a critical threshold is crossed over a critical crop stage, or a period when farmers have less capacity to cope (Seneviratne et al., 2012). Changing weather patterns, thus, threaten agricultural production and increase the vulnerability of most of the world's poor who depend on agriculture for their livelihood (Lipper et al., 2014).

The timing and interactions of stresses at different crop growth stages may cause higher losses and increase food insecurity in the future (Philip K Thornton et al., 2014). A growing literature addresses the role of the timing and severity of climate hazards, to identify the adaptation interventions required to improve resilience at the farm level (Heltberg et al., 2009; Wilby & Dessai, 2010). Weather hazards may also disrupt farm operations and field workability at crucial stages, affecting production costs in addition to impacting crop yields and quality. Even if farmers cope with a hazard, there may be a cost associated with these coping measures (Mandryk, Reidsma, & van Ittersum, 2017). Net farm income is affected by both change in yield and cost (Thamo et al., 2017). The level of risk to impact on net farm income is high if an adverse weather event coincides with a sensitive crop stage and other adverse effects such as higher incidence of weeds, diseases and workability issues that affect a farmer's capacity to cope are included (H. Shah, Siderius, & Hellegers, 2020; Toeglhofer, Mestel, & Prettenthaler, 2012).

Most climate change impact research has been confined to disciplinary silos, mostly either studying a hazard's probability or its effects on yields largely ignoring the impacts of coping and indirect effects. Adaptation tends to target impacts of changes in the mean climate and estimates on the benefits of adaptation mostly do not account for possible changes in climate variability, or in related condition such as local water resources availability (Burke & Emerick, 2016; Butler & Huybers, 2013). Impacts of hazards vary by location, agro-ecologies and cropping seasons, as do coping possibilities (Penalba & Elazegui, 2013). Even within a homogeneous production region, adaptation needs to be tailored to local conditions (Perry, Yu, & Tack, 2020).

Considering the importance of the time dimension of hazards – and the likelihood of increased climate variability in the coming years – regarding the vulnerability of agricultural livelihoods, we introduce the concept of "critical moments" (CMs), which we define as periods of risk during the year when livelihoods are vulnerable to specific climate hazards. We elaborate on the concept of CM through a review of the literature focusing on the following key question: "When, within a crop production cycle, farming communities are most vulnerable to climate hazards?" Within the context of CMs, 'when' is not a single hazard incidence or crop phenology, but rather a multifaceted concept that encompasses the time window of risk, with respect to the occurrence of a climate hazard, the exposure of the crop and the possibility for a farmer to implement a coping strategy. To better understand the 'when', we identify three types of CMs based on the literature.

In section 2, a conceptual design is proposed to classify three types of CMs. In section 3.1, three streams of literature are reviewed to assess the extent to which they address CMs. The three types of CMs, and their dimensions related to hazard occurrence, vulnerability and coping, are further examined and classified in section 3.2. Section 3.3 provides insight into the applicability of the concept under climate change. Section 4 discusses three key recommendations to apply the concept in practice.

2.2 Conceptual design

The CM concept integrates the time dimension of hazards, their effects on crop production and their impacts through different pathways on farm incomes. An initial conceptualization of critical moments was suggested by Groot et al. (2017). Here, a three-type conceptual design is developed to structure evidence on CMs. It considers direct and indirect impacts and provides insights into flexibility to cope with the hazards. The CM concept explicitly includes the total effects of individual and multiple hazards by crop stage covering the cost of coping. Based on this design we synthesize findings from the literature to answer the research question presented above.

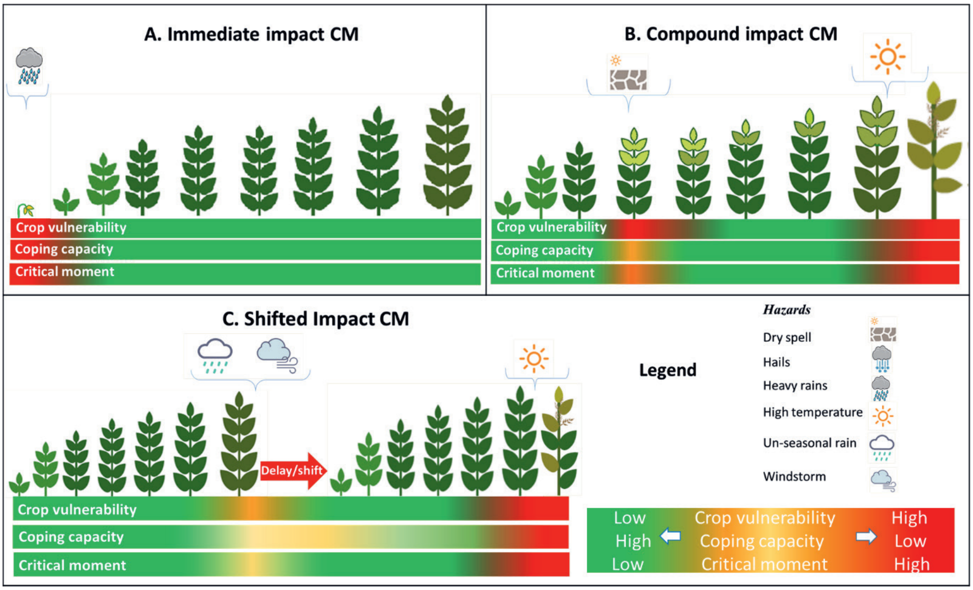

Figure 3. Conceptual design of critical moments (CMs), illustrated over a cropping calendar with A. Immediate Impact CM arises from a hazard causing immediate crop/income loss; B. Compound Impact CM causes loss from multiple hazards over the same cropping season; C. Shifted Impact CM causes major loss over the next crop due to a hazard occurring during the later period of the previous crop, especially in a double cropping system. Hazards presented per crop stage are purely indicative, but are informed by hazards reported to be most common in wheat-based, multi-cropping systems in the Indo-Gangetic plain (H. Shah, Siderius, et al., 2020))

The Immediate Impact CM (Fig. 3A) describes a CM arising from vulnerability to a single weather hazard, like a heavy rain after sowing causes waterlogging and results in seedling death or an un-seasonal rain between sowing and germination stage leads to crust formation and blocks seed germination. It causes loss of resources used for first sowing and farmers need additional resources for re-sowing as a coping option. Another example is a heat stress or waterlogging around the reproductive stage, which directly affects crop growth and leads to yield losses. In such situations, coping is hardly possible, either due to very short response time or due to no coping option for the pathway to loss; the crop never recovers to its full yield potential.

Compound Impact CM (Fig. 3B) represents a CM arising from the combined effect of two hazards, like a seasonal drought affecting crop development in the initial crop growth stage and a windstorm at maturity that produces lodging. Even if there is a coping possibility for a hazard at one stage, it has a cost and affects net income. The second hazard at a later crop stage with the fewer coping possibility (limited time to respond or no coping options) leads to higher yield loss. The compound effect of two or more moderate hazards can amplify vulnerability (IPCC, 2012). Yield loss and the costs of coping determine the net impact of a CM. Another example is the simultaneous occurrence of two hazards that have a synergistic effect, like moisture stress coupled with heat stress at the grain-filling stage.

The Shifted Impact CM (Fig 3C), depicts the ripple effect of a hazard and an initial attempt to cope, like a weather event that causes a farmer to shift sowing or harvesting, which then affects the next crop under a double cropping system. The main impact is shifted to the next crop season with no or minor losses, during the first season. For example, an un-seasonal rain at maturity may delay harvesting of a first crop, leading to a conflict between harvesting and seedbed preparation operations, compelling farmers to delay or abandon sowing of the next crop, resulting in yield loss in the next crop.

We review climate modelling research to synthesize hazard frequencies for critical time periods relevant to crop production. Risk is defined as the product of the probability of a hazard and its adverse consequences (IPCC, 2012). For the causal relationship between a weather hazard and yields considering threshold levels for the different crop growth stages, we included CM-relevant examples from agronomy research. We review socio-economic research to link these effects to farm incomes. Where reported, examples on indirect impacts, including weeds, diseases, quality or workability issues were also included from these streams of literature.

The conceptual design informed the inclusion and exclusion criteria for the literature (Annex 1A). Based on these criteria, 721 papers and reports were collected. Out of these, only those that explicitly described time-related aspects of climate risk, with respect to the occurrence of a climate hazard, coping possibility and/or its impacts were further screened, reducing the number to 126. References to literature covering CM relevant issues such as workability issues, quality and cost of coping at specific moments expanded the total to 135. Our review aggregates prior findings on different aspects of hazards and their impacts. The review scope was confined mainly to syntheses of hazards during crop production due to weather variability, biophysical impacts of adverse weather events and other indirect pathways causing yield and income losses. The examples, by type of CM, consider crop vulnerability by crop stage and pathways to loss by type of hazard. For coping, possible coping options, and associated costs are considered. The concept of CM integrates these dimensions to assess the vulnerability of crop production based livelihood systems. The hazards we included are similar to the simple extremes referenced by the IPCC (2001) in its typology of climate extremes and described as individual local weather variables exceeding critical thresholds, like high or low temperatures, high or low rainfalls and extreme winds (Seneviratne et al., 2012).

2.3 Results

2.3.1 Elements of CM derived from literature

2.3.1.1 Climate modelling studies

Climate modelling science tends to focus on long-term changes in mean climate variables and their impacts like temperature extremes, seasonal droughts and increased stress due to excess water over land areas (IPCC, 2007, 2018). Most research follows a top-down approach, both temporally and spatially, to study changes in extremes under different scenarios (Stocker et al., 2013), though some climate modelling does attempt to differentiate climate hazards at smaller temporal and spatial scales. Initial data and model limitations have made it difficult for climate modellers to converge on a certain crop growth stage during the year at a spatial scale sufficiently specific to identify CMs (Rosenzweig et al., 2014). Recently, though, climate modelling studies have converged down from the global to the regional scale (Stocker et al., 2013) and started to identify the most sensitive time windows over the crop growth cycle wherein variability in climate factors explain maximum variability in crop yields. For example, a spatial assessment of heat stress in wheat, maize, rice and soybean at the global level found a high risk of yield losses at the reproductive stage for many parts of Asia and central North America (Teixeira, Fischer, van Velthuizen, Walter, & Ewert, 2013). Similarly, a study on winter crops in Australia identified the reproductive stage as the most sensitive to climate hazards, explaining up to 88% of yield variability (Shen et al., 2018).

This stream of literature has typically focused on heat stress and to a lesser extent drought, leaving other weather hazards over the crop production cycle under-illuminated. The analysis of the exposure of global harvested areas of rice, maize, soybean, and wheat found that exposure to five days above critical temperatures in the reproductive stage will likely increase globally, from 8% to 27% for rice, from 15% to 44% for maize and from 5% to 18% for wheat from 2000 to 2050 (Gourdji, Sibley, & Lobell, 2013). Simulations of the impact of extreme heat and frost on wheat yields show that frost causes the greatest damage at the reproductive stage, while heat stress tends to affect the grain formation stage (Barlow, Christy, O'Leary, Riffkin, & Nuttall, 2015). In contrast, the heat tolerance of cassava increases its suitability in large parts of Africa under future climate projections although the changing geographic distribution of pests and diseases is likely to bring additional challenges at different crop stages (Jarvis, Ramirez-Villegas, Herrera Campo, & Navarro-Racines, 2012). Other vulnerability mechanisms from the climate modelling literature aligned with our CM concept include precipitation deficits (seasonal droughts) and excess soil moisture. Even small projected changes in the available period of cultivation due to changes in seasonal precipitation and flooding were found to affect the stability and productive capacity of the multiple rice crop system in Vietnam Mekong Delta (Kotera, Nguyen, Sakamoto, Iizumi, & Yokozawa, 2014).

In general, climate science studies highlight the probabilities of unseasonal weather events and their implications on yield. The assessment of probabilities and magnitude of such anomalies can aid in making a timely adjustment and avoid losses (Rosenzweig et al., 2001). The projection of these anomalies is mostly on a large temporal and spatial scale. There is greater uncertainty about when, where and how much these predicted anomalies climate change will manifest (Heltberg et al., 2009). Explanations for crop vulnerability during the crop cycle to individual stresses during different crop stages over a production system scale are seldom explained in climate modelling literature.

2.3.1.2 Agronomy studies

Agronomy research typically uses experiments and modelling to discern cause and effect relationships between weather variables, and fluctuations therein, and crop yields. For most crops, upper and lower thresholds of these variables have been established for different phenological stages (Luo, 2011). Sensitivity at the different stages (time) to levels of stress (magnitude) relates strongly to the CM concept. The effect of different hazards varies with the growth stage of the individual crops concerned. For cereals, the reproductive stage is usually held to be more sensitive to drought and heat than the vegetative stage. Each stress influences the reproductive process differently (Barnabas, Jager, & Feher, 2008), as pollen viability, fertilization and grain formation may be affected (Hatfield et al., 2011).

Similarly, to climate modelling studies, the most reported CMs are temperature-related. Temperature extremes, in the form of either heat stress or cold stress, damage crops differently at different stages (Bhandari et al., 2017). Temperature thresholds, critical months and thresholds for critical crop stages have been studied at the regional level, such as for rice crops in Asia (Wassmann, Jagadish, Sumfleth, et al., 2009). The reproductive stage of rice is considered more sensitive to heat than the vegetative stage, with reduced grain weight in rice due to spikelet sterility (Wassmann, Jagadish, Heuer, et al., 2009). Wheat yields are more affected by heat stress at the early grain-filling stage (Luo, 2011). Experimental studies have further differentiated crop sensitivities to time duration of exposure. Short exposure to high temperatures at anthesis drastically reduces spikelet fertility, which drops from 80% to 20% with a two-hour exposure to 38^0C, and falls to zero if a rice crop is exposed to 41^0C for more than one hour (Yoshida, 1981). Rainfall variability is another hazard often reported for different CMs. Both heavy rainfall and drought at different stages affect germination, weed infestation and insect and disease incidence (Chakraborty & Newton, 2011; Juroszek & von Tiedemann, 2013). Other vulnerability mechanisms aligned with our CM concept are seasonal droughts or excess soil moisture due to heavy rain at different stages in a variety of different crops and regions (Groot et al., 2018; C. Siderius et al., 2016; Van Oort, Timmermans, Meinke, & Van Ittersum, 2012; Wassmann, Jagadish, Sumfleth, et al., 2009). The accumulated impacts of a combination of abiotic stresses like heat and moisture stress are also studied (H. A. Hussain et al., 2019; Sara I. Zandalinas, Mittler, Balfagón, Arbona, & Gómez-Cadenas, 2018). Rains with storms can be particularly damaging and mostly cause lodging that leads to heavy losses for example 60-70% diminishment of yield in wheat (P. M. Berry & Spink, 2012). Agronomy research helps to understand the pathway to loss and quantify the effect of weather stresses on yield by crop stage and tends to be more detailed in its definition of crop vulnerability, but generally does not consider hazard frequency, the effectiveness, and costs of coping and associated vulnerability at crop production system level.

2.3.1.3 Socio-economics studies

The social sciences provide qualitative and quantitative measures to describe risk and risk causation processes (Cutter, 2010; IPCC, 2012). This discipline employs costing and valuation methods to measure the impacts of uncertainties (IPCC, 2001; Prettenthaler, Köberl, & Bird, 2016), and econometric models that integrate long-term weather and crop production variables as well as household survey data to draw conclusions on climate risk management and the impacts of climate hazards on yield stability, farm income, food security and farmers' coping strategies (Ben-Ari & Makowski, 2016; Ma & Maystadt, 2017; Molua, 2011). Many studies explain seasonal level yield variability at large spatial scale employing statistical techniques using time series meteorological and crop yield data (Ray, Gerber, MacDonald, & West, 2015), and correlate these with crop stages (Hlavinka et al., 2009). Hazards related to CMs that are reported in the social science literature tend to be more varied, from heavy rains during planting or harvesting periods, long early season droughts, to warm winters and unusual weather events like hailstorms (Diogo, Reidsma, Schaap, Andree, & Koomen, 2017).

Examples from the socio-economics literature, though fewer, tend to link hazards to more aggregated outcomes like household income. The crop revenues were found to be harmed by extreme heat exposure and the cropped area also declined where an increase in extreme heat was more severe (Burke & Emerick, 2016). The estimates of the impacts do vary when the impact with adaptation is included (Butler & Huybers, 2013). Farmers reduce aggregate input quantity in response to detrimental weather conditions. Weather conditions at different crop stages do not only have a direct effect on production, but also indirectly via reductions in inputs which are not often captured in economic models (Ortiz-Bobea et al., 2021). Farmers growing maize in US cope by reducing aggregate input quantity in response to detrimental weather conditions (Butler & Huybers, 2013). Farmers' knowledge about variability and changes in climate and the perceived risks of extreme events determines their willingness and ability to adapt crop production systems (Abid, Scheffran, Schneider, & Elahi, 2019). Local knowledge about climate hazards and farmers' coping practices is considered a source of relevant adaptation practices (Ogalleh, Vogl, & Hauser, 2013). However, despite the considerable socio-economic literature on farmers' perceived risks of extreme events, focus is largely on ex-ante coping practices, such as planting decisions, or ex-post coping strategies, e.g., in terms of alternate livelihood options, and less on those decision taken during the cropping season (H. Shah, Siderius, et al., 2020).

In terms of specific critical moments, distinct intra-seasonal fluctuations of temperature and soil moisture were identified, with specific emphasis on the risks of extreme cold after planting and high temperatures at maturity in winter varieties of wheat and barley (Gammans, Mérel, & Ortiz-Bobea, 2017; Tack, Lingenfelser, & Jagadish, 2017). Different environmental stressors were found having time-varying effects during different crop stages to crop yields (Ortiz-Bobea et al 2019; Attavanich and McCarl, 2014; (Urban, Roberts, Schlenker, & Lobell, 2012) though most seasonal level effects are still difficult to link to stresses at specific period of crop growth as the time series does not include historical adaptations (Schlenker & Roberts, 2009). Recent studies have investigated the impacts of future climate, biophysical and socio-economic conditions using integrated assessments and scenario analysis from the local to the national level identifying detailed crop-specific CMs (Antle et al., 2015; Roberts, Braun, Sinclair, Lobell, & Schlenker, 2017; Schaap, Blom-Zandstra, Hermans, Meerburg, & Verhagen, 2011; Schaap et al., 2013; van Wijk et al., 2014) with some putting specific emphasis on shifts of growth phases over time (Dalhaus, Musshoff, & Finger, 2018). But generally, little evidence is reported related to specific CMs and associated agronomic costs of coping and the net impact on agricultural livelihoods.

With socio-economic research primarily relating hazards and vulnerability to yield loss, other associated pathways including workability issues, quality concerns, additional cost involved for coping with such hazards during the crop season that contribute to vulnerability, tend to be underreported, the development of weather index based flexible insurance designs, studying the impact of weather hazards during the crop growing period (Conradt, Finger, & Spörri, 2015; Tack, Coble, & Barnett, 2018), being an exception. With increase in the frequency and severity of weather extremes, the costs for adaptation measures were found to strongly reduce gross margins under future scenarios (Mandryk et al., 2017).With increased risks due to climate change and higher losses expected, the cost of insurance is projected to increase (Perry et al., 2020; Tack et al., 2018). The nature of the methods applied – econometric models – would allow for analysis of such associated pathways without the need for full process knowledge or the explicit inclusion of all hazards in process models. It should also be relatively straightforward to assess compound effects through econometric methods.

2.3.2 Integrating hazard occurrence, crop vulnerability and coping; three types of CMs

To derive a time-specific description of the risk and classify different CM we integrated the hazard risk aspect from climate literature and the crop vulnerability findings from agronomic literature with coping strategies as described mostly in socio-economic literature. Considering the direct and indirect impacts of climate hazard and coping possibility during the crop production cycle, three types of CMs are classified, here presented in order of complexity.

2.3.2.1 CM's with Immediate Impact

If a hazard has a direct impact on crop development or required coping strategies have a strong impact on income we define them as Immediate Impact CMs (iCMs). A thick surface crust formed following rain after wheat sowing, can lead to very low or no germination and require re-sowing. In such a case, farmers must bear the extra cost of immediate re-sowing at a time when the availability of seeds is often limited and labor scarce, which drives up costs (Shah et al., 2020). A simplified example of such an iCM is presented in Figure 3A. iCMs can also occur at other crop stages.

Most commonly reported in the literature are temperature related iCMs with increased risk especially at later crop stages (see Table 1 for an overview). High yield losses occur at the reproductive stage in summer legumes (Bhandari et al., 2017), soybean (Salem, Kakani, Koti, & Reddy, 2007), wheat (B. Liu et al., 2014), maize and soybean (Hatfield, Wright-Morton, & Hall, 2018; Teasdale & Cavigelli, 2017) and rice (F. Shah et al., 2011). Heat stress at the grain filling stage of wheat also causes losses, with sudden exposure to higher temperatures more devastating than gradual exposure to heat (Luo, 2011). Losses from such iCMs are inevitable as there is hardly a coping option available after the crop is exposed to heat stress. The second most reported iCMs relate to moisture stress or excess, occurring at different crop stages for different crops. In sorghum in sub-Saharan Africa, germination is often affected, while also during the tillering stage a crop is vulnerable (Hadebe, Modi, & Mabhaudhi, 2017). In the northern Netherlands, dry weather between March and April leads to late or no sowing of seed potato (Schaap et al., 2011). In maize in semi-arid eastern Africa, moisture stress was found to cause up to a 75% yield loss at the flowering stage and 40% at the grain-filling stage (Barron, Rockström, Gichuki, & Hatibu, 2003). Moisture related CMs are more common in rainfed agriculture, as farmers have limited or no coping options and severe yield losses or even crop failure is a likely outcome. Other CMs of the immediate impact type often mentioned, relate to crop lodging due to a windstorm at the maturity stage, e.g. in wheat (P. M. Berry & Spink, 2012; A. N. Shah et al., 2017).

A hazard affects more than just the volumetric yield of a crop; often it also affects yield quality, which can render a crop unmarketable. An iCM may indicate the period of a heightened risk of such a loss of quality of the produce. For example, temperature variability at different crop stages affects not only yield quantity but also quality (Tripathi et al., 2016), as both photosynthesis and enzyme activity are affected (Porter & Gawith, 1999). High daytime and night-time temperatures during the grain-filling stage diminish the quality of rice (Shi et al., 2017). A study of heat stress at the late kernel growth stage in four maize genotypes found that both protein and starch content decreased up to 38% (Mayer, Savin, & Maddonni, 2016). Other examples are potato tubers rotting due to heavy rains (when producing anaerobic conditions for 24 hours or more) and mycotoxins forming in winter wheat due to humid weather at maturity (Schaap et al., 2011).

We define a critical moment not only by a crop's vulnerability at different crop stages. CMs also arise by the lack of affordability or inability to timely respond (due to labor or some other constraint) to avoid yield loss. Along with biophysical impacts, weather hazards disrupt farm management and field workability, causing conflicts in the timing of crucial farm operations and labor allocation. Additional costs incurred due to workability issues often arise from too wet conditions at sowing (Kistner, Kellner, Andresen, Todey, & Morton, 2018) and constraint the use of heavy machinery during harvesting (G. Cooper, McGechan, & Vinten, 1997). The literature provides examples of a number of workability issues such as overly wet or cool weather causing lodging and difficulty in wheat and potato crop management in Europe (Schaap et al., 2011; Trnka et al., 2014; Van Oort et al., 2012), wet conditions constraining the use of heavy machinery in Scotland (G. Cooper et al., 1997) and management, labor and machinery conflicts during maize planting in the central USA (Kucharik, 2006). Similarly, crop lodging due to wind or a storm can cause workability issues, making harvesting operations then more difficult, and taking more time, against increasing cost (P. M. Berry et al., 2004).

A good example of a stock-taking of associated economic impacts of seasonal climate risks is that done for the arable regions of the Netherlands (Schaap et al., 2011; Schaap et al., 2013). Based on economic impacts, major risks – those causing more than €1,000 per hectare losses annually – were heat waves causing secondary growth, warm winter temperatures inducing early sprouting of seed and ware potatoes, and higher temperatures and wet conditions contributing to fungal disease in seed onions. Greater climate variability and unstable weather reduce pesticide efficacy, leading to higher losses (Patterson, Westbrook, Joyce†, Lingren, & Rogasik, 1999). Evidence shows that regionally, too, particular weather conditions can induce disease epidemics and pest outbreaks on a large scale (Rosenzweig et al., 2001). These indirect impacts are difficult to measure, and the associated losses are hardly reported in the literature. The level of loss and coping possibility varies by the time of hazard incidence within the crop production cycle. In the US, the overall impact of hailstorms was found to be lower early in the growing season, even when damage is severe because of the option to replant; hailstorms later, between June and September, can cause losses of $52 million annually (Vorst, 1991). A review on hail influence on maize reported a progressive increase in yield loss from early vegetative to the reproductive stage (Battaglia, Lee, Thomason, Fike, & Sadeghpour, 2019). Most iCMs present a very small time window for adjustments and adaptations and farmers must be capable to invest additional resources (often incurring a higher cost) to prevent yield losses. On the other hand, at early crop stages, farmers foresee the impact, which provide them a larger time window to ameliorate the outcome and give some flexibility to decide between on-farm and off-farm coping options, like temporary work in cities.

Beside yield, weather influences cropping area intensity (Iizumi & Ramankutty, 2015) like a delayed monsoon in Thailand limits water for seedbed preparation which reduces the area planted with rice (Sawano et al., 2008). There is a higher financial impact on farm income if decrease in cropped area is accounted along with other direct and indirect impacts. When a single hazard affects crops via multiple impact pathways this often leads to higher yield and income loss. A dry spell during the reproductive stage of groundnut crop, grown under rainfed conditions in the Pothwar region of Pakistan, causes loss through insect attack (additional cost of insecticide) as well as yield loss due to reduced pegging. Similarly, rice farmers in irrigated plains of Punjab, Pakistan experience losses by insects as well as reduced grain setting due to higher pollen sterility from an exposure to high temperatures at reproductive and grain formation stages (H. Shah, Siderius, et al., 2020).

2.3.2.2 CM's with Compound Impact

Occurrence of two or more hazards, even if moderate, over a single crop cycle increases vulnerability (IPCC, 2012). Compound CMs (cCMs) impacts arise either when one - potentially moderate - hazard is followed by another later in the cropping season (as depicted in in Figure 3B) or when the effect of one hazard at a sensitive crop stage is exacerbated due to the simultaneous interaction with another stress condition. Impacts are exacerbated when the farmer has less capacity to cope with the second hazard- e.g. having spent all finances to coping with the first - or if there is no coping strategy at later crop stages. Several studies have started to examine the probability of multiple hazards within a season. Data from 14 sites representing wheat-producing regions in Europe suggest that the likelihood of two hazards per season doubled under one projected scenario, and rose more than six-fold under the most severe global climate model compared to the baseline and were likely to affect 11 of the 14 sites (Trnka et al., 2014). Another analysis for 379 European sites indicated that every site was prone to the risk of multiple hazards during the wheat production cycle (Hlavinka et al., 2009; Trnka, Hlavinka, & Semenov, 2015). In other regions, increasing probability and intensity of temperature and rainfall extremes have recently been reported as well (Naveendrakumar et al., 2019; Sun et al., 2019; D. u. A. Umar, Ramli, Aris, Jamil, & Aderemi, 2019; K. Xu et al., 2019).

Sequential cCMs originate when a hazard at an early crop stage with lower coping capacity, increases a crop's vulnerability or increases a crop's exposure to a second hazard later in the season. Moisture stress at the sowing stage under rainfed conditions causes delay in wheat sowing and exposes the crop to higher risk of heat stress later in the season. Similarly, a decrease in temperature at sowing stage causes slow germination or may require re-sowing of the wheat crop in high mountains of Pakistan. This delay may expose the wheat crop to higher risks of low temperature later in the season when an early onset of winter can jeopardize a good yield (H. Shah, Siderius, et al., 2020). Other examples of sequential cCMs were reported from Belgium, for winter wheat, barley, potato, sugar beet, maize, and rapeseed. High rainfall with low radiation in spring, moisture and heat stress at grain formation followed by storms at maturity resulted in low wheat yield. Frost in the early season, dry spell in the mid-season and high temperature during the late season resulted in low winter barley yield. Similarly, low maize yields and low winter rapeseed were associated with the combined impact of multiple hazards at different crop stages (Gobin, 2018). An unprecedented wheat crop loss in northern France during 2016 is attributed to a combination of a warm winter followed by wet conditions during spring (Pfleiderer et al., 2021).

Weather hazards occurring simultaneously often create complex CMs due to the extra demand for labour or inputs. Examples are soil moisture stress that exacerbates the effect of heat stress at the reproductive stage (Hatfield et al., 2011) and high humidity alongside high daytime temperatures during the reproductive stage of rice plays a role in increasing spikelet sterility (F. Shah et al., 2011; Wassmann, Jagadish, Sumfleth, et al., 2009). Wheat producing regions across the world are likely to have concurrent heat and moisture stress leading to high yield losses (Mahrookashani, Siebert, Huging, & Ewert, 2017; Mukherjee, Wang, & Promchote, 2019; Qaseem, Qureshi, & Shaheen, 2019; Toreti, Cronie, & Zampieri, 2019), and the compound effect was found to be higher than the additive effect of individual hazards (P. V. V. Prasad, Pisipati, Momcilovic, & Ristic, 2011). Both high and low temperature under moisture stress produces a synergistic effect on the photosynthetic process in wheat in the USA (P. V. V. Prasad et al., 2011). Our review found that high temperatures and drought are the hazards most commonly reported as simultaneously affecting crop growth and yield especially at the reproductive stage. A cCM exists either because the crop is more susceptible (e.g. less well-developed roots) or because coping capacity is reduced (e.g. finances have been exhausted to cope with earlier hazards). In the high mountains of the Hindu Kush Himalayas, low temperatures followed by a frost spell after the wheat crop is planted causes seedling death at germination and it reduces water supply due to low snow melt while the crop at this stage requires irrigation not only for growth but also as a coping strategy to reduce losses from wilting of the crop under low temperature (H. Shah, Siderius, et al., 2020).

The impact is exacerbated as the same hazard limits coping possibility and increases the risk of a second hazard. Multiple hazards can produce conditions conducive for pest and diseases, like high temperature and high humidity near onion maturity causing fungal infection affecting quality and requiring additional costs for chemical protection (Schaap et al., 2011; Schaap et al., 2013). Moisture and heat stress at the grain formation stage also affect the quality and reduces feed value of maize, wheat and barley (Y. Wang & Frei, 2011). A windstorm with heavy rain causes higher crop lodging at later crop stages and higher yield loss along with workability issues (P. M. Berry et al., 2004). Under field conditions the crops responses become complex if multiple stresses occur simultaneously (Suzuki, Rivero, Shulaev, Blumwald, & Mittler, 2014). Multiple hazards can lead to higher income loss. cCMs were found to have a significantly higher impact than the individual CMs (Sara I Zandalinas, Mittler, Balfagón, Arbona, & Gómez-Cadenas, 2018).

2.3.2.3 CM's with Shifted Impact

In regions dominated by integrated multi-cropping systems – i.e. most of the world breadbaskets - the complexity further increases when CMs are defined across crop seasons. A weather hazard during one crop season might have no serious consequences, but it may nonetheless affect yield or lead to conflicts in terms of the allocation of land, finances or labor in producing the following crop, thereby cascading impacts and raising costs. This we classify as a 'shifted impact CM' (sCMs). In most double-crop systems, such sCMs are important (see Figure 3C).

Cascading impacts originate from conflicts in the allocation of land, labor, machinery and other resources in different multi-crop systems. The most reported sCM of this kind is the harvesting season of the first crop, when un-seasonal rains may delay harvesting, pushing back the sowing of the next. This reduces the period available for the necessary farm operations and disrupts the next crop's production cycle, as in multi-crop rice systems in the Mekong Delta (Kotera et al., 2014) and South Asia's rice-wheat cropping systems (Arshad et al., 2017; H. Shah, Siderius, et al., 2020). On the irrigated plains of Punjab, a minor weather hazard like a wind at rice maturity stage or even just modest rain event at rice harvesting makes harvesting and threshing operation difficult causing higher cost as well as delay in wheat sowing, causing an estimated 8-18% yield loss in the following wheat crop (H. Shah, Siderius, et al., 2020). Other studies of the rice-wheat growing region of South Asia found that in Indian Punjab, a delay in rice harvesting due to weather or management issues and resultant late sowing of wheat led to yield losses of 0.7-0.8% per day of the delay after 15 November (Ortiz-Monasterio, Dhillon, & Fischer, 1994) or an average decrease the potential wheat yield by up to 1 ton per hectare (P. Aggarwal, Talukdar, & Mall, 2000). In the wheat-maize system in the northern mountains of Pakistan, rainfall and/or low temperatures cause a delay in wheat maturity resulting in a delay in wheat harvesting (H. Shah, Siderius, et al., 2020). This pushes maize sowing back with an early onset of the winter season affecting its grain formation so that farmers can only use it as fodder.

A focus on CMs can reveal more tentative links between the moment of the initial hazard and the final impact: In the rice-wheat cropping system of Pakistan, H. Shah, Siderius, et al. (2020) found that a '*Jhakar'* (storm) immediately after the rice transplanting, before the seedling is fully rooted, often results in complete or partial uprooting. As a coping option, framers need to arrange labour and replacement seedlings immediately to fill the gaps, but often there are delays with many agricultural activities competing for labour and the widespread nature of the event leading to a lack of seedlings in nurseries nearby. Even if full re-transplanting can be avoided, the use of seedlings of different age or variety results in differential ripening which affects the quality at harvesting and often pushes the harvesting date backwards, thereby affecting the time available to plant the subsequent wheat crop. This again increases risk of heat exposure later in the season.

Summarizing across the literature evaluated, we found the reproductive stage most often reported as high risk, especially for iCM, with heat and moisture stresses the major hazards and wheat the most studied crop (see also Table 1). CMs during early growth stages are also relatively often reported, especially among cCM and sCMs, with a variety of coping options still feasible at this stage. In terms of complexity, most CMs studied were of the immediate impact type, followed by the compound type. The geographic spread indicates the more complex CMs with shifted impacts are only reported in few, often related studies from Europe and to a lesser extent mentioned in studies focussing on South and East Asia (Figure 4). We found few CMs examples from South America and Africa in the literature. We also found few specific studies on the Middle East and Central Asia region, but because wheat is one of the major crops here, and with many global modelling studies focussing on wheat, the region is partly covered by the global count. The global count, with global coverage of climate variability hazards includes mainly studies on wheat crop.

Figure 4. Geographic distribution of the sample literature by type of CM. ‘Global’ CMs refer to global studies that report mostly on a crop level.

Table 1. Summary of different types of CMs from the examined literature

Type of CM	Hazard	Time period/crop stage & pathways	Coping practice
Immediate Impact CM	Dry/wet season	Sowing: Workability, cost, short season, loss of seed vigour	Late sowing, Potato, Netherlands (Schaap et al., 2011); NA, Potato, (Van Oort et al., 2012)
	Low temperature	Germination: Seedling death due to frost or advanced senescence	NA ('Not Applicable' for reported CM for which no coping is specified), Wheat (Barlow et al., 2015); Delayed planting, wheat, Australia (Fuller, Fuller, Kaniouras, Christophers, & Fredericks, 2007)
	Low temperature T. extremes	Germination: Root damage	Early sowing, Wheat, Netherlands (Schaap et al., 2011; Schaap et al., 2013)
		Germination: Seedling death	NA, Wheat (Barlow et al., 2015); Food legumes, (Bhandari et al., 2017), NA, Food legumes, (Bhandari et al., 2017); Wheat, (Porter & Gawith, 1999)
		Vegetative: Leaf damage, soil-borne diseases	NA, Wheat (Barlow et al., 2015); Food legumes, (Bhandari et al., 2017)
		Vegetative: Stunted growth, diseases	NA, Food legumes, (Bhandari et al., 2017); Wheat, (Porter & Gawith, 1999)
	Wind, rain	Vegetative to maturity: Lodging, more time and cost to harvest, quality issue	Planting method, date of sowing (DoS), Plant population, nutrient & disease management, Cereals, (Rajkumara, 2008); Seeding rate (SR), adjust DoS, tillage & fertilizer, Cereals, (A. N. Shah et al., 2017); Rice, Japan (Ishimaru et al., 2008)
	High temperature, Heat stress, T. extremes	Reproductive: Yield and quality loss	Change of variety (CoV), Soybean, USA (Salem et al., 2007); NA, Wheat, (Nuttall et al., 2017)
		Maturity/ Ripening (lodging, yield & quality loss)	NA, Canola, Canada, (Wu & Ma, 2018); NA, Canola, Canada, (Wu & Ma, 2018)
		Reproductive: low yield	CoV, DoS; Wheat, maize, rice and soybean, Asia and Central North America (Teixeira et al., 2013); Maize and rice, (Gourdji et al., 2013); irrigation during flowering; Rice & Wheat in Pakistan (Arshad et al., 2018); (Arshad et al., 2017); NA, Rainfed maize, USA (Lobell et al., 2013)
		Reproductive and grain formation: small grains, affect the composition of protein and starch (quality), higher probability, forced maturity	CoV; Wheat, (Luo, 2011); Indus delta (G Rasul et al., 2012); NA, Maize, Argentina (Mayer et al., 2016)
			Changing DoS, Wheat, China (B. Liu et al., 2014); Heat tolerant variety (HTV), shifting DoS, seasonal weather forecasts, direct drill seeding; Rice, S. Asia, (Wassmann, Jagadish, Sumfleth, et al., 2009); HTV (Stratonovitch & Semenov, 2015)
		Reproductive (grain filling): higher probability & variability, sterility, grain shrivelling, affect quantity and quality, pest and diseases, yield and quality	CoV, change DoS, IPM; Maize, sorghum, cotton, rice, bean, soybean and wheat, (Hatfield et al., 2011); weather forecast, intercropping, shift and adjust management practices, IPM; Wheat, rice, maize, (Tripathi et al., 2016); NA, Legumes, maize, rice, (Luo, 2011); Cereals, (Hatfield et al., 2011); Wheat, (Porter & Gawith, 1999); Wheat, rice, maize, (Tripathi et al., 2016); Crops, USA (Wienhold, Vigil, Hendrickson, & Derner, 2018); Food legumes, (Bhandari et al., 2017); Rice, Philippines (Shi et al., 2017); Wheat, (Barlow et al., 2015); Wheat, (Porter & Gawith, 1999); Winter crops, Australia (Shen et al., 2018)
	Heavy rains	Vegetative: Submergence	Drainage, rainfed rice, Bangladesh, (Wassmann, Jagadish, Sumfleth, et al., 2009)

Type of CM	Hazard	Time period/crop stage & pathways	Coping practice
	Less rain (Dry spell)	Vegetative: Poor crop establishment	Supplement irrigation, Onion, Netherlands (Schaap et al., 2011; Schaap et al., 2013): Partial irrigation, and shift DoS, drought tolerant variety (DTV), soil and water saving tillage, crops, Czech Republic (Hlavinka et al., 2009); DTV Aman rice; Rainfed rice in Bangladesh, (Wassmann, Jagadish, Sumfleth, et al., 2009); nutrient and pest management, maize and soybean, USA (Teasdale & Cavigelli, 2017)
		Reproductive & Grain filling: higher dry spell probabilities, most sensitive stage, reduction in the rate of net photosynthesis, and poor grain set and grain development	Improved field water management strategies, water harvesting, Maize, Africa (Barron et al., 2003); HEIS, Maize, (Tripathi et al., 2016); DoS, conservation agriculture, Grain legumes, Tropics (Farooq et al., 2017); DoS, DTV and fertilizer inputs, wheat, Global (S. Asseng et al., 2014)
	Unseasonal rain (heavy rains) Hailstorm	Maturity/harvesting: Anaerobic condition rotting, Pre-harvest sprouting, quality, and value, wet fields, workability, cost, delay harvest, soil compaction, rotting of tubers, no harvest	Drainage, Potato, Early planting and harvesting, Netherlands (Schaap et al., 2011; Schaap et al., 2013); NA, White wheat Australia, South Africa, Canada, Central Asia and Europe (Biddulph, Plummer, Setter, & Mares, 2008); Weather forecast, Sugarcane, Swaziland (Mhlanga-Ndlovu & Nhamo, 2017)
		Maturity/harvesting, pest and disease,	Early harvesting of maize and peanut, Senegal (Roudier et al., 2014).
		Different stages: Stand reduction and defoliation	Replanting at early growing season, row spacing, Maize, USA (Battaglia et al., 2019; Vorst, 1991);
Compound Impact CM	High temperature at early crop stages	Sowing and germination: delay sowing, poor growth, reduced tillering, dry weight, exposure to stress at later stages	Change date of sowing (DoS), Wheat, (Porter & Gawith, 1999); Wheat S. Asia, (Wassmann, Jagadish, Sumfleth, et al., 2009); (M. V. Sivakumar & Stefanski, 2011); DoS, cold storage for seed, Potato, Netherlands (Schaap et al., 2011; Schaap et al., 2013); Supplement irrigation, Rice, (F. Shah et al., 2011); HTV, Rice, Asia, (Wassmann, Jagadish, Heuer, et al., 2009)
	Unseasonal rain (Wet or dry)	Sowing/transplanting; higher probability of exposure to extreme events later in the season	DoS; Potato, the Netherlands (Van Oort et al., 2012); adjust DoS with rain, Rice, North-east Thailand (Sawano et al., 2008); delayed transplanting; Rice, Indonesia- (Rosenzweig et al., 2001)
	Moisture & frost	Germination: delay sowing, poor crop establishment (frost)	Early sowing with supplemental irrigation; Wheat, Turkey, (Ilbeyi, Ustun, Oweis, Pala, & Benli, 2006)
	Humidity & high night temperature	Reproductive: sterility	HTV, DoS, and exogenous application of plant hormones, Rice-review (F. Shah et al., 2011)
	Low rain and frost Moisture and heat stress High humidity (rain), wind	Reproductive & grain filling; sterility, low yield, Pest outbreak, high cost, Synergistic effect on the photosynthetic process of both high and low temperature under moisture stress, exacerbate the adverse effect of high temperature, The combined effects of high temperature and drought were greater than additive effects for leaf chlorophyll content, grain numbers and harvest index in wheat	Cross stress tolerant varieties, wheat, USA (N. H. Shah & Paulsen, 2003); NA wheat USA (P. V. V. Prasad et al., 2011);wheat and maize, (Suzuki et al., 2014);.NA Barley Germany (Rollins et al., 2013), Lentil, India, (Sehgal et al., 2017); Wheat, Germany (Mahrookashani et al., 2017); Insecticide; Soybean, USA (Rosenzweig et al., 2001); reduced tillage, mulching & weed control; Corn & soybean, USA (Teasdale & Cavigelli, 2017); no specific coping recommended (NA), Maize, USA (Hatfield et al., 2018); Cereals, (Y. Wang & Frei, 2011); Maize, USA (Westcott, Hollinger, & Kunkel, 2005); Cereals, (Barnabas et al., 2008); Perennial grass, China, Improvement in thermotolerance by genetic methods (Z. Z. Xu & Zhou, 2006).
	Moisture extreme & frost/heat/wind	Reproductive: Pollen viability	NA, Rice, (Tripathi et al., 2016); Japan, (Matsui, Kobayasi, Kagata, & Horie, 2005)
		Reproductive: Lodging	NA, Cereals, (P. M. Berry et al., 2004); NA,, Wheat, UK (P. Berry et al., 1998)

Type of CM	Hazard	Time period/crop stage & pathways	Coping practice
	High temperature and humidity heavy rain (wet)	Reproductive: Spikelet sterility	Adjustment of DoS, choice of varieties, and exogenous application of plant hormones; Rice, (Wassmann, Jagadish, Heuer, et al., 2009); (F. Shah et al., 2011); NA, rice China (Yan et al., 2010)
		Early crop stages and later (reproductive to maturity) stages yield loss	NA, wheat, France unprecedented yield loss (Pfleiderer et al., 2021)
		Maturity: Fungi infection	Chemical protection, Seed onion, Netherlands (Schaap et al., 2011; Schaap et al., 2013);
	Wind & rain	Different stages: Disease, lodging, management issues, pests and pathogen, mycotoxin with rains, quality issues,	Early ripening cultivar; wheat, Europe (Trnka et al., 2014); pesticide; Brazil, Uruguay, Argentina and the UK; Crops, (Chakraborty & Newton, 2011); NA; Arable crops, Europe, (Trnka et al., 2015)
	Multiple stresses (different stages)	Different stages: Decrease in gross margins & total NPV	NA, Seed onion, potato, wheat and sugar beet, Netherlands (Mandryk et al., 2017); Arable farming, Netherlands (Diogo et al., 2017)
	Unseasonal rain & storm	Harvesting (rice), Sowing/grain formation (wheat): wet field, lodging, workability heat stress	Adjusting DoS, weather forecast, crop insurance, No till for early wheat sowing, Short duration rice varieties; Rice-Wheat system, S. Asia, (Wassmann, Jagadish, Sumfleth, et al., 2009); (Arshad et al., 2017)
	Unseasonal rain & storm & high temperature	Early stages: affecting the cropped area & cropping intensity	NA, Crops, (Iizumi & Ramankutty, 2015); Seasonal forecast, Philippine (Koide et al., 2013), NA Rice, Vietnam (Kotera et al., 2014)
		Grain formation & harvesting: Tuber bulking stage. Heat stress in both rice and wheat in rice wheat system	Supplement irrigation on well-drained soil, Potato, US (Woli & Hoogenboom, 2018); Short cycle cultivars, early rice harvesting and wheat sowing varieties (Arshad et al., 2018)
Shifted impact	Heavy rain	Harvesting, Wet field, workability issue for harvesting & land preparation, higher cost, quality loss, delay sowing of next crop, heat stress in wheat	NA, Wheat, Netherlands (Schaap et al., 2011); Early sowing & harvesting, Potato, Netherlands (Van Oort et al., 2012); Drainage (rice filed), early wheat sowing by surface seeding with weed control (Krupnik et al., 2015)
	Unseasonal rain	Sowing and harvesting: workability issues and delay in sowing and harvesting operations, which narrows the time for maturity and harvesting	Adjusting sowing and harvesting dates, preparation of planting beds, Potato Netherlands, (Schaap et al., 2011; Schaap et al., 2013): Weather forecast, Sugarcane, Swaziland (Mhlanga-Ndlovu & Nhamo, 2017); Early sowing with ZT drill, rapid rice harvesting, Rice & Wheat in Pakistan (Arshad et al., 2018); NA, rice Philippine (Sawano et al., 2008)

NA=Not applicable where no coping is specified; DoS=Date of sowing; DTV=Drought tolerant variety, HEIS=High efficiency irrigation system; HTV=Heat tolerant variety; SR=Seed rate; CoV=Change of variety

2.4 Discussion and conclusions

Three types of critical moments, periods of heightened risk during the year when farm households are vulnerable to specific climate hazards, were defined and illustrated by examples from three streams of literature. Existing literature tends to focus on individual hazards or vulnerabilities; reported risk is high at early crop stages, when access to additional resources to cope with hazards is often limited, and during the reproductive stage with many studies focussing on heat stress in wheat. Relatively little evidence exists on CMs due to compound or shifted impacts, despite the fact that an increasing number of people rely on crops grown in regions with high cropping intensities (Iizumi & Ramankutty, 2015; Liu, Li, & Waddington, 2014; Christian Siderius et al., 2016; Siebert, Portmann, & Döll, 2010), often in climate change hotspots (De Souza et al., 2015).

Differentiation of CMs can help to distinguish suitable coping mechanisms to ameliorate in-season losses, or to improve the livelihoods of vulnerable households by alternative means if in-season coping fails. As a framework, the concept of CMs is closely aligned with IPCCs definition of risk as a function of hazard, vulnerability and exposure (IPCC, 2012). While this definition is well known, our literature reviews shows scientific application tends to skew to one dimension depending on the research domain, with climate modelling focussing mostly on hazards, agronomy research on crop vulnerability and socio-economic research, sometimes including coping aspects.

To apply the CM concept, we consider three key recommendations: First, our findings point to the importance of integrating different disciplines to look at the vulnerability of agriculture in a holistic manner. General recommendations like ‘adjust sowing time’ or ‘use short-season varieties’ or ‘shift to some other crop’, made at the crop level and based on changes in mean temperature and/or precipitation, ignore in-season variability and overlook the limited flexibility farmers have once the crop is planted or even planned. Resource constraints in developing countries are often aggravated by the short time window to respond (H. Shah, Siderius, et al., 2020). Impact assessments should include coping complexities with respect to time limits and associated additional costs.

Second, take into account compound risks as climate change increases the likelihood of hazards occurring during the same crop season, if not at the same time (IPCC, 2021). The increase in frequency of extreme events, projected ten years ago by the IPCC (2012) is already being felt by farmers, especially those that farm at the margin (H. A. Hussain et al., 2019; Qaseem et al., 2019). To facilitate awareness and a better recognition of CMs, surveys design could be improved such that questions explicitly address the combination of crop vulnerability – hazard – coping strategies and their timing. Inclusion of all possible combinations could lead to a multitude of reported CM for any given cropping system. Often, however, farmers are well able to identify those CMs most relevant to them. In a study of 273 farm households for four cropping systems in Pakistan (H. Shah, Siderius, et al., 2020), farmers identified 61 CMs at different crop stages, from pre-sowing to harvesting, but classified six as most problematic due to the compound and shifted impacts. Given the importance of food production, a consorted effort to identify the most relevant CMs, for dominant cropping systems in the most important food producing regions is warranted and would improve initiatives such as the Agricultural Model Inter-comparison and Improvement Project (Antle et al., 2015).

Third, assess the intensity of the cropping system and the duration between crops in rotation to appreciate the likelihood of cascading effects. Land and operational conflicts between crops in double-cropping systems that may arise under increasing climate variability need to be identified. The shifted impact CM also helps to characterize impacts in a connected system. (H. Shah, Siderius, et al., 2020) show detailed conflicts in land and labour allocation, leading to workability issues affecting both crops in double cropping systems for various cropping systems. These cascading effects can extend beyond agriculture. For instance to the severe deterioration of air quality in South Asia, attributed in part to stubble burning farmers, has been linked to energy saving regulation at the start of the rice crop season, prohibiting farmers to use ground water before the monsoon. This forces farmers to delay the transplanting of rice and shortens the time available to prepare the land for the consecutive wheat crop (Mukherji, 2019). In order to anticipate and assess these risks, hydrology-crop and land surface models, meanwhile, should be improved to simulate multi-cropping (Hester Biemans & Siderius, 2019; Mathison et al., 2021).

More practically, the CM perspective could contribute to user-relevant climate risk metrics and climate services such as the development of vulnerability maps integrating weather forecasts with crop stage sensitivities and coping options. Climate services can provide farmers timely information on changing planting times that will not coincide with periods of risk (heavy rains, heat waves etc) at a sensitive crop stage and extension services can train farmers in best risk management practices keeping in view the possibility and potential of coping options considering pathways to loss by type of hazard and array of losses. The analysis of CM can also support the insurance services in improving flexible weather-based index insurance design by capturing the hazards occurrence dates along the progress and shift of critical plant growth phases over time and space. Considering losses by hazards pathways could further reduce farmers' downside risk exposure (Conradt et al., 2015; Dalhaus et al., 2018).

Climate change will exacerbate existing risks, cascading potentially across multiple cropping systems, sectors and even regions *(Shukla et al., 2019).* Extreme events may offset any positive impacts of mean climate change on farm economic performance and are expected to substantially undermine the future economic viability of crop farming (Diogo et al., 2017), with crop profitability varying significantly by climate hazard (Molua, 2011) and farmers' capacity to adapt to ameliorate yield loss (Moore & Lobell, 2014). A better understanding of climate risks through CMs can support the development of robust national and regional agricultural policies. To scale up from the farm level to the crop production system level, CMs could be integrated with scenario analysis and vulnerability threshold approaches (Diogo et al., 2017; Kwadijk et al., 2010; Wilby & Dessai, 2010). The diversity of climate risks needs an array of coping responses which are interdisciplinary in nature. The analysis of CMs can help target policy interventions and contribute to a diagnostic and planning framework to determine institutional fit for coping and adaptation responses and to complement climate services for the rural farm sector (Cuevas, Peterson, & Morrison, 2014).

We argue that the identification of CMs under future projections would provide useful insights to inform risk management decisions and promote successful adaptation for sustainable crop production. Strategies proposed to deal with shifting and changing hazards range from reducing crop vulnerability through genetic improvement and other breeding approaches (Barlow et al., 2015; Bhandari et al., 2017) to seasonal and short-term weather forecasts (Mhlanga-Ndlovu & Nhamo, 2017) and a better understanding of CMs to support planning (Iizumi & Ramankutty, 2015) (see also Annex-1B). However, additional costs associated with each of these measures will reduce gross margins (Mandryk et al., 2017) and cropping systems and regions with poor economic performance will remain vulnerable (Diogo et al., 2017). Even at present, the capacity to implement improvements is often limited (Christian Siderius et al., 2021; Thamo et al., 2017). These challenges require coordination between science, policy and practice and interdisciplinary engagements to identify, develop and promote effective coping and adaptation technologies and user-relevant support mechanisms to reduce vulnerabilities specific to particular places and moments.

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Annexures

Annex 1A. Inclusion and exclusion criteria, and methods for searching literature

No.	Documents included dealing with ...	Documents excluded dealing with ...
1.	Analytical relevance - Climate and weather - Temperature (min/ max, day/night, intra-seasonal, intra-annual, by crop stage, heat stress, consecutive min/max temperature) - Rainfall (intra-seasonal/intra-annual precipitation variability, variability in runoff for supplemental irrigation, seasonal drought/flooding) - Trends and variability (probability of occurrence) of rain, temperature, change in intensity	Analytical relevance - Climate and weather - Mean climate changes - Climate variability not specific to crop stage - Non-climate drivers - Inter-annual and long-term trends with no indication or discussion of intra-annual weather changes
2.	Theoretical perspective and methods used - Climate models (top-down, projection of weather variability (intra-annual) and discussion of seasonal changes or changes in a certain crop stage) - Crop simulation models focusing on a stressor(s) at a certain crop stage or stages - Agronomy (field trial identifying stress level at a specific time and associated yield risk) - Vulnerability (bottom-up field level studies measuring crop-related impacts at farm, household or community level; discussion of level of losses, changes in practices and conflicts in crop management practices due to weather or variability during the crop season) - Econometric models (analysing impacts of variations in weather variables by crop stage, biophysical factors, perceptions and field experiences) - Direct (changes in yield) and indirect impact (change in insects, pests, etc.) on crops due to weather variability - Positive or negative impacts on yield	Theoretical perspective and methods used - Climate models (top-down, projection of inter-annual and decadal variability in general, no discussion of crop stage or discussion linked to non-crop sector) - Crop simulation models (not focused on individual hazard to crops at specific time) - Agronomy (not focused on climate and weather variability) - Vulnerability (bottom-up field level studies measuring impacts other than crop at household or community level) - Econometric models (analysing impact not specific to crops at seasonal level) - Long-term shifts in cropping system or management practices due to shift in mean climate conditions - Market and price impacts, even due to weather variability at certain crop stage - Vulnerability to extremes
3.	Type of studies - Peer reviewed journal article - Book chapters, research reports, doctoral theses, institutional technical reports (IPCC, World Bank, FAO, CGIAR and other research institutes)	Type of studies - Non-peer reviewed journal article - Reports from non-research organizations, NGOs and newspaper articles
4.	- Spread -Global (regional, country, zone, field level)	
5.	Language : English	Language: Non-English
6.	Time period published - 1985 and onward	Time period published - Before 1985
7.	Coverage - Crops in general, wheat, rice & maize in particular	Coverage - Other than crops,

Method: We searched for and screened the relevant literature using keywords, phrases, Boolean and proximity operators, consulting different databases including the Web of Science, EBSCOhost and Ovid. The snowball technique was used to identify further literature on specific aspects like crop stage, hail, workability, etc. The relevant literature was reviewed focusing on garnering evidence on the concept of CM, synthesis of examples for different types of CMs and associated factors other than yield that lead to vulnerability.

Annex 1B. Summary of different types of CMs and general recommendation from the examined literature

Type of CM	Hazard	Time period/crop stage & pathways	General recommendations proposed to deal with shifting and changing CMs
Immediate Impact CM	Dry/wet season	Sowing: Workability issue, cost, late sowing & shorter growing season, seed potato vigour loss	Identify key climate risks to production using long term crop and weather observations; The Netherlands (Van Oort et al., 2012); Risk assessment using Agro-climate calendar by crop stage (Schaap et al., 2011)
	Low temperature	Germination: Frost, seedling death or advanced senescence	Greater understanding required for impacts of extreme by duration and compound impact of heat/frost interaction with other abiotic stresses (moisture stress), Wheat- review, (Barlow et al., 2015)
	Low temperature T. extremes	Vegetative: Seedling survival, leaf damage, soil-borne diseases, poor crop establishment	Genetic improvement, Wheat, (Barlow et al., 2015); Agronomic and breeding approaches, Food legumes, (Bhandari et al., 2017); Chickpea, Inclusion of heat tolerant genes in varieties for warmer areas (Devasirvatham et al., 2013)
		Vegetative: Seedling death, stunted growth, increased susceptibility to diseases, Heat/chilling shock in broad bean reduce growth and quality	Improved breeding and agronomic management, Food legumes, (Bhandari et al., 2017); Broad bean, heat/chilling shock (Hamada, 2001); Full impact require assessment of combine & multiple impacts over crop season; Wheat, (Porter & Gawith, 1999)
	High temperature, Heat stress, T. extremes	Reproductive: Yield and quality loss (protein concentration decreases),	Predictive capability of crop models to incorporate grain quality for adaptation strategies; Wheat, (Nuttall et al., 2017);
		Maturity/ Ripening (lodging, yield & quality loss)	Lodging resistance variety through breeding, selection for a root system with high anchorage strength; Canola, Canada, (Wu & Ma, 2018)
		Reproductive: low yield	Improve crop management; Rainfed maize, USA (Lobell et al., 2013); Develop heat tolerant varieties; Rice, South Asia, (Wassmann, Jagadish, Heuer, et al., 2009)
		Reproductive and grain filling: low yield, affect composition of protein and starch (quality),	Further studies on quality and chemical changes; Maize- Argentina (Mayer et al., 2016); Develop short duration stress tolerant varieties; Wheat, Indus delta (G Rasul et al., 2012)
		Reproductive and maturity: Higher probability, forced maturity	Quantify future impacts, after heading tolerant varieties, cultivars with earlier heading; Wheat, China (B. Liu et al., 2014); Geo-spatial vulnerability assessments for targeted adaptation, Rice, S. Asia, (Wassmann, Jagadish, Sumfleth, et al., 2009)
		Reproductive (grain filling): higher probability & variability, sterility, grain shrivelling, affect quantity and quality, pest and diseases, yield and quality, in chickpea abortion of flowers, pods and impaired seed filling in chickpea	Quantify probabilities of extreme events; Legumes, maize, rice, (Luo, 2011); Coupling physiological responses with genetic traits; Maize, sorghum, cotton, rice, bean, soybean and wheat, (Hatfield et al., 2011); kidney bean, USA ,(P. V. Vara Prasad, Boote, Allen Jr, & Thomas, 2002), Cotton, USA, Short period stress tolerant varieties (Reddy, Hodges, & Reddy, 1992) Explicit modelling for impact on grain formation stage; Wheat, (Porter & Gawith, 1999); Genetic improvement; Wheat, rice, maize, (Tripathi et al., 2016); Genetic improvement, land use changes and water management, Crops, USA (Wienhold et al., 2018); Genetic selection & improvement; Food legumes, (Bhandari et al., 2017); Chickpea, sucrose mobilization and its utilization in the seeds for developing cold tolerance (Kaur, Kumar, Nayyar, & Upadhyaya, 2008), Rice, Philippines (Shi et al., 2017); Incorporation of time of exposure

Type of CM	Hazard	Time period/crop stage & pathways	General recommendations proposed to deal with shifting and changing CMs
			in the yield impact model; Wheat, (Barlow et al., 2015); Identification of heat tolerant varieties (Talukder et al., 2010); Research on combined effect of extreme events on grain set; wheat, (Porter & Gawith, 1999); Early warning system; Winter crops, Australia (Shen et al., 2018)
	Heavy rains	Vegetative (Submergence)	Submergence-tolerance traits, rainfed rice, Bangladesh, (Wassmann, Jagadish, Sumfleth, et al., 2009)
	Wind & rain	Vegetative to maturity, lodging	Planting density and method, fertilizer use and genotype affects lodging, wheat, Ireland (Easson, White, & Pickles, 1993)
	Less rain (Dry spell)	Reproductive & Grain filling: higher dry spell probabilities, most sensitive stage, reduction in the rate of net photosynthesis, and poor grain set and grain development	Development of appropriate cultivars, Grain legumes, arid and semiarid tropics (Farooq et al., 2017)
	Unseasonal rain (heavy rains) Hailstorm	Maturity/harvesting: Anaerobic condition rotting, Pre-harvest sprouting, quality and value, wet fields, workability, cost, delay harvest, soil compaction, rotting of tubers, no harvest	Increase permeability of sub-soil and drainage, Potato Netherlands (Schaap et al., 2011; Schaap et al., 2013); Improve pre-harvest sprouting tolerance in cultivars, White wheat Australia, South Africa, Canada, Central Asia and Europe (Biddulph et al., 2008); Weather forecast, Sugarcane, Swaziland (Mhlanga-Ndlovu & Nhamo, 2017); Identify key seasonal climate risks, Potato, The Netherlands (Van Oort et al., 2012)
Compound Impact CM	Unseasonal rain (Wet or dry season)	Sowing/transplanting; higher probability of exposure to extreme events later in the season	Develop yield prediction model combining crop calendar model with crop growth model as a function of water availability; Rice, North-east Thailand (Sawano et al., 2008)
	Low rain and frost Moisture and heat stress High humidity (rain), wind	Reproductive & grain filling, sterility, low yield, Pest outbreak (two spotted spider mites on soybean), high cost, Synergistic effect on photosynthetic process of both high or low temperature under moisture stress, feed value	Innovative strategies through coordinated efforts of geneticists, agronomists, and agricultural meteorologists, Maize, USA (Hatfield et al., 2018); Cereals, (Y. Wang & Frei, 2011); Location specific response crop climate models, projections based crop movement to future higher production regions; Maize, USA (Westcott et al., 2005); Breed improvement using genetic maps based on molecular marker, expression profiling for interactive tolerance, proteomic studies and genomic approaches along with field evaluation; Cereals, (Barnabas et al., 2008); Wheat varieties resistant to high temperature Wheat, USA (N. H. Shah & Paulsen, 2003)
	Low rain & frost Moisture & heat stress High humidity (rain) & wind	Reproductive: viability of pollination	Identify morphological traits associated with tolerance to stress, stress tolerant varieties, Rice, (Tripathi et al., 2016); (Matsui et al., 2005);
		Reproductive: Lodging	Strengthening the stem and the anchorage system by exploiting the wide genetic variation in plant characters and through crop management decisions, Cereals, (P. M. Berry et al., 2004);
	High temperature and humidity	Reproductive: spikelet sterility	Target breeding environments into hot and humid versus hot and dry zones and tailor the selection protocols Rice, (Wassmann, Jagadish, Heuer, et al., 2009); (F. Shah et al., 2011);
	Wind & rain	Different stages: increase in risk, disease, lodging, management issues, pests and pathogen, disease due	Extreme probability based planning, impact analyses with multiple extremes; wheat, Europe (Trnka et al., 2014); Crop stage and region-specific strategies; Arable crops, Europe, (Trnka et al., 2015);

Type of CM	Hazard	Time period/crop stage & pathways	General recommendations proposed to deal with shifting and changing CMs
		to moisture stress, mycotoxin with rains, post production quality issues	incorporating heterogeneity into crop and risk mitigation processes, deploying cultivars multiple resistance genes; Crops, Brazil, Uruguay, Argentina and the UK; (Chakraborty & Newton, 2011)
	Two moderate extremes (different stages)	Different stages: Higher frequency, decrease in gross margins & total NPV, threaten future economic viability of Dutch arable farming)	Crop and farm (diversification) targeting farm economics considering; Seed onion, potato, wheat and sugar beet Flevoland, the Netherlands (Mandryk et al., 2017); Scenario based prioritising adaptation strategies; Arable farming, the Netherlands (Diogo et al., 2017)
	Unseasonal rain & storm Extreme weather events	Harvesting (rice), sowing/grain formation (wheat): wet field, land preparation, sowing, heat stress	Development of early maturing rice and heat tolerant wheat varieties (Krupnik et al., 2015)
		Different stages - Crop area & intensity	Impact assessment for less studied extreme weather events on crop area, intensity, and production, changes in the work calendar and field workability considering farmer responses within different economic conditions and access to technology for developing climate-resilient crop production systems; Crops, (Iizumi & Ramankutty, 2015)
Shifted impact	Heavy rain	Harvesting (Wet field – inability to harvest, workability issue, higher cost, quality loss)	Maintain good soil quality & structure matters, Wheat-Netherlands (Schaap et al., 2011);

Chapter 3

This chapter is based on: Shah, H., Siderius, C., & Hellegers, P. 2020. Cost and Effectiveness of In-season Strategies for Coping with Weather Variability in Pakistan's Agriculture. *Agricultural Systems, 178*, 102746. https://doi.org/10.1016/j.agsy.2019.102746

3. Cost and effectiveness of in-season strategies for coping with weather variability in Pakistan's agriculture

Crops are vulnerable to weather hazards throughout the growth season, with periods of heightened risk described as critical moments. Farmers have a number of ex-ante and in-season options for coping with these events, and ex-post adjustments to farm-household portfolios to further limit the impact on livelihoods if these options fail. Adaptation-related research has focussed mainly on ex-ante or ex-post coping strategies, because in-season approaches tend to be seen as a given, meaning their cost effectiveness is ignored. Based on detailed survey data collected from 287 households in four of the main cropping systems in Pakistan, this study evaluates the impact pathways of hazards and the cost effectiveness of in-season coping strategies. Yield losses varied by 10–30% for 43% of the cases and by 31–50% for another 39%, with the most severe losses caused by the compounding effect of two hazards in one crop season or if both crops in a multi-crop rotation were affected simultaneously. In-season coping options were mostly restricted to the early crop stages and constrained by a short window of time for the response. The application of in-season coping strategies resulted in a yield recovery of 40–95%, with an additional cost of 4-34% of the value of recovered yield. The major critical moments identified were the harvest season, with farming often affected by un-seasonal precipitation, and the germination stage, with an additional high risk for low temperatures at high altitude. A better understanding of the differentiated risks and effectiveness of in-season coping strategies could support the promotion of sustainable crop production in similar agro-ecologies. Moreover, the effectiveness of present-day coping strategies, rather than the use of coping approaches itself, could signal a potential ability to adjust to future climate change.

3.1 Introduction

Crop production is an uncertain business, particularly for the poor (Clarke, 2016; Dercon, 2005). Any departure from optimum growing conditions, such as too much or too little rainfall, too high or too low temperatures, increased cloudiness or sudden wind or hailstorms, can affect crop yields in both rainfed and irrigated conditions (Bhatta & Aggarwal, 2016; Gobin, 2018; Hatfield et al., 2018; Hollinger & Angel, 2009). The timing of weather hazards is important; while strong winds might not matter during the development states of a crop, it can lodge a full-grown crop close to harvesting, leading to severe yield loss. Similarly, a mature crop with a well-developed root system might cope with a period of drought that would wilt a small seedling. Critical moments (CMs) are periods of heightened risk within the production season, when crops are more sensitive to certain weather conditions, whether biophysically or due to management or operational constraints (H. Shah, Hellegers, & Siderius, 2021).

Farmers have developed a variety of ways to cope with weather variability. Three generalised types of coping approach can be distinguished; ex-ante (e.g., adjustments in sowing time, leaving land fallow when rains have been insufficient (Christian Siderius et al., 2016; C Siderius, Hellegers, Mishra, van Ierland, & Kabat, 2014), or choice of crop or crop diversification in the crop planning stage (Roesch-McNally, Arbuckle, & Tyndall, 2018)), in-season (e.g., adding or withholding inputs such as irrigation or fertiliser, or delaying activities such as harvesting during the crop growth season (Mishra, Siderius, Aberson, van der Ploeg, & Froebrich, 2013; Rurinda et al., 2013)) and ex-post (e.g., taking loans or selling assets after harvest (Berman, Quinn, & Paavola, 2015; Landicho et al., 2015; Nazir et al., 2018)). Ex-ante and in-season options are mostly performed at the field-scale, while ex-post post options relate to the household level and are often a last resort if ex-ante and in-season options have failed. In season, farmers undertake many intermediate steps to recover yield loss. These traditional risk-spreading and impact-mitigation strategies (P. J. M. Cooper et al., 2008), are often complex due to the need for rapid response and have uncertain trade-offs between expected yield recovery and the extra costs involved. The in-season possibilities for avoiding or responding to damage vary; for example, shifting to another crop is often difficult after a crop has been planned (Schlenker & Roberts, 2006). Even if the option to switch or replant is available, the mechanisms to support this flexibility are not developed enough in many countries, and new or additional seed or seedlings or other resources (labour, machinery) may be unavailable within the given time to respond. In multi-cropping systems, farmers are further limited; any change in planting date might affect the subsequent crop growing season or conflict with crop management practices (Ortiz-Monasterio et al., 1994).

There is less written in the literature on in-season coping than on other aspects of climate risk management, such as utilising savings or credit, or selling assets (as in Below et al., 2012; Birkmann, 2011; R. Pandey, Jha, Alatalo, Archie, & Gupta, 2017). Household survey-based impact studies mainly relate coping and adaptation strategies to household characteristics, livelihood assets and market access (Berman et al., 2015; Landicho et al., 2015; Nazir et al., 2018). The type of coping strategies emphasised also has an epistemological explanation; biophysical impacts and field-scale ex-ante coping strategies are more frequently highlighted in climate impact studies relying on models, in which the exploration of the potential of seasonal weather forecasting is an expanding research field (Senthold Asseng, McIntosh, Thomas, Ebert, & Khimashia, 2016; Ramírez-Rodrigues et al., 2016). Despite these insights, it often remains uncertain to what extent forecasts benefits farmers (Meinke & Stone, 2005; Roudier et al., 2014). Workability issues (Iizumi & Ramankutty, 2015) and conflicts of time management in cropping systems (as in Tomasek, Williams, & Davis, 2017) and other pre-requisites of beneficial forecast use (Hansen, 2002) are less commonly described. Details on when farmers are vulnerable, their options for coping and the effectiveness of coping strategies for specific CMs is generally lacking.

Unusual weather during a particular cropping season imposes a management cost or yield loss (Moore & Lobell, 2014). The cost-effectiveness of coping is a factor of the yield recovered and the extra costs a farmer will incur to achieve this recovery. Climate research is mostly focused on adaptation (the ex-ante adjustments) or ex-post coping, making empirical evidence on the cost and effectiveness of in-season coping - those tactical risk management strategies during the crop season to cope with weather hazards - scarce. Though farmers respond to within-season weather anomalies, little has been reported about the effectiveness of different coping and yield mitigation strategies in terms of their costs, potential for yield recovery and the possible trade-offs and synergies.

The aim of this study is therefore to assess; i. farmers' CMs, when they feel most at risk; ii. which coping strategies they apply; iii. the costs of these strategies and iv. the effectiveness of the coping strategy, in terms of the amount of yield loss recovered. We will also address the limitations on using coping strategies, including the non-availability of inputs or management issues such as conflicts in the allocation of labour, land or machinery. We mainly focus on in-season coping strategies and their cost and effectiveness, while also taking into account ex-ante strategies for dealing with weather hazards close to the start of the cropping season. A distinction is made between coping and adaptation, with coping considered to be a response to present-day hazards within given conditions and adaptation considered to include autonomous or planned changes in anticipation of, or in response to, long-term and gradual change (Agrawal, 2008; Birkmann, 2011). For example, a one-off or occasional choice to change to a drought-tolerant variety due to un-seasonal weather conditions is captured as coping, while a permanent shift to a late-sowing variety in response to the changing weather conditions over the past few years is considered an adaptation. In this study, we will only look at those approaches considered to be coping strategies for in-season hazards.

A purely crop-based analysis obscures the complexity of the multi-crop rotations dominating Pakistan's agriculture. In an agricultural context, compounding effects can either be multiple hazards leading to a more severe impact, or a single hazard impacting multiple crops in overlapping crop rotations, leading to a more severe impact overall. In addition, cascading effects can occur, whereby a single event can lead to reactions and subsequent events, cascading risk in an interconnected system, leading to potentially much larger impacts (Pescaroli & Alexander, 2016; Zaidi, 2018). A systems perspective will therefore be applied to the multi-crop context of Pakistan, which is an extension of current work in this field.

3.2 Material and Methods

3.2.1 Approach

We investigated farmers' experiences in coping with the most common hazards, focussing on 2008–2018. Primary data were collected from 287 farm households in Pakistan. A cause-effect chain analysis, originally developed by Kaoru Ishikawa in 1943 (Kiprutto et al., 2015; Kuster et al., 2015), was adopted to explore the different levels of cause and effect, from hazard to yield loss, as well as the coping strategies and their effectiveness in terms of the amount of yield loss recovered. Cause-effect chain analyses are a useful tool for understanding the impact of weather hazards that lead to moderate impacts, in contrast with large-scale but less frequent disasters (Zaidi, 2018). Monitoring and the identification of causal factors provide opportunities to not only prepare for negative outcomes, but also to inform the types of coping intervention by location and time (Dilley & Boudreau, 2001).

Similar to Gobin (2018) and Schaap et al. (2011), the yield impacts of hazards and farmers' coping strategies were recorded for the most common hazards by crop stage. First, the impacts of individual hazards on crop yield were differentiated for the various loss-causing pathways, which enabled the identification of CMs. Second, the cost-effectiveness of each coping strategy was evaluated in terms of yield recovery and additional cost. Considering the importance of cropping systems (Claas Nendel et al., 2018; Reidsma et al., 2015; Toffolini et al., 2017), the limitations on coping strategies and the conflicts between coping options were identified from a system perspective rather than for crops individually.

The individual respondents were asked to estimate their yield after each hazard i without coping strategies (Y_i, ton/ha), the yield with coping strategies applied ($Y_{c,i}$) and the yield in a season without any particular hazard (Y_{norm}). We estimated the yield loss without coping as:

$$Y_{loss} = Y_{norm} - Y_i \qquad \text{-------------- (i)}$$

And the yield loss recovered with coping as:

$$Y_{rec,i} = Y_{c,i} - Y_i \qquad \text{-------------- (ii)}$$

The effectiveness of each coping option, EoC, was then estimated as a percentage of the yield loss recovered with using the following formula:

$$EoC_i = (Y_{rec,i} / Y_{loss,i})\ 100 \qquad \text{-------------- (iii)}$$

The estimates are based on the responses from farmers involved in crop management practices and decision-making, mostly household heads. To ensure the accuracy of estimates, farmers' responses on Y_{norm} were also crosschecked with district level crop yield data and consensus developed during focus group discussions. Values that appeared extreme were validated through cross-questioning with respondents regarding their crop management practices, soil conditions and input use level during the field survey. The total cost for each coping strategy adopted by each individual farmer was measured as the sum of cost of all inputs involved in Pakistani rupees (Pak Rs.) per unit area. Opportunity cost was included if their own resources (labour or input) were used. Contrary to the cost-effectiveness analysis used to identify the least costly intervention by comparing the alternatives (Bambha & Kim, 2004), we evaluated the effectiveness of the current coping option to each of the hazard pathways in terms of the yield loss recovered. The benefits of a coping strategies from the yield recovered with its adaption were also valued in Pak Rs. using the average farm gate prices reported by sample farmers at each site. To compare the cost with benefits, the cost as percentage of the value of the recovered yield was also estimated.

The costs and effectiveness of a coping strategy can vary by the loss-causing pathway. A few coping strategies required no additional costs, including late sowing to avoid unfavourable temperatures at the time of sowing. Still, such decisions were included as coping strategies rather than being considered standard variation in agricultural operations because they constituted a deliberate effort to recover yield that would otherwise have been lost.

A distinction was made between farmers who are not able to cope because they have no coping possibilities and those who decide not to cope, for example because of the high coping costs, short time to respond or the unavailability of required input. Limitations to coping were derived in a qualitative manner based on focus group discussions conducted at each study site and from informal discussions with the sample respondents. These discussions were also helpful in identifying the compounding effects of simultaneous events (for example, drought coupled with heat) or the occurrence of more than one hazard affecting crops grown in sequence during the different seasons of the year. In the context of the multi-crop system of Pakistan, cascading effects originated from the impact of a hazard on the first crop, triggering a coping response such as delayed harvesting, which then adversely affected the growing conditions, or complicated the management, of the next crop within an agricultural calendar. Conflicts caused by the overlap in harvesting one crop and planting the next, either in terms of limitations in land, labour or other operational issues, are specifically addressed.

3.2.2 Study area and sample design

We focused on agriculture in the Indus basin in Pakistan, where agriculture contributes 22.7% of the GDP and employs 37.4% of the labour force (Government of Pakistan, 2022). The Indus basin covers most of Pakistan's agricultural regions and the combination of climate change, population growth, limited investments in agriculture and existing water stress in this region poses severe challenges to agriculture and threatens the food security of more than 200 million people (H. Biemans et al., 2016; K. Malik, 2013; J.-E. Parry et al., 2013; World Bank, 2011). A multi-stage stratified random sampling framework was employed to achieve a representative sample of farmers, using a climate- and physiography-based agro-ecological classification of the country as the basis for the stratification of the study population. Pakistan is divided into 10 main agro-ecological zones (Figure 1), which are categorised based on climate, geography and cropping patterns (Pakistan Agricultural Research Council, 1980). Three of them were considered for the further selection of study sites, each representing a distinct but important cropping system, transecting from the high mountains to the rainfed mid-hills and irrigated plains (respectively, agro-ecological zones VII, V and IVa). In each zone, the dominant cropping system was selected based on its contribution to food security and similarity in growing season and crop management practices, and was considered one stratum. In the high mountains, there is a clear distinction between cropping systems in the main valleys and those higher up, so a fourth stratum was added to include cropping system at higher altitude in the mountains. Multiple cropping with two major crops is practiced in all four selected cropping systems. Wheat (*Triticum aestivum*) is grown as the staple food crop across all systems, with the second food crop grown mostly for commercial purposes. Wheat is grown in a multi-crop rotation system with potato (*Solanum tuberosum*) in the high mountains (HM), maize (*Zea mays*) in the mountain valleys (MV), groundnut (*Arachis hypogaea*) under the rainfed conditions in the mid-hills (MH) and rice (*Oryza sativa*) in the irrigated plains (IP). The characteristics of the strata are shown in Table 2.

For each cropping system, one study site comprising a cluster of 6–9 villages with the same cropping system was selected with the support of local agricultural research and development experts. For each site the selected cluster of villages was located within a radius of 10 km to ease data collection. Pakistan is a highly diverse country in terms of geography, ecology and climate, with the three selected agro-ecologies being important ecologies within the country and across the Hindu-Kush-Himalayans and the Indo-Gangetic floodplain. The study sites represent particular climate and farming conditions with distinct cropping systems that are not only important in terms of food security but have variable vulnerability to climate change due to site specific climate features. This study provide empirical evidence from the selected cluster of villages, the study sites within the selected agroecological zones and may not be generalized for all farmers in the selected agroecological zones or all farmers at country level.

Table 2. Characteristics of the four selected strata

Sites/Description	Irrigated plains (IP)	Mid-hills (MH)	Mountains valleys (MV)	High mountains (HM)
Agro-ecological zones	**Northern Irrigated Plains (IVa)**	**Barani Lands (V)**	**Northern Dry Mountains (VII)**	**Northern Dry Mountains (VII)**
Location of study sites	Bhera-Bhulwal (Sargodha)	Talagang (Chakwal)	(MV), Jaglot valley (Gilgit)	Gojal valley (Upper Hunza)
Cropping system	Rice-wheat	Groundnut-wheat	Maize-wheat	Potato-wheat
Geographical regions	Low lands Plains	Mid hills Pothwar region	High lands Hindukush region	High lands Karakorum Range
Altitude range (m)	200	450–500	1,600–1,800	2,500–3,000
Crop season	2 crops - 2 seasons	2 crops - 2 seasons	2 crops - 2 seasons	2 crops - 1 season
Land parcel	Same in sequence	Separate in sequence	Same in sequence	Separate & parallel
Source of irrigation water	Canal + tube well	NA (rainfed)	Snow- and glacier meltwater	Glacier meltwater
Rainfall (mm)	~ 200–300	~ 250–350	~150–200*	~150–200*

* Snowfall (~1,000 mm) in mountains is main source of water. Source: (Hashmi & Shafiullah, 2003; Pakistan Agricultural Research Council, 1980).

3.2.3 Sampling and data collection

A total of 7–12 farm households were randomly selected from each village. Overall, 287 farmers, mostly household heads, were interviewed. The sample size and characteristics of the various respondents in the case study sites are shown in Table 3. A structured questionnaire was developed based on a preliminary study (Groot et al., 2017). In the second round, the questionnaire was pretested by interviewing eight individual farmers and improved in light of field observations and insights from a focus group discussion with a group of farmers. In-house trained enumerators, who spoke the local dialect and were familiar with the use of local units and terminology, received two days of field training at each site, and were then responsible for guaranteeing the homogeneity and consistency of the questioning and the avoidance of repetition. In light of field observations during this training, minor modifications in the questionnaire were made by including site-specific events and practices. The formal survey was conducted through face-to-face interviews followed by the central cross-checking of each questionnaire on a daily basis.

Table 3. Sample size and characteristics of respondents

Site/variables	**IP**		**MH**		**MV**		**HM**		**Overall**	
	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.
Education (years)	5.85	4.88	8.08	3.81	8.33	5.14	7.96	4.79	7.54	4.75
Age (years)	50.52	10.53	51.33	11.97	48.49	12.91	50.71	12.03	50.29	11.86
Farming experience (years)	24.96	9.72	24.25	9.83	23.04	10.23	25.54	10.04	24.46	9.94
Family size (#)	7.85	3.23	9.03	5.27	11.78	5.27	7.72	3.42	9.06	4.66
Operational land holding (ha)	5.39	5.13	3.89	3.29	0.78	0.61	0.52	0.36	2.68	3.71
Sample Size (#)	**73**		**73**		**69**		**72**		**287**	
Sample Size (%)	25.4		25.4		24.0		25.1		**100**	

Information was collected on socio-economic farm and household characteristics, land allocation, cropping pattern and crop management practices, farmer experiences of weather hazards and coping practices (see the full questionnaire in Annex I). To select from the multitude of small and moderate hazards that might have affected farming over the past decade, we asked farmers about the most common hazards by crop stage. From these, we then asked about the frequency of occurrence and the opportunity for and cost effectiveness of coping strategies for the most recent hazard. At each crop stage, details of only one hazard (the most recent) were recorded and analysed for the two main crops grown in a year.

In total, 1,834 responses regarding exposure to hazards at various crop stages over the agricultural calendar were recorded from the sample households (Table 4). The cost and effectiveness of the coping strategies were calculated when the farmer had actually adopted a coping option. Numbers presented in the results refer to the subset of farmers that reported using a particular type of coping for the most recent hazard. The cost and effectiveness of similar coping strategies reported by multiple farmers are presented as averages. For some of the hazards and impact pathways, few responses were available because very few farmers were exposed to, or adopted a coping strategy during, the last event; for example, the losses of potatoes near maturity due to freezing during a sudden decrease in temperature was reported by four farmers. In those cases, we highlight insights as examples.

Table 4. Sample of farmer responses by crop stage

Site/Crop stage	IP	MH	MV	HM	Overall
Pre-sowing	36	117	0	0	153
Sowing	82	39	17	21	159
Germination	122	123	8	89	342
Vegetative	54	93	38	78	263
Reproductive	89	80	87	51	307
Grain formation	113	99	72	66	350
Harvesting	74	102	35	49	260
Total	**570**	**653**	**257**	**354**	**1,834**

3.3 Results

3.3.1 CMs, impacts and coping strategies

Hazard pathways vary by cropping system and crop stages at each of the study sites (Figure 5). Moisture stress due to less precipitation from a below average rainfall or no rainfall, issues of un-seasonal rains during early crop stages, and heat stress during grain formation were common in IP and MH. In MV and HM, sowing was often delayed due to low temperatures associated with reduced water supply and less snowmelt during early crop stages, while crops were also affected by moisture stress caused by damage to water supply channels during flash floods. Insect and disease infestation under hot and humid weather was common in MV and HM during the reproductive and grain formation stages. The harvesting season was affected by un-seasonal precipitation in all cropping systems. Comparatively, the pre-sowing and sowing crop stages were less exposed to hazards, in terms of the number of events reported during these phases (150–160), than the germination, reproductive and grain-formation stages (300–360 hazards), when considering both crops grown within the agricultural calendar.

The frequency of occurrence of different hazards for the individual crop stages ranged from once in five years to once in two years, with most occurring once every three to four years, implying a high probability of more than one hazard affecting farming during a single agricultural year. Higher frequencies were reported for decreases in water supply (canal and snowmelt), seasonal drought, temperature fluctuation (high at low altitude and low at high altitude) and un-seasonal rains during critical crop stages. Higher levels of hazard diversity were reported during later crop stages at all sites, particularly during the reproductive and grain formation stages, due to the different weather hazards being associated with various loss-causing pathways (insect, disease, disturbance in reproductive process, wilting and grain shrivelling or no ripening) (see Annex 2A for details).

The same hazard occurring at different crop stages could cause losses through different pathways. In IP, heavy precipitation during the sowing stage of wheat causes a delay in sowing; higher weed infestation during the vegetative stage, or wilting and subsequent harvest loss, while in rice it causes wilting and submergence during germination and insect attack at the reproductive stage. In HM, low temperatures during the start of the sowing season reduce snowmelt and cause water shortages, delaying the sowing of both wheat and potato. A decrease in temperature during wheat germination causes the seedlings to wilt, while a sudden decrease in temperature during potato germination reduces seed vigour and affects its germination. The yield loss varied by 10–30% for more than half of the hazards, and by 31–50% for one third of the hazards (see Annex 2A for details). In a few cases (8%), the hazards led to a complete crop failure, such as when sowing was impossible due to dry conditions, or when the crops were submerged or wilted due to a shortage of water. The impact of the hazards varied in their intensity, by the associated pathways causing losses and by the crop stage across cropping system.

The coping options differed per pathway, with multiple coping options available for some situations. In IP, farmers adopted a range of coping strategies to break the soil crust following a light rain before the germination of wheat. Among these choices, 43% applied supplemental irrigation, 36% used bar harrows (light cultivator or planking), 12% adopted a partial re-sowing and 10% opted for a full re-sowing. During rice transplanting, the majority of farmers avoided losses from moisture stress by adopting supplemental irrigation using tube well water (71%), delayed sowing until the start of the rains (21%), or used a higher number of seedlings (8%). Late sowing, the use of additional inputs and partial re-sowing (re-transplanting in case of rice) were the main coping strategies for temperature- (high) and moisture-related (dry/wet) issues during early crop stages. Farmers applied frequent supplemental irrigation to avoid wilting during the germination and vegetative stages of rice. Farmers could not cope with heat stress at the reproductive and grain-formation stages, with the exception of a few farmers who applied supplemental irrigation and evapotranspiration, which releases excess heat to reduce its impact on wheat yield (Figure 5A).

In MH, with its dominant rainfed ecology, farmers had limited coping options during most CMs, but showed diversity in applying the coping options that were available (Figure 5B). To avoid losses from crust formation before the germination of wheat, many farmers (46%) adopted a partial re-sowing, with others (25%) opting for a full re-sowing. Some chose to use a bar harrow (22%), while others (8%) used additional fertiliser in combination with the bar harrow. For the groundnut crop, most farmers (54%) used a light cultivator followed by a partial (38%) or full (8%) re-sowing.

At higher altitudes, in MV (Figure 5C) and HM (Figure 5D), farmers delayed sowing during periods of low temperature or low water supply to avoid losses during the early crop season. If these stresses continued for extended periods, farmers could only plant one crop and suffered a harvest loss for the other. Farmers used pesticides against insect attack in maize and potato during periods of hot-humid weather (locally called as "*lome*"), although they did not have access to coping strategies for diseases in wheat caused by similar weather conditions. Flash floods from a heavy shower disturbed the water supply system in the mountains and caused moisture stress, which sometimes led to crop failure if farmers were unable to repair the water channels quickly. A description of coping strategies is given in Table 5.

Table 5. Description of the coping strategies

Coping Strategies	Description
Add fertilizer	Additional fertilizer use than common practice in normal season
Add seed fertilizer	Additional seed and fertilizer use than common practice in normal season
Changed variety	Changed variety than planned for normal season
High seed rate	Higher seed rate than recommended to maintain planting density
Late sowing	Late sowing than recommended sowing time
No coping	No coping strategy at all (if none of the farmer in study area practiced a coping)
Supplemental irrigation	Additional irrigation to avoid loss from high temperature, seasonal drought/frost
Add cultivator + fertilizer	Additional ploughing and use of additional fertilizer than normal practice
Drained water	Draining excess water by natural flow or by pumping out from the field
No adoption	Farmer did not adopted a coping when other farmers practice for the same hazard
Partial re-sowing	Re-sowing in the same field with less seed (25-35%) than initial sowing or filling gaps with new seed/seedlings on patches where it has not germinated/established
Bar harrow	Use of bar harrow or light cultivator to break the crust
Bar harrow + fertilizer	Bar harrow used to break the crust with application of additional fertilizer
Hoeing	Manual hoeing for weeding or breaking hard surface to facilitate pegging
Pesticide use	Use of pesticides (including insecticide, weedicide or fungicide)
Repair w. channel	Repaired water channel destroyed by flash flood (heavy rain) in mountains
Stop irrigation	Stop irrigating fields when fields are too wet after a heavy rain or crop lodging
Drying	Drying of harvested crop in case of rain before crop is threshed
Delayed harvesting	Delaying crop harvesting (wet field or crop not matured due to low temperature)
Early harvesting	Early harvesting than normal to minimize loss from low temperature (in potato)

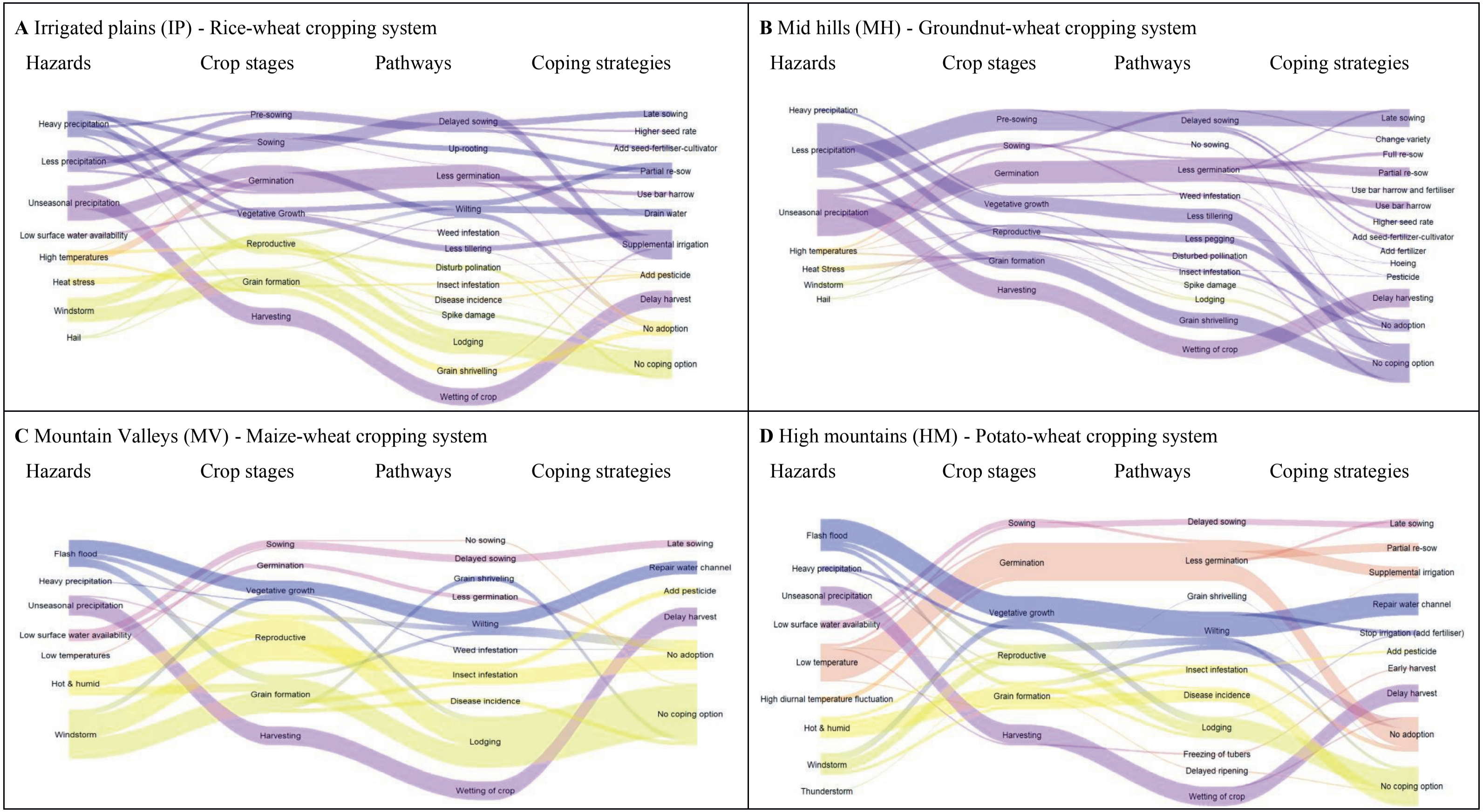

Figure 5. Sankey diagrams of the cause and effect pathways by crop stage. A. IP, from 570 responses. B. MH, from 653 responses. C. MV, from 257 responses. D. HM, from 354 responses. The width of the pathway is based on the (relative) number of responses.

3.3.2 Coping possibilities and adoption rate

There was no coping strategy possible for 22% to 45% of the events reported in the different study sites. For most of the hazards at later crop stages, which caused lodging, disturbed pollination, damaged spikes or shrivelled grains, farmers had hardly any coping options available. Lodging is a sudden issue caused by strong winds, rain, hailstorms, while delays in harvesting or threshing could result from lodging or rain affecting mature or harvested crops across all sites. Drying harvested crops is the only option to decrease losses and costs during harvesting and threshing. A lack of precipitation prevents sowing or leads to permanent wilting, often causing a complete loss of yield with limited coping options available in MH.

If coping options were available, the adoption rate varied from 60% in MV to 86% in IP. Coping strategies with high levels of adoption were typically related to making adjustments to sowing in response to moisture availability, crust breaking, weeding, the use of pesticides and the drying of harvested crops. Among all sites, farmers in IP showed the highest rate of adoption (86%), which can partly be explained by to the commercial nature of the crop farming, higher level of input use, larger average farm sizes and greater availability of an alternate irrigation sources compared with the other study sites. In IP specifically, a coping option for most of the pathways related to moisture and heat stress involved accessing an alternate irrigation source. Also in MH as compared to the other two mountainous sites, a high adoption rate (85%) was reported, with the risk of crop failure in rainfed farming reported as the explaining factor. In MV, the lowest adoption rate (60%) was attributed to the dual purpose maize crop and the lower dependence of the farmers on local wheat for food security. Maize was converted to fodder if it was wilted by water shortage or affected by insects. Only 20% of farmers used pesticides during an insect attack. Severe cases of water channel destruction during flash floods were not repaired in a timely manner in about 40% of cases in MV. In HM, though land holdings were very small, commercial crop farming was practiced, with potatoes as a cash crop. An adoption rate of 69% of available coping strategies was reported at this site (see Annex 2B for details). Overall, in 45% of the stress events, farmers were unable to cope with a certain hazard either because of non-availability of a coping option (30%) or they chose not to adopt (15%) among the available options. Hence, the coping with in-season hazards was mainly constrained by non-availability of a coping option. (Figure 6).

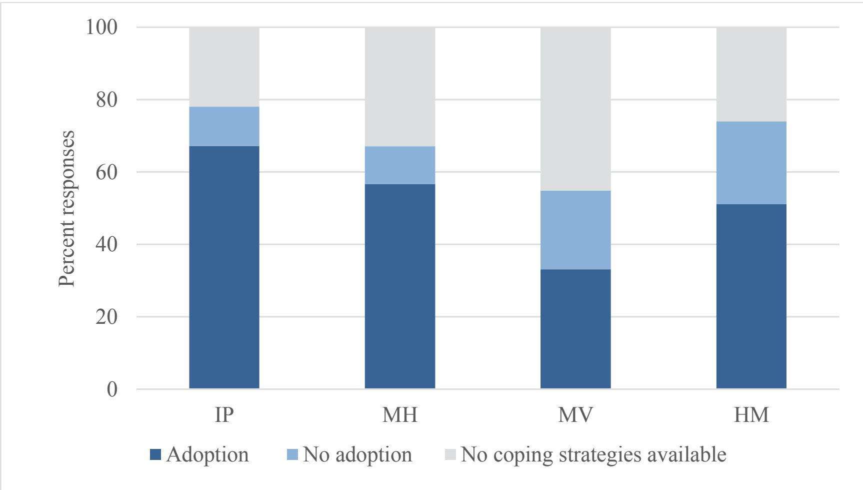

Figure 6. Coping strategy availability and adoption rates at the four study sites.

3.3.3 Cost effectiveness of coping strategies

The effectiveness of a coping strategy was measured in terms of the percentage of potential yield loss recovered by adopting a coping strategy. The yield loss recovery varied from 40% to 95% of the potential yield loss caused by a hazard, with an average recovery of around 77% (Table 6). The cost of in-season coping strategies varied from 4% to 34% of the recovered yield value, with an average of 19% with significant differences (*P<.0001*) among the study sites due to differences in output prices, cost of inputs involved and variations in yield recovery. A higher cost ratio was found in IP, mainly due to higher cost of the most popular coping strategies (Annex 2C). Each hazard had its own implications, as farmers could not recover the full yield loss even if they were able to adopt a coping strategy.

Farmers reported response time as an important factor for effectiveness; for example, the effectiveness of draining excess water under wet conditions following heavy rain in IP ranged from almost zero (complete loss) when delayed to 90% for timely drainage. Similarly, repair to damaged water channels after flash floods in MV and HM were much more effective if repaired in time.

The effectiveness of coping also varied by the level of input use for a similar pathway. Using higher seed rate along with additional fertiliser was more effective at maintaining a plant population and improving germination than only applying a higher seed rate to cope with delayed sowing. Similarly, the yield recovery varied with input use level. For example, the yield recovery was higher when full seed rate with cultivation and additional fertiliser was used as compared to partial seed rate with a light cultivator and without additional fertilizer in case of re-sowing to cope with crust formed due to an un-seasonal rain after sowing (see Table 4 for a description of coping strategies). Occasionally, coping strategies using increased inputs resulted in a higher yield than would have been expected under normal conditions; for example, in MH under rainfed conditions, when an un-seasonal rain delayed sowing, the farmers who applied additional fertiliser (n=16) benefitted from the additional moisture and recovered a 5% higher yield .

A weak positive correlation was found between cost of a coping strategy and its effectiveness across all four sites (Figure 7). In MH, several high-cost coping strategies (re-sowing, partial re-sowing, hoeing, additional fertiliser and seed) resulted in relatively high yield recoveries. The effectiveness of using additional seed and fertiliser in IP was less than for MH, mainly due to differences in moisture levels and the base input levels, which were already higher on average. Farmers in MH coped by using higher inputs only if additional moisture was available after an un-seasonal rain during the sowing period. The cost of coping varied mainly due to differences in the prices of inputs involved in a coping approach. Farmers in IP incurred higher costs for supplemental irrigation using tube wells, while water was available at no added costs in MH and HM. In HM, however, the cost of repairing a water channel damaged by flash floods was highly variable, depending upon the level of damage, the hours of labour required to repair the damage and the urgency of the repairs, with cheap hired labour and machinery absent in these remote areas. The costs also differed by crop, with the costs of seed for re-sowing wheat, rice and maize much lower than for potato and groundnut. Similarly, considerable differences in sowing and transplanting costs were reported for the different crops. Several coping options came without additional cost, such as a late sowing due to high temperatures in IP and MH or due to low temperatures in MV and HM, or the halting of irrigation after heavy rains to avoid loss from wilting and insect attack. Potatoes could be harvested early with no additional cost to avoid loss from low temperatures, since night frosts make potatoes fluffy and unmarketable. Each of these decisions constituted a deliberate response and resulted in partial yield recoveries.

Table 6. Cost of coping strategies (Pak Rs./ha), benefits as value of the recovered yield (Rs./ha) and effectiveness (% of the yield loss recovered) by study sites

	IP				MH				MV				HM				Overall			
Coping strategies	Cost (Rs./ha)	Benefits (Rs./ha)	Effectiveness (% of Y recovered)	n	Cost (Rs./ha)	Benefits (Rs./ha)	Effectiveness (% of Y recovered)	n	Cost (Rs./ha)	Benefits (Rs./ha)	Effectiveness (% of Y recovered)	n	Cost (Rs./ha)	Benefits (Rs./ha)	Effectiveness (% of Y recovered)	n	Cost (Rs./ha)	Benefits (Rs./ha)	Effectiveness (% of Y recovered)	n
Stop irrigation													0	17036	39	8	0	17036	39	8
Add cultivator + fertilizer	3089	11425	76	4	3562	18826	105*	16									3404	16359	95	20
Add fertilizer					1758	19565	65	8					7989	70846	90	3	3835	36659	73	11
Add seed fertilizer	6002	10510	85	10													6002	10510	85	10
Bar harrow	1599	24782	81	16	1659	40161	75	41									1639	35035	77	57
Bar harrow + fertilizer					4003	24031	87	5									4003	24031	87	5
Changed variety					1606	17480	70	6									1606	17480	70	6
Drained water	2034	28031	72	31													2034	28031	72	31
Drying	2903	9896	79	74	2100	11832	80	102	1977	8067	70	35	1693	9308	90	41	2279	10138	80	252
High seed rate	1730	9630	67	8	729	17480	70	11									1396	12246	68	19
Hoeing					5498	35630	73	5									5498	35630	73	5

	IP				MH				MV				HM				Overall			
Coping strategies	Cost (Rs./ha)	Benefits (Rs./ha)	Effectiveness (% of Y recovered)	n	Cost (Rs./ha)	Benefits (Rs./ha)	Effectiveness (% of Y recovered)	n	Cost (Rs./ha)	Benefits (Rs./ha)	Effectiveness (% of Y recovered)	n	Cost (Rs./ha)	Benefits (Rs./ha)	Effectiveness (% of Y recovered)	n	Cost (Rs./ha)	Benefits (Rs./ha)	Effectiveness (% of Y recovered)	n
Partial re-sowing	5906	28718	85	64	6005	39718	89	52					7016	31202	79	20	6309	33213	84	136
Pesticide use	3498	11617	73	18	3120	25740	74	6	2113	9803	92	11	5766	46189	78	5	3647	22874	76	40
Repair w. channel									1932	20579	80	25	2855	36098	56	52	2436	29044	67	77
Early harvesting													0	93739	88	4	0	93739	88	4
Re-sowing	7598	27535	90	4	10594	49436	95	20									9596	42136	93	24
Supplemental irrigation	2544	14341	80	127									200	35301	72	27	1919	19931	78	154
Total	**3275**	**17973**	**78**	**570**	**4051**	**29205**	**81**	**653**	**1964**	**17252**	**81**	**257**	**3200**	**37283**	**69**	**354**	**3359**	**25724**	**77**	**1834**

n=Number of responses **=Unseasonal rain resulted in late sowing but fertilizer application as coping under additional moisture resulted in higher recovery*

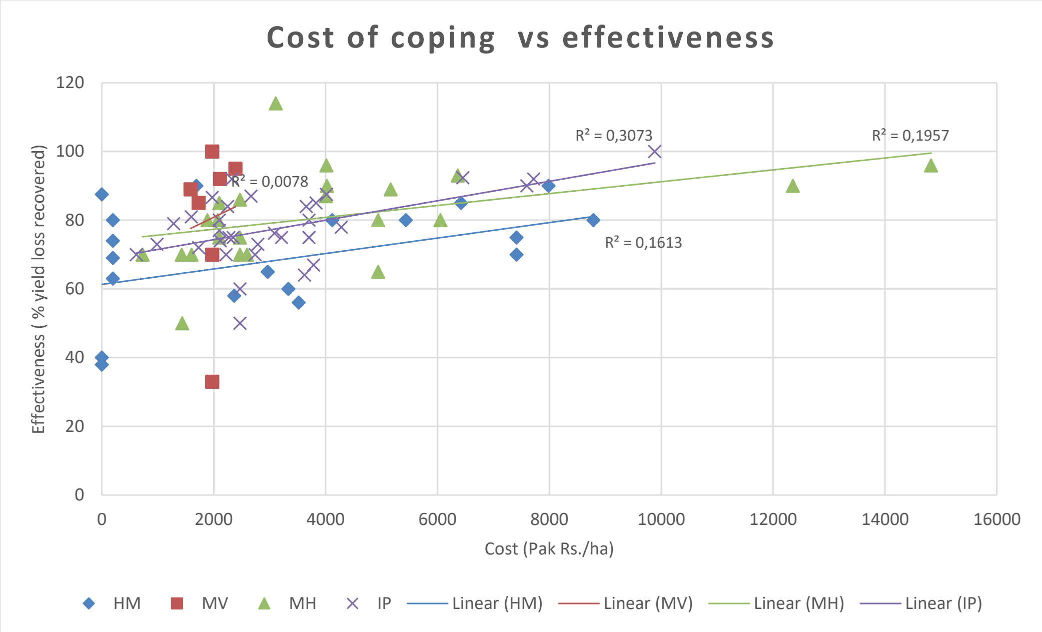

Figure 7: Scatterplot of the cost and effectiveness of coping strategies at the four study sites. Each dot represents the mean cost and effectiveness of a coping strategy during a crop season.

3.3.4 Compounding and cascading impacts

The occurrence of two moderate hazards in one crop season can generate compounding impacts and more extreme yield losses (IPCC, 2012). Similarly, the impacts accumulate if a single hazard affects two crops grown in a sequence in a multi-cropping system. In our sites, we found that a delay in rice harvesting due to un-seasonal rain or lodging affected both rice yields and wheat yields because of delays in sowing (Figure 5A). The impact worsens if operational costs are accounted for alongside crop yield and quality.

Similar examples were also found in other cropping systems; for example, rain during the harvesting stage of wheat (causing a 5.8% yield loss) led to a crust formation that affected groundnut germination (leading to heavy losses of up to 50%) in MH. Similarly, heat stress at the wheat grain formation stage caused a 17% wheat yield loss, but also led to a 14% loss of groundnut yields due to the early sowing and subsequent wilting of this second crop caused by the higher evapotranspiration and moisture stress it experienced during germination. Moisture stress affected groundnut yields at the pod formation stage (with a 35% reduction in yield), which affected the pre-sowing stage of wheat during which farmers conserve moisture in fallow lands. Low or no rainfall during this pre-sowing period leads to a delay in sowing, partial fallowing or even harvest loss, especially on marginal soils with less water-holding capacity. Heavy rain at the harvesting/threshing stage of groundnut (pre-sowing of wheat) has a contrasting effect, reducing groundnut yields (7%) and quality, causing a price decline (10–30%) and incurring higher threshing costs, but increasing wheat yields due to the better moisture conditions supporting the timely sowing and enhanced germination of this crop (Annex-2A).

In the mountains (Figure 5 C&D), compounding impacts were found for crops grown in sequence or side-by-side. Rainfall and/or low temperatures delay wheat maturity and harvesting, pushing maize back to late in the season and negatively affecting its grain ripening, meaning it is often only usable as fodder. Warm and humid weather affects both wheat and potato grown in same season around the grain/tuber formation stage by increasing disease infestation in wheat, leading to reduced grain formation and insect attacks in potato, causing up to a 40% yield loss in wheat and 30% in potato. Flash floods, occurring mostly from the vegetative to grain formation stages, damage water channels and impact the water supply, affecting both wheat and potato simultaneously.

Coping with in-season hazards was perceived to be more difficult when a hazard led to multiple impact pathways requiring a different coping strategy, often at the same time. In MH, seasonal drought at the reproductive stage of groundnut induced insect attack and hindered pegging, decreasing peg viability and reducing pod set (Haro, Mantese, & Otegui, 2011). Similar examples were found in IP, where high temperatures affected reproductive and grain formation processes, as well as inducing insect attack in rice. In HM, a decrease in temperature during wheat germination caused the seedlings to wilt and decreased the water supply (snowmelt), meaning farmers required more water to supplementary irrigate as a coping option. The complexity further increased because farmers in HM also require water for the concurrent sowing of potatoes. Coping with these exacerbating hazards in intensive multi-cropping systems within a single crop season becomes challenging, and even a single hazard can generate an extreme condition if assessed from a system perspective. The situation was aggravated when farmers had no coping strategies available at all (for example, for crop lodging, moisture stress under seasonal drought, grain shrivelling due to heat stress) or did not have timely access to labour (for manual hoeing to encourage pegging in MH) or input (additional rice seedlings in IP or potato seed in HM for re-sowing/re-transplanting) beside the cost of coping.

3.3.5 Operational conflicts and short turnaround between crops

The use of coping strategies is often constrained by the short time farmers have to respond. Re-transplanting rice seedlings if partially uprooted, applying timely supplemental irrigation in case of drought or heat stress, re-sowing wheat or groundnut if germination affected from crust formation and repairing water channels after a flash flood to maintain the water supply before crop wilt all require timely action. The timely availability of resources including farm machinery and the ability to purchase additional seed, fertiliser and labour during such moments is critical. Timely re-transplanting rice was found to be 92% effective and had acceptable additional costs for purchasing seedlings and labour. Delays in re-transplanting or a difference in seedling age or variety led to differential ripening at maturity, causing harvesting and threshing problems and impacting rice quality and prices. Unfortunately, the availability of the required seed (quantity and variety) in such situations, either leftover from the farmer's own stock or purchasable from the market, was reported to be problematic, and the shortage of labour was challenging.

A multi-crop rotation poses additional challenges. Overlapping labour or land demands strongly limit the coping options for cropping systems with a short turnaround (Figure 8). In IP, for example, the time between rice harvesting and the optimum period for wheat sowing is very short (Figure 8A). Farmers reported that even a minor weather hazard, most commonly wind for mature rice (75%) or un-seasonal rain during harvesting (38%), leads to a workability conflict and delay in wheat sowing, causing an 8–18% decline in wheat yields. The demand for resources (labour, machinery, and cash) to complete rice harvesting and wheat sowing within a short window of time is high. In addition to the direct impact of lodging due to wind and rain on rice yields and the following impact on wheat yields, higher costs were also reported, since lodging slows maturation and hampers mechanised harvesting.

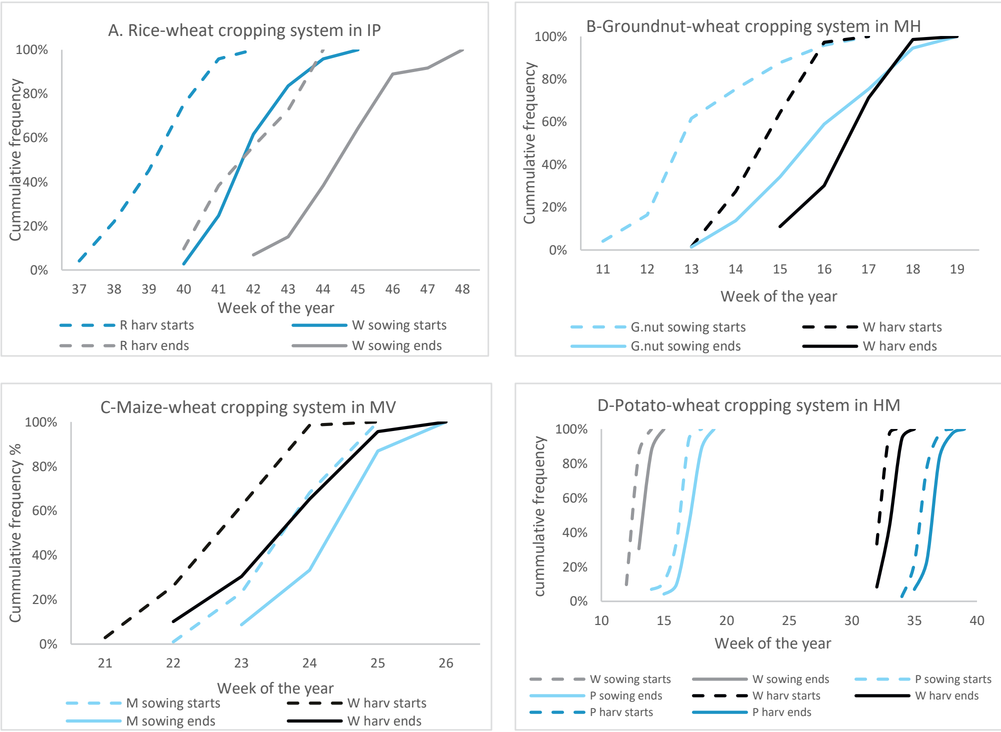

Figure 8. Conflicts in land and labour allocation in multi-cropping systems; A. IP, showing land and labour conflict between rice harvesting and wheat sowing. B. MH, showing labour conflict between groundnut sowing and wheat harvesting. C. MV, showing land and labour conflict between wheat harvesting and maize sowing. D. HM, no land or labour conflict. .

In MH, there is no conflict regarding land; wheat is planted on lands left fallow during the monsoon rains in the summer to conserve soil moisture, while groundnut is planted mainly on lands left fallow during the winter season. Despite this, there is some overlap between the wheat harvesting and groundnut sowing periods (Figure 8B), causing a labour and machinery conflict in the case of an un-seasonal weather pattern. The rains during the wheat maturation period normally provide moisture for groundnut sowing. Insufficient rains during the pre-sowing period for groundnut lead to a delay in sowing and, when followed by delayed rains during wheat maturation, this pushes farmers to complete groundnut sowing to avail the available moisture, generating conflicts of labour and machinery with the wheat harvesting and threshing tasks.

In MV, wheat and maize are sequentially grown in the same field, with a 2.5-month break between maize harvesting after the 1st week of November and the start of wheat sowing from mid-January. This shortens the growing period of the crops and farmers have to quickly switch from wheat to maize, making this a critical period (Figure 8C). Usually, due to the small scale of farms and small plot sizes, farmers manage to complete the farm operations within the short time available; however, a decrease in temperature often coincides with rainfall during the wheat harvesting stage, causing a delay, which in turn delays maize sowing. If maize sowing is delayed, the crop does not mature in time and it can only be used for fodder.

In HM, sowing begins at the start of spring as the ice melt starts to flow. Here, subsistence farmers rely mostly on family labour, with agriculture practiced on very small land holdings (<0.5 ha). Wheat and potatoes are planted on separate plots, and are sown and harvested simultaneously one after the other in the same season, from the last week of March to the middle of October, with a two week gap between the sowing of both crops (Figure 8D). A delay in the onset of spring results in a delay in sowing. Farmers reported they had few coping options to mitigate such losses. Starting the sowing of wheat early to avoid conflict with the next crop often led to reduced germination or wilting due to the low temperatures or even snowfall, which required re-sowing and caused further delay. Fluctuations in temperature at the initial crop stages also led to trade-offs in the allocation of scarce water resources. If sowing of wheat is disturbed by low temperature, farmers cope by a delay in sowing and they tend to apply irrigation during the early germination stage to avoid loss from wilting of seedlings under these conditions. However, this increases water demand when irrigation water is also needed to provide irrigation for the sowing of potato crops. Water scarcity further increases as low temperatures also mean less melt water, thereby limiting supply of water. Under such conditions, partial fallowing or not sowing any wheat are common strategies to avoid the yield loss of potato, which is the cash crop. Over the past 10 years, temperatures were generally reported to have increased, yet temperature fluctuations were perceived to have increased and low temperature stress during sowing and germination was still reported by half of the farmers.

3.4 Discussion

A farm household survey was conducted to assess the cost effectiveness of in-season techniques used to cope with adverse weather conditions in four main cropping systems located in the Indus basin, Pakistan. Methods to cope with weather variability have previously been discussed largely from an adaptation angle, including recommendations for changes in land use, cropping patterns, variety selection or ex-post coping techniques such as credit and migration (Bhatta & Aggarwal, 2016; S. S. Hussain & Mudasser, 2007; Thamo et al., 2017). In the present study, we used field evidence to provide a clear distinction between the impact pathways of similar hazards, differences in coping requirements and the possibility of coping during different crop stages. This study thereby provides new insights into the effectiveness and costs of coping strategies, crop-stage-specific coping requirements and farmer coping practices. Farmers had more flexibility and ability to cope during early crop stages because they had access to a wider variety of coping strategies than they did at later crop stages, during which there were no coping strategies available for some of the hazards, such as heat stress or lodging. As a result, the adoption rates at early crop stages were higher. Higher adoption rates were also found in cropping systems with access to irrigation water resources, with supplemental irrigation from tube wells used to cope with both moisture and heat stress.

With the multitude of moderate hazards, impacts and coping strategies defining farming, any questionnaire on these aspects in terms of crop stage faces time limitations. In cases where two or more different hazards were reported for the same crop stage by the same respondent, details on costs and yields for only the most recent hazard were included in the survey. This helped to improve the quality of the data (based on memory recall and by limiting the required interview time and the associated response fatigue), although it meant that details of other common hazards that may have occurred previously were missed. Despite the detailed questionnaire with more than 1,800 responses regarding hazard-impact pathways, only a few responses were recorded for some hazards. These were reported merely in an illustrative context. For questions on the cost and effectiveness of coping, the number of responses reduced further; in nearly half of the reported impact pathways, farmers were unable to cope, either because no coping strategies were possible or because they chose not to adopt them.

Each of the coping strategies involved additional cost. Interventions resulting in significant yield improvements are not adopted if they do not meet economic rationale (H. Shah, Hussain, Akhtar, Sharif, & Majid, 2011). While a cost ratio of 18.81% of the recovered yield seems to make the decision to cope rational, even to risk-averse farmers, and explains the high adoption rate, these extra costs have to be put in perspective against the overall low marginal returns in farming and the low net income of smallholder farmers in Pakistan (A. W. Bhutto & Bazmi, 2007; S. J. Malik, Sheikh, & Jilani, 2016). A timely response was considered important for increasing the effectiveness of coping strategies, but a shortage of labour, machinery or required inputs often prevented such a response. The cost-effectiveness of coping strategies depended mainly on the cost of inputs and the field conditions rather than the yield recovery.

Assessing coping or adaptation options individually or under controlled test conditions does not take the actual limitations into account, especially in regions dominated by complex multi-cropping systems. The analysis of various multi-crop systems shows various land, water and management (labour and machinery) conflicts. Rice and wheat, staple crops for hundreds of millions of people, are sequentially grown on the same land throughout Indo-Gangetic plain, which brings complementary as well as conflicting practices (Timsina & Connor, 2001). Wheat sowing in this region is already delayed because of the dominance of long-duration late-maturing Basmati rice varieties, shortage of mechanical harvesters (Tahir, Sardar, Quddus, & Ashfaq, 2008) and the time required for residue management through intensive tillage (I. Hussain et al., 2012). Due to these, wheat sowing is already spanning the optimal time limit (mid-November); almost half of the sampled farmers began wheat sowing after mid-November, even under normal weather conditions. Wheat yields were previously shown to decline by 10% if planting is delayed from 10th November to 25th November in Punjab, Pakistan (M. Khan, Zulkiffal, & Imran, 2004). Weather hazards such as heavy rain or wind during the rice maturation period caused lodging, leading to a delay in rice harvesting and wheat sowing that cause yield losses, additional costs and eventually a loss of income. Our estimates of an 8–18% reported wheat yield decline due to a weather hazard causing delay in sowing are similar to the earlier finding on effect of late sowing on wheat yield (M. A. Ali, Ali, Sattar, & Ali, 2010; Ortiz-Monasterio et al., 1994). The compounded impacts and operational conflicts in multi-cropping systems can be better understood when studied as a connected system.

Climate change is expected to have a big impact on agriculture in Pakistan and the Indus basin (H. Biemans et al., 2019; S. S. Hussain & Mudasser, 2007). Insights from this study are particularly relevant given the expectation that climate variability will increase, affecting future crop yields (Ashok & Sasikala, 2012; Camargo & Marcelo, 2009; P. J. M. Cooper et al., 2008; Van Aalst, Cannon, & Burton, 2008) and posing considerable risks to the sustainability of agriculture in many regions (Barasa, Oteng'i, & Wakhungu, 2015; Lansigan, 2007; M. V. K. Sivakumar, Das, & Brunini, 2005). A global lack of preparedness regarding increasing climate variability has been highlighted by the Intergovernmental Panel on Climate Change (IPCC), with a reduction in vulnerability to present-day climate variability considered a first step towards effective climate change adaptation (IPCC, 2014). While efforts are now shifting towards the development of ever more regionalised or even local scenarios (Lopes & Aguiar, 2008), farm-level coping mechanisms are still often overlooked (White et al., 2011). By explicitly addressing the effectiveness of coping strategies during CMs, this study adds a new angle to a growing literature on the characterisation of weather hazards and ways to improve resilience at the farm level (Füssel, 2007; Heltberg et al., 2009; IPCC, 2012; Wilby & Dessai, 2010; World Bank, 2015).

Supporting effective in-season coping goes beyond the farm level and requires broader policy support and investment, such as improved weather and early warning information, technical guidance, rapid access to production inputs or finance through a functioning market system. For about one fourth to nearly half of the cases in the four cropping systems studied, farmers were unable to cope with in-season hazards due to non-availability of a coping option. This requires a policy shift to direct R&D efforts to fulfil this gap. Often, inputs were not available in time, which indicates markets should be strengthened. Effectiveness strongly dependent on response time. Advisory and support services needs to be aligned with these challenges to respond timely. Understanding effectiveness of current and alternate coping options for different CMs provides opportunity for devising viable and cropping system compatible coping options.

3.5 Conclusion

A multitude of moderate hazards affects each of the cropping systems studied, with the frequency of occurrence ranging from once in five years to once in two years. In-season coping strategies were available for 55–78% of the hazard events in different cropping systems. When a coping option was available, the adoption rate varied from about 85% in plains and mid hills to as low as 60% in the mountain valley site. Coping strategies were found to be strongly constrained by the limited amount of time to respond and the availability of the required inputs.

The effectiveness of coping varied from 50-90% at the cost of 4-34% of the value of recovered yield. This study shows how compounding and cascading impacts can lead to conflicts in the allocation of time, land, labour, machinery and other resources in multi-crop systems. Our results emphasise the need to address farmer coping strategies from a system perspective. A better understanding of the differentiated risks and the effectiveness of in-season coping strategies could support the promotion of sustainable crop production in similar agro-ecologies.

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Annexures

Annex 2A Impacts on crop yield by cropping systems

The potential damage measured as average yield loss from each of the pathways of a hazard under no coping situation is summarized by pathways and crop stages in Table 2A.

In the IP, rice crop though planted under irrigated conditions, rainfall was still an important factor affecting crop yield and farmers crop management decisions throughout rice season. A delayed start of summer rains (monsoon)/decrease in surface water supply caused delay in rice sowing leading to 15% yield decline. Farmers experienced such events almost once in three years. A heavy rain shower plus wind if coincides with completion of rice transplanting time (day), results in uprooting of seedlings. Farmers had experienced such events twice in a decade and on an average it resulted in one third yield decline. Dying of seedlings just after transplanting due to high temperature was causing 26% yield decline. The rice crop was also prone to high temperature during vegetative stage resulting in wilting of plants leading to 20% yield decline. Submergence of rice fields at low lands due to events of heavy (continuous) rains and localized floods was a common issue that caused wilting leading to heavy loss (harvest loss) if farmers could not cope. Even if farmer could drain out excess water, yellowing of leaves with 10-20% yield loss was reported. About 15% lower yield was associated to less tillering in case of less rains during vegetative stage. Heavy/continuous rains, heavy winds, high temperature and hailstorm during rice reproductive stage affected reproduction process and caused lodging leading to harvesting and threshing losses. Disease incidence due to higher temperature and continuous rains (hot humid weather) at reproductive and grain formation stage caused poor grain filling/empty grains. The yield loss from higher temperature varied from 15 to 40% during reproductive and grain formation stages in rice. The yield loss from lodging due to rain at maturity stages varied for 9% to 32% depending upon the intensity of the hazards beside rice quality deterioration and additional cost of drying, harvesting and threshing. The over wet conditions due to rain or flooding around rice harvesting had worse impacts as delay in harvesting and loss in rice could not be avoided while harvest loss due to no wheat sowing was reported for low lands with less drainage.

Farmers considered early vegetative stage of wheat more sensitive to the moisture excess in R-W cropping system. It caused higher level of yield loss (68%) in wheat after rice at low lands during vegetative as compared to reproductive (38%) and grain formation stage (48%). There were also some commonalities in hazards and their impacts on wheat crop in R-W and G-W cropping systems. Moisture stress led to 10 % yield loss during vegetative stage in IP while 27% in MH due to less tillering and lower plant growth under rained conditions. Increasing frequency of less moisture (low water supply and less rains) was reported as compared to excess moisture from a heavy or continuous rains for wheat crop. The yield loss from an un-seasonal rain just after wheat sowing (pre-germination stage) caused from 35 to 40% yield loss because of crust formation once in four years. Short heat spike and higher temperature than normal at grain formation was one of the common hazards with increasing trend and caused grain shrivelling leading to 20 to 25% yield loss in rice, groundnut and wheat. Rain at harvesting stage for rice, wheat and groundnut led to 5-10% yield loss due to wetting of crop. Though it causes minor yield loss but creates operational difficulty and require more time for threshing that increases cost. Higher risk of storage losses for wheat due to high moisture contents and higher losses (upto 30%) from price decrease in groundnut due to quality concerns if it rains during harvesting stage.

A seasonal drought during pre-sowing stage of groundnut caused delay in sowing resulting in 20% yield decline. A heavy rain at sowing also caused delay in sowing but relatively less yield loss than moisture stress. Higher temperature during sowing, germination stages and pod formation (especially under dry weather) affects groundnut yield. A yield decline by 14% during sowing and 40 %t during germination and 25% during pod formation stages was associated with high temperature. Less rains or seasonal drought at early vegetative stage leads to 32% yield loss because of less tillering and wilting, 42% yield loss because of less pegging at reproductive stage and 35% yield loss due to small/single pods at grain formation stage. Higher insect attack was also common problem reported in case of less rains at vegetative to pod formation stage leading 30 to 40% yield loss in groundnut.

Among other common issues in different cropping systems, high weed infestation from heavy rains during early vegetative stage caused 10 to 25% yield loss in wheat, maize and groundnut. The winds (with rain) caused lodging leading to yield loss due to disturbance in flowering, less grain formation, difficulty in harvesting and threshing ranging from 10 to 30% of the normal season yield across in different crops from low to high altitude.

In MV and HM, low temperature during early and late stages was common hazard affecting germination or ripening of crops. The delay in winter (decrease in temperature) result in delay in sowing due to two reasons, i) lower temperature affects germination, ii) shortage of water (delay in snowmelt). The pre-sowing season of wheat is dormant period in both of the mountainous sites. The sowing starts with water availability from snowmelt at end of January. Low temperature (non-availability of water) was the main factor causing delay in wheat sowing and 20 to 30 % yield loss while at germination stage it caused 20 to 40% yield loss due to wilting of early seedlings. Higher frequency of water shortage in HM (4 times per decade) as compared to MV (2 times per decade) during wheat sowing was reported. Less water supply leads to late sowing with partial fallowing. Farmers also reported 2 to 3 events of decrease in temperature per decade during wheat germination stage.

Heavy or continuous rains caused higher weed infestation at early vegetative stage of maize resulting in 14% yield loss. Flash floods from a heavy rain shower disrupting water supply was also common problem in the mountainous agriculture. It mainly affected the maize crop while few incidences during wheat growing season were also reported in MV. The yield loss varied from 20 to 45% due to wilting of crop but in severe cases a harvest loss, once in five years was also reported. Among other common hazards, hot-humid weather conditions "lome" cause 30 to 50% yield decline in wheat, maize and potato in these systems. Winds especially a wind with rain caused severe lodging in wheat and maize after vegetative growth stages. Yield loss from 20 to 40% was reported from lodging in maize and wheat in MV an HM. Wetting of harvested crop from rains was another common issue for wheat in mountainous agriculture as well.

In HM, potato crop was affected by decrease in temperature starting from delay in potato sowing causing 14% yield loss. A sudden decrease in temperature after sowing of potato makes potato seed fluffy that does not germinate resulting in yield loss upto 50%. The temperature fluctuations during potato germination (freezing at night or high during day) cause wilting and 11 to 28% yield loss. A sudden decrease in temperature at maturity before harvesting caused higher losses in potatoes especially a sudden cold spike near maturity caused freezing of tubers (quality deteriorates leaving potatoes unmarketable) leading 30 to 40% losses in potato. Heavy or continuous rains caused root water logging in potato that led to wilting and yellowing of potato plants resulting in yield decline upto 27%. The impact of individual hazards by considering the pathways for each cropping system is summarized for individual crops in Table 2A.

Table 2A. Impact on crop yield by pathways and crop stage (% yield loss)

Cropping systems	IP		MH		MV		HM		Overall
Row Labels	**Rice**	**Wheat**	**G.nut**	**Wheat**	**Maize**	**Wheat**	**Potato**	**Wheat**	
Pre-sowing		**11.65**	**47.00**	**48.65**					**38.11**
Heavy rain		**17.54**							**17.54**
Delay sowing (PF*)		17.54							17.54
Less rain (w. supply)		**8.70**	**47.00**	**48.65**					**40.16**
Delay sowing (PF)		8.70	20.50	35.81					25.21
No sowing			100.00	100.00					100.00
Sowing	**20.44**	**17.88**	**16.75**	**4.29**		**53.32**	**14.35**	**32.42**	**22.86**
Heavy rain	**30.98**								**30.98**
Up-rooting	30.98								30.98
High temperature	**26.79**		**13.88**	**8.57**					**16.41**
Delay sowing (PF)				8.57					8.57
Less germination	26.79		13.88						20.34
Less rain (w.supply)	**14.81**					**61.05**		**32.42**	**33.16**
Delay sowing (PF)	14.81					22.09		32.42	19.79
No sowing						100.00			100.00
Low temperature						**37.86**	**14.35**		**26.11**
Delay sowing (PF)						37.86			37.86
Less germination							14.35		14.35
Un-seasonal rain		**17.88**	**18.18**	**4.29****					**15.72**
Delay sowing (PF)		17.88	18.18	4.29**					15.37
Weeds			18.18						18.18
Germination	**39.99**	**35.12**	**45.30**	**34.67**		**45.71**	**21.08**	**33.78**	**35.12**
Heavy rain	**48.59**								**48.59**
Submergence	48.59								48.59
High temperature	**20.32**		**39.79**	**12.37**			**10.99**		**21.86**
Less germination	20.32		39.79	12.37			10.99		21.86
Less rain (w.supply)	**60.91**					**45.71**	**20.58**	**48.08**	**43.55**
Less germination	21.82					45.71	20.58	48.08	34.14
Wilting	100.00								100.00
Low temperature							**28.15**	**19.47**	**24.68**
Less germination							28.15	19.47	24.68
Un-seasonal rain		**35.12**	**48.05**	**40.25**					**40.68**
Less germination		35.12	48.05	40.25					40.68
Vegetative	**46.89**	**29.86**	**22.72**	**18.85**	**50.25**	**68.75**	**54.03**	**33.93**	**36.56**
Flooding	**78.78**				**81.36**	**68.75**	**81.78**	**45.36**	**74.74**
Wilting	78.78				81.36	68.75	81.78	45.36	74.74
Heavy rain			**15.63**	**14.66**	**13.89**		**26.28**		**17.39**
Insect attack			2.65						2.65
Weeds			24.28	14.66	13.89				19.34
Wilting							26.28		26.28
Less rain (w.supply)	**15.00**	**10.12**	**40.46**	**27.22**					**22.62**
Insect attack			31.87						31.87
Less tillering	15.00	10.12	49.05	27.22					21.08
Un-seasonal rain		**39.73**							**39.73**
Weeds		10.61							10.61
Wilting		68.85							68.85
Winds (rain)					**24.41**			**28.22**	**26.95**
Lodging					24.41			28.22	26.95
Reproductive	**21.01**	**33.33**	**36.42**	**23.52**	**45.18**	**27.09**	**23.35**	**55.54**	**31.07**
Flooding					**45.44**	**25.00**	**40.43**	**84.36**	**54.17**
Wilting					45.44	25.00	40.43	84.36	54.17
Hails	**39.94**	**18.09**		**32.53**					**30.19**
Spike damage	39.94	18.09		32.53					30.19

Heavy rain	**17.07**	**40.28**					**15.42**		**26.78**
Disease	15.13								15.13
Disturb rep	20.95	20.13							20.54
Wilting		50.35					15.42		38.71
High temperature	**19.14**	**28.57**		**18.94**					**20.68**
Disease	17.50								17.50
Disturb rep	20.77	28.57		18.94					22.26
Hot-humid					**56.04**	**29.76**	**12.52**	**20.38**	**26.83**
Disease								20.38	20.38
Insect attack					56.04	29.76	12.52		28.12
Less rain (w.supply)			**36.42**						**36.42**
Insect attack			30.69						30.69
Less pegging			42.14						42.14
Low temperature							**35.86**		**35.86**
Wilting							35.86		35.86
Un-seasonal rain				**21.59**		**24.26**			**22.93**
Disturb rep				21.59					21.59
Lodging						24.26			24.26
Winds (rain)	**21.22**	**32.51**		**21.02**	**33.80**	**26.69**		**33.08**	**27.08**
Disturb rep	18.85								18.85
Lodging	23.58	32.51		21.02	33.80	26.69		33.08	28.45
Grain formation	**26.41**	**31.77**	**33.74**	**21.37**	**34.93**	**29.20**	**34.79**	**33.82**	**30.81**
Flooding					**38.44**	**30.00**	**46.39**	**29.40**	**35.98**
Wilting					38.44		46.39	31.60	38.81
Grain shrivel						30.00		25.00	27.50
Hails	**38.33**	**31.23**		**22.73**					**30.76**
Spike damage	38.33	31.23		22.73					30.76
Heat stress		**19.69**		**17.75**					**19.04**
Grain shrivel		19.69		17.75					19.04
Heavy rain		**41.93**							**41.93**
Lodging		30.26							30.26
Wilting		47.76							47.76
High temperature	**20.39**		**24.79**						**21.49**
Insect attack	23.06								23.06
Grain shrivel	19.05		24.79						20.96
Hot-humid					**33.35**	**31.52**	**31.78**	**43.49**	**33.95**
Disease						31.52		43.49	37.51
Insect attack					33.35		31.78		32.17
Less rain (w.supply)			**38.22**	**22.64**					**33.02**
Insect attack			41.43						41.43
Grain shrivel			35.00	22.64					28.82
Low temperature								**33.15**	**33.15**
Delay ripening								33.15	33.15
Thunderstorm							**20.59**		**20.59**
Wilting							20.59		20.59
Winds (rain)	**32.57**	**25.98**		**21.88**	**29.48**	**26.07**		**38.06**	**27.99**
Lodging	32.57	25.98		21.87	29.48	26.07		38.06	29.01
Grain shrivel				21.88					21.88
Harvesting	**8.86**	**7.07**	**7.01**	**5.81**		**14.22**	**35.31**	**13.41**	**13.14**
Low temperature							**35.31**		**35.31**
Freezing of tubers							35.31		35.31
Un-seasonal rain	**8.86**	**7.07**	**7.01**	**5.81**		**14.22**		**13.41**	**9.97**
Wetting of crop	8.86	7.07	7.01	5.81		14.22		13.41	9.97
Grand Total	**28.77**	**27.53**	**32.44**	**27.54**	**43.45**	**36.55**	**30.78**	**36.06**	**31.48**

*PF=Partial Fallow

**.Increase in yield due to additional moisture from rain compensates for delay in sowing in rainfed ecology;

Annex-2B. Possibility of coping and adoption level

Table 2B. Coping possibility and current level of adoption of coping practices by farmers

Coping/cropping system	IP	MH	MV	HM	Overall
Coping possibility	**Responses to cope by hazards' pathway (# of responses)**				
Yes	445	436	141	262	1284
No	125	217	116	92	550
Total	**570**	**653**	**257**	**354**	**1834**
Adoption of coping strategy	**Current level of adoption of coping practices (# of responses)**				
Yes	383	370	85	181	1019
No	62	68	56	81	267
Total	445	438	141	262	1286
	Coping possibility and adoption level from available choices (%)				
Coping possibility	78.07	66.77	54.86	74.01	70.01
Adoption	86.07	84.86	60.28	69.08	79.36
No-adoption	13.93	15.60	39.72	30.92	20.79

Annex-2C. Cost (% of the value of recovered yield) and effectiveness of coping (% of yield recovered)

Table 2C. Cost (% of the recovered yield value) and effectiveness of coping (% of yield recovered)

Study sites	IP		MH		MV		HM		Total	
Row Labels	**Cost**	**Effectiveness**	**Cost**	**Effectiveness**	**Cost**	**Effectiveness**	**Cost**	**Effectiveness**	**Cost**	**Effectiveness**
Flooding	**8.89**	**85.00**			**18.51**	**80.40**	**17.83**	**56.17**	**17.37**	**68.67**
Repair w. channel					18.51	80.40	17.83	56.17	18.14	67.18
Drained water	8.89	85.00							8.89	85.00
Heat stress	**17.59**	**74.00**							**17.59**	**74.00**
Supplemental irrigation	17.59	74.00							17.59	74.00
Heavy rain	**13.76**	**81.40**	**17.82**	**73.75**			**5.64**	**64.00**	**13.76**	**75.95**
Stop irrigation							0.00	38.00	0.00	38.00
Pesticide use	28.69	75.00	16.30	71.67					19.40	72.50
Drained water	3.72	73.67							3.72	73.67
Hoeing			22.37	80.00					22.37	80.00
Add fertilizer							11.28	90.00	11.28	90.00
Partial re-sowing	21.35	96.20							21.35	96.20
High temperature	**21.38**	**73.24**	**24.45**	**88.00**			**12.93**	**79.50**	**20.40**	**77.06**
Pesticide use	30.72	71.00							30.72	71.00
Supplemental irrigation	15.03	76.67					0.89	74.00	12.21	76.13

Study sites	IP		MH		MV		HM		Total	
Partial re-sowing	28.06	64.00	24.45	88.00			24.96	85.00	25.48	81.25
Hot-humid					**21.55**	**92.00**	**13.99**	**78.33**	**15.88**	**81.75**
Supplemental irrigation							0.28	80.00	0.28	80.00
Pesticide use					21.55	92.00	20.85	77.50	21.09	82.33
Less rain (w.supply)	**34.22**	**79.21**	**9.26**	**69.17**			**32.33**	**75.00**	**23.99**	**74.63**
Hoeing			11.18	65.00					11.18	65.00
High seed rate	29.70	60.00	4.17	70.00					16.93	65.00
Add fertilizer			9.66	65.00					9.66	65.00
Changed variety			9.19	70.00					9.19	70.00
Partial re-sowing							32.33	75.00	32.33	75.00
Additional seed fertilizer	59.19	78.00							59.19	78.00
Pesticide use			11.68	80.00					11.68	80.00
Supplemental irrigation	30.13	83.30							30.13	83.30
Low temperature							**5.22**	**74.88**	**5.22**	**74.88**
Supplemental irrigation							2.18	66.00	2.18	66.00
Partial re-sowing							16.53	80.00	16.53	80.00
Early harvesting							0.00	87.50	0.00	87.50
Un-seasonal rain	**23.56**	**77.94**	**16.17**	**88.64**	**24.50**	**70.00**	**18.18**	**90.00**	**20.13**	**82.81**
Drained water	21.65	62.50							21.65	62.50
High seed rate	9.04	73.00							9.04	73.00
Pesticide use	31.53	73.00							31.53	73.00
Bar harrow	6.45	81.00	5.24	75.00					5.65	77.00
Bar harrow +Fertilizer			16.66	87.00					16.66	87.00
Drying	29.38	78.50	19.43	80.00	24.50	70.00	18.18	90.00	23.39	79.50
Supplemental irrigation	8.76	84.00							8.76	84.00
Partial re-sowing	14.23	84.00	11.91	89.50					12.68	87.67
Additional seed fertilizer	56.02	92.00							56.02	92.00
Re-sowing	27.59	90.00	22.51	94.50					24.21	93.00
Add. cultivator + fertilizer	27.04	76.25	21.51	105.00					23.35	95.42
Winds (rain)							**0.00**	**40.00**	**0.00**	**40.00**
Stop irrigation							0.00	40.00	0.00	40.00
Grand Total	**23.64**	**77.94**	**15.35**	**80.91**	**19.30**	**80.57**	**13.73**	**68.50**	**18.81**	**76.63**

Chapter 4

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4. Limitations to adjusting growing periods in different agroecological zones of Pakistan

Climate change affects the timing and length of crop seasons. Adjusting sowing dates is a commonly recommended adaptation, but little is known about its efficacy in practice. This study investigated farm-level adjustments to sowing and harvesting dates (i.e., the growing period) in response to shifts in meteorological crop seasons during the last 30 years. Impacts on yields and farmers' complementary adaptation strategies were also examined. Using data from 287 farm households in four agroecological zones of the Indus Basin, Pakistan, we explored farmers' perceptions of shifts in seasons and adjustments in crop growing period. We verified these using meteorological station data on temperatures, precipitation and growing degree days.

At lower altitudes (irrigated plains and mid-hills), the summer crop season had lengthened and the winter season shortened, but in both seasons the growing period was shorter, due to higher temperatures. The summer growing period was shorter by 5 (±11) days on the irrigated plains, while there was no significant change in length of the summer growing period in the mid-hills. The winter growing period was shorter by 15 (±6) days on both the plains and in the mid-hills, which negatively impacted yields. As an adaptation strategy, changing sowing dates was only somewhat effective in preventing yield losses. Farmers adopted complementary strategies, but these brought additional costs. At higher altitudes (valleys and mountains), the frost period had shortened, resulting in longer summer and winter crop seasons, and longer growing periods. The summer growing period was extended by 7 (±4) days in the valleys and 10 (±6) days in the mountains, while the winter growing period was extended by 3 (±3) days in the valleys and 13 (±5) days in the mountains, positively impacting yields. Farmers' adjustments in sowing dates did not necessarily parallel to seasonal shifts, as farm decision-making also had to consider risks linked to climate variability and management limitations. For the future, farmers at lower altitudes indicated limited further scope for adjusting sowing and harvesting dates. Our results contribute to a contextual understanding of farmers' responses to shifts in crop seasons. They indicate the need for adaptation planning to take advantage of extended growing periods in higher altitude zones, while supporting farmers in areas where seasonal shifts have negative impacts. Our findings furthermore indicate limits to adaptation in regions where agriculture is already challenged and provide suggestions for crop system-specific complementary measures.

4.1 Introduction

Shifts in onset dates and length of cropping seasons are a main manifestation of climate change (Allen & Sheridan, 2016; Dong, Jiang, & Yang, 2010; Dwyer, Biasutti, & Sobel, 2012; Kutta & Hubbart, 2016; Linderholm, 2006). Changes have been documented in many seasonal parameters (Kutta & Hubbart, 2016; Linderholm, 2006). Key among these are changing temperatures, combined with shifting rainfall patterns (timing and amounts) (Bhatti, Balkhair, Masood, & Sarwar, 2018; Philip K Thornton et al., 2014). Shifts have also been observed in phenoclimatic indicators, such as frost dates, growing period length, growing degree units and more complex indices representing different phases of plant development, such as spring indices (Cleland, Chuine, Menzel, Mooney, & Schwartz, 2007). Farmers have sought to adapt to these changes by aligning sowing dates with the 'new normal' to avoid impacts such as too high temperatures at critical crop stages, or to take advantage of improved growing conditions. Indeed, changing sowing dates is one of the most common recommendations for adapting to climate change (S. Ahmad et al., 2017; Nelson et al., 2010; Paymard, Bannayan, & Haghighi, 2018; Sultana, Ali, Iqbal, & Khan, 2009).

Often reported and recommended changes are delayed sowing of winter crops due to increased autumn temperatures, earlier harvesting due to higher temperatures in spring, and the possibility of an early start of summer crop sowing (Ashutosh, Tripathi, Chauhan, Niraj, & Singh, 2016; S. A. Bhutto, Wang, & Wang, 2019; Dong et al., 2010; Luo, 2011). However, aligning the growing period to shifts in seasons is not straightforward. A delay in sowing may prevent a successful second crop, due to higher temperatures later in the season, especially at lower latitudes. At higher latitudes, delayed sowing may mean that later crop stages are more likely to coincide with sudden drops in temperature, which can hinder tiller growth and cause chilling damage (R. B. Matthews, M. J. Kropff, T. Horie, & D. Bachelet, 1997; Shimono & Okada, 2013; C. Wang, Cai, & Zhang, 2015). Such impacts are also dependent on the prevailing mean local climate (Kutta & Hubbart, 2016). In some parts of the world, like South Asia and the Midwestern United States, temperatures are already near the threshold limits for crop production. Climate change and climate variability here are immediately detrimental, bringing heat stress and greater water losses by evapotranspiration, while also leading to earlier maturation and harvest times, which can diminish yields (Gornall et al., 2010; Hatfield et al., 2018; Kistner et al., 2018).

Adaptation of crop production to climate change is a farm-level decision influenced by many factors, including climate variability risks, workability issues, and input and output prices (Huh & Lall, 2013; Kabir, Alauddin, & Crimp, 2017; H. Shah, Siderius, et al., 2020). Studies of the impacts of and adaptation to shifts in seasons indicate that alternate sowing dates must typically be accompanied by different crop management practices (Shakeel Ahmad et al., 2019; Bhatti et al., 2018; C. Nendel, Kersebaum, Mirschel, & Wenkel, 2014). Most studies, however, ignore the complexity of farm-level adaptations. Modelling studies have highlighted the potential of adjusting crop production to seasonal shifts (Bhatti et al., 2018; Kutta & Hubbart, 2016; Linderholm, 2006; Sparks & Menzel, 2002; Sultana et al., 2009), but have tended to ignore the complexities, diversity and limitations that characterize farm-level decision-making. Farmers face many constraints in adapting their practices, not least in relation to harvest times. Farm household-based surveys are generally better capable of capturing these complexities, but alternate sowing and harvesting dates are often one of many measures addressed, resulting in a lack of the detail required to understand the extent to which farmers can or do modify their practices (Abid, Schilling, Scheffran, & Zulfiqar, 2016; Arshad et al., 2017). As such, relatively little is known about the array of adaptations farmers must make to implement changes in sowing dates.

In the coming decades, further increases in maximum and minimum temperatures are anticipated (IPCC, 2018). Ongoing shifts in seasons and changing growing conditions are expected to continue to affect strategic, farm-level decision-making (Dong et al., 2010). Farm-level sowing and harvesting operations define the crop growing period, and changes in these practices can be indicative of shifts in crop seasons. This points to the importance of understanding how shifts in the meteorological crop season might affect farmers' sowing and management decisions and, consequently, crop yields and production. To identify limits to production and develop alternate farming strategies, research is needed on current shifts in sowing dates and the extent to which farmers may be able to further adapt (Nelson et al., 2010). A better understanding of farmers' perceptions of adaptive strategies and the practices they use to cope with adversities under climate change can help prevent maladaptation (Tripathi et al., 2016). Finally, comparing farm-level adaptations during the crop season in different agroecological zones can help identify where agriculture is or will be most challenged in the future (Ruane, Phillips, & Rosenzweig, 2018).

This paper examines (i) the adjustments that farmers have implemented to cope with perceived shifts in crop seasons; (ii) the limitations to further adjustments and the residual impacts on crop yields; and (iii) farmers' expectations of the potential to further adjust sowing times under anticipated climate change. We focus on the Indus Basin of Pakistan, where much of the population is dependent on agriculture and climate change is already manifesting and expected to lead to further impacts (Bhatti et al., 2018; H. Biemans et al., 2019; Yu et al., 2013).

4.2 Methodology

4.2.1 Approach

Using a farm household survey, we collected data on farmers' perceptions of changes in the local climate, their strategies to adapt to shifts in crop seasons, and expected opportunities and limitations to adapt to future climate change (following Arshad et al., 2017; Elum, Modise, & Marr, 2017). Farmers' perceptions of climate risks and their knowledge about climate changes was considered indicative of their willingness and ability to adapt (Abid et al., 2019) and of their views on the importance of climate conditions for farm-level operations (Abid et al., 2016). Changes in seasonal temperatures and precipitation were used to indicate the impact of climate change on crop production, as these were deemed more relevant than mean annual changes (Gornall et al., 2010). Perceptions of changes were based on memory recollection, spanning a 30-year study period. Data was obtained by interviewing older farmers still involved in day-to-day crop management and farm decisions. Most survey subjects were household heads (Table 3). To check the consistency between the climate changes reported by farmers and those observed at meteorological stations, daily maximum and minimum temperatures and precipitation data were obtained for stations nearest the study sites from the Pakistan Meteorological Department (PMD). For our comparison of perceived and observed changes in seasonal temperatures and precipitation, winter was defined as November to February and summer was defined as June to September. Trend lines were based on a simple linear regression, only plotted when $p < 0.1$.

We defined the 'crop season' as the period in which local weather conditions (rainfall and temperature) permitted normal plant growth. Crop seasons varied with elevation and latitude. Farmers generally had a good understanding of crop seasons in their area, and changes therein, as this was crucial for effective farm management and to adapt to the effects of climate variability. For example, farmers carefully chose sowing dates for optimal crop development and harvesting. Sowing dates were perhaps the most important decision in crop production, as they affected not only farmers' ability to achieve the desired yields and quality, but also the need for and availability and cost of other inputs, such as insect and disease control interventions. Moreover, sowing dates influenced harvest times, which could have a large bearing on the prices obtained for farm outputs (KZN Agriculture and Rural Development, 2020). In choosing sowing dates, farmers therefore had to consider many factors, not least the expected time to maturity and harvest and the expected length of the growing period.

We traced shifts in crop seasons based on farmers' estimates of changes in both the start and end dates of seasons, considering changes in temperatures and frost periods at the study sites, and reported in days of the month. These estimates were cross-checked with observations of associated shifts, for example, in spring thaws, the blooming of spring flowers, germination of seasonal weeds and germination rates associated with different sowing dates. To promote the accuracy of the estimates and reduce inconsistencies in responses, we began our interviews by seeking annual and seasonal-level information, and then narrowed our questioning to changes in the start and end dates of crop seasons.

We defined the 'growing period' as the actual period in which farmers grew a crop (i.e., their farming practice in a given agroecological setting) – as distinct from the 'crop season', which is based on meteorological conditions in which crop growth and development was possible. The growing period began on the date sowing operations started and ended with the harvesting of a crop, as practiced by the respondent farmers within a crop season. Adjustments made by the farmers in the growing period were estimated based on respondents' recollections over the 30-year study period. These estimates were verified, especially where contradictions arose between shifts in crop season and growing period.

To guide the interviews, critical moments were identified at which crops were deemed particularly sensitive to certain climate conditions, whether due to biophysical vulnerability or to management or operational constraints. The sowing and harvesting stages each brought specific critical moments, which were explored in detail through survey interviews (H. Shah, Hellegers, et al. (2021). To supplement the survey interviews, four focus group sessions were held (one at each site) with 8-12 farmers at each.

To measure the shift in crop season, we used the sum of the mean change in the start and end date of the season, calculated as the mean change in the number of days the season started early (+) or late (-) and ended early (-) or late (+), compared to 30 years earlier, $t - 30$:

$$Scs_{ijk} = (\sum_{i=1}^{n} cs_{ijkt}/n) - (\sum_{i=1}^{n} cs_{ijkt-30}/n) \qquad (1)$$

where Scs_{ijk} is the shift in crop season at site s_i for crop x_j and season y_k at time *t.*

Similarly, the change in growing period was measured as the sum of the change in the mean date of sowing, whether early (+) or late (-), and harvesting, early (-) or late (+), for each study crop, compared to 30 years earlier:

$$Cgp_{ijk} = (\sum_{i=1}^{n} gp_{ikjt}/n) - (\sum_{i=1}^{n} gp_{ijkt-30}/n) \qquad (2)$$

where gp_{ijkt} is the length of the growing period in days at site s_i for crop x_j and season y_k at time *t* (currently practiced), gp_{ijt-30} is the length of the growing period as practiced by farmers at time t−30 years and *n* is the sample size at site s_i. The change in the growing period was cross-checked with the change in number of growing degree days (GDD) as per the meteorological observations from nearby stations. GDD were computed according to Gallagher & Biscoe, (1978):

$$GDD = \sum_{1}^{n} \frac{(T_{max} - T_{min})}{2} - T_{base} \qquad (3)$$

where T_{base} is the base temperature, taken as 4.5°C for wheat (Acevedo, Silva, & Silva, 2002; Dar, Brar, & Yousuf, 2018) and 8°C for maize (Lizaso et al., 2018). Changes in *GDD* were estimated for both the start and end period of the crop seasons.

Shifts in seasons and adjustments in growing periods impact crop yields. Farmers were found to be aware of yield differences corresponding to delays in sowing and/or early maturity and resultant changes in harvest times. Crop growing periods varied between different plots on the same farm. This was due to diversification strategies (Abid et al., 2019), crop rotation (Jabbar et al., 2020) and management constraints (especially associated with labor, machinery or a previous crop being harvested late in a particular year) (H. Shah, Siderius, et al., 2020). Such variation, combined with a variable climate, meant that some years were more representative of historical climate conditions, while others were reflective of the 'new normal'. Over the years, farmers' experiences had given them insight into probable yield differences resulting from changes in season lengths and their own adaptation responses.

We first asked respondents for yield data for the most recent crop seasons, reflecting the sowing and harvesting times currently practiced, that is, for the current, dominant growing period. Second, we asked respondents to estimate the yield levels that could be obtained by sowing and harvesting under conditions similar to those prevalent three decades ago, but assuming all other practices and technology were like those of today. The difference provided an illustrative estimate of the yield change that could be attributed to shifts in seasons and farmers' responses to these shifts.

The impact of a shift in seasons on yield ($ISSY_{ijk}$) was measured as the change in yield per day of change in the growing period, as follows:

$$ISSY_{ijk} = \frac{(Ygp_{ijkt} - Ygp_{ijkt-30})}{|(gp_{ijkt} - gp_{ijkt-30})|} \quad (4)$$

where Ygp_{ijkt} is the yield in kilograms per hectare at site s_i of crop x_j for crop season y_k at time t (year), and $Ygp_{ijkt-30}$ is the yield in kilograms per hectare at site s_i of crop x_j for crop season y_k with a growing period similar to one at time $t-30$ years; gp_{ijkt} is the length of the growing period in days at site s_i for crop x_j and crop season y_k at time t (currently practiced), and $gp_{ijkt-30}$ is the length of the growing period as practiced by farmers at time $t-30$ years. At one of the study sites, the mountain valleys, farmers planted wheat during the dormant period in winter, with germination occurring when temperatures reached a certain threshold. Thus, sowing practices here did not need to change for farmers to take advantage of the shift in seasons. To estimate the impact of seasonal shifts on wheat yields at this site, in yield per day of change, we used the change in estimated start date of germination rather than the change in date of sowing.

Adjusting sowing and harvesting dates is not the only adaptation strategy available to farmers to mitigate potential yield losses due to changes in the seasons. Other complementary adaptation options include switching crop varieties, increasing seeding rates and applying additional nutrients. We measured the cost of these in Pakistani rupees (PKR) per unit area, both applied individually and as a sum of different options combined. In our cost estimates, we included both monetary costs and opportunity costs. To estimate the opportunity costs, we considered operations performed with own farm machines, family labor and farm inputs (seed). Hence, the total cost (C_{hij}) of adaptation option x_h at site x_i for crop x_j in growing period t was measured as follows:

$$C_{hij} = \sum_{k=1}^{K} \sum_{t=1}^{T} p_{kijt} a_{kijt} \quad (5)$$

where p_{kijt} is the unit price of the k^{th} variable input used as a complementary adaptation option at site s_i applied to crop x_j at time t; a_k is the amount of the k^{th} input for crop x_j at site s_i at time t; and the subscript t=1, ..., T identifies the time intervals for different crop seasons within a year.

The potential for adapting to further shifts in seasons under climate change was also explored. We asked farmers their expectations regarding climate change, its implications for crop production and their adaptation options. Farmers were explicitly asked how much more they thought they could adjust sowing and harvesting dates to respond to shifts in seasons.

4.2.2 Study area, sample design and data collection

Our study focused on crop production in the Indus Basin of Pakistan, specifically in the Hindu Kush Himalayas and the Indo-Gangetic Plain (see Table 7). Here we chose four study sites, representing different agroecological zones. Each had a distinct cropping system, differing in terms of their importance to food security and their vulnerability to climate change due to spatial-climatic features posing particular challenges for sustainable crop production (H. Biemans et al., 2019; Fowler & Archer, 2006; G Rasul et al., 2012; Sultana et al., 2009).

The four study sites were as follows: (i) the high mountains (mountains) with a dominant potato and wheat cropping system grown in a single crop season; (ii) mountain valleys (valleys) with a maize-wheat cropping system; (iii) the mid-hills with a rainfed groundnut-wheat cropping system; and (iv) the irrigated plains (plains) with a rice-wheat cropping system.

For sowing and harvesting operations at the study sites, we considered two main meteorological seasons: summer and winter (Trenberth, 1983). These parallel Pakistan's two primary crop seasons, which are kharif (summer) and rabi (winter). The sowing and harvesting periods for crops in both seasons varied by agroecological zone (S. Ali et al., 2014; Government of Pakistan, 2018b; Hashmi & Shafiullah, 2003; S. Khan & Khan, 2019; Mehmood et al., 2019). At the low-altitude sites (the plains and mid-hills), summer (kharif) crops were sown from April to June, with harvesting from October to December. Wheat was grown in the winter (rabi) crop season, with sowing starting at the end of October and extending to mid-December and harvesting done in April and May (S. Khan & Khan, 2019). At the high-altitude sites, in the valleys (2,300–3,000 m), maize was grown from June to November and wheat from February to June. In the mountains (above 3,000 m), wheat and potatoes were grown in a single crop season, from April to September (S. Ali et al., 2014; Hashmi & Shafiullah, 2003; Mehmood et al., 2019).

Each study site comprised a cluster of 6–9 villages located in close proximity and considered part of a distinct agroecological zone. Respondent farmers were selected using stratified randomization to minimize differences in cropping patterns, soil, water availability, water quality and market conditions. Some 7–12 farm households were randomly selected from each village. In total, 287 farm households were considered for analysis: 73 each on the plains and in the mid-hills, 69 from the valleys and 72 from the mountains. For further details on the study sites, cropping systems, sampling, data collection, the questionnaire and characteristics of the sample farmers, see H. Shah, Siderius, et al. (2020).

Table 7. Study sites, sample size and characteristics of the respondents

Study Sites	**Plains (Sargodha)**	**Mid-hills (Chakwal)**	**Valleys (Gilgit)**	**Mountains (Upper Hunza)**
Agroecological zone	Northern irrigated plains (IVa)	Barani lands (V)	Northern dry mountains (VII)	Northern dry mountains (VII)
Altitude range (m)	200	450–500	1,600–1,800	2,500–3,000
Cropping system	Rice-wheat	Groundnut-wheat	Maize-wheat	Potato-wheat
Sample size (#)	73	73	69	72
Age of respondents (years)	50.52 (10.53)	51.33 (11.97)	48.49 (12.91)	50.71 (12.03)
Education of respondents (years)	5.85 (4.88)	8.08 (3.81)	8.33 (5.14)	7.96 (4.79)
Respondent is household head (%)	85	78	71	79

Note: Figures in parenthesis are standard deviations.

4.3 Results

4.3.1 Farmers' perceptions of changes in temperatures, rainfall and shifts in seasons

At each study site, most farmers reported changes in climate conditions over the past three decades. Perceived changes differed by site. Most farmers (>90%) at the sites exposed to the most extreme temperature conditions, that is, the hot summers of the plains and mid-hills sites and the cold, snow-dominated winters in the mountains, reported increased temperatures in both summer and winter. There was less agreement among farmers in the mountain valleys (valleys), where the climate was more moderate (Figure 9). Farmers in the valleys who reported 'no change' or decreased temperatures often did mention increased climate variability. Farmers gave recent examples of sudden drops in temperatures associated with unseasonal rains at the start or end of a season.

At the low-altitude sites (the plains and mid-hills), most farmers reported decreased rainfall (mm) in both summer and winter (Figure 9). Among farmers in the mountains, 84% reported increased summer rainfall and that the area remained snow-packed with no crop production during winter. During focus group sessions at both high-altitude sites, participants generally agreed that snowfall had diminished, as evidenced by the lack of snow or smaller amounts of snow at the foot of the mountain peaks, compared to the past. Farmers in the mountain valleys were not in agreement regarding changes in summer rainfall, and had different impressions of changes in the amount of snowfall in winter. They reported decreased frequency of rain in the summer, though reporting increased short-duration high-intensity summer rainfall events. Regarding winter precipitation, mountain valley farmers reported a decrease or no change.

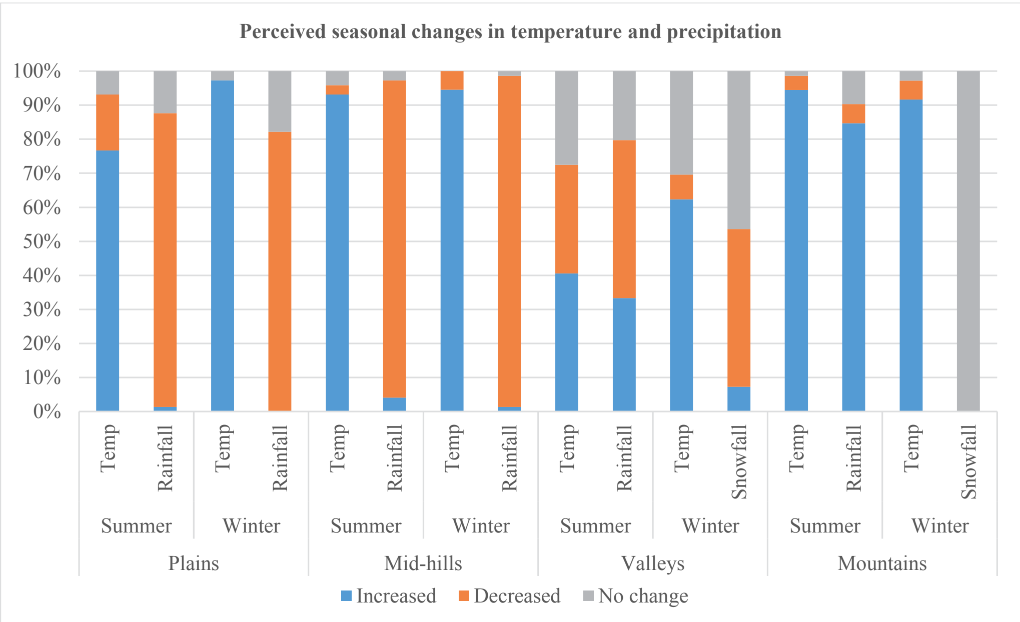


Figure 9. Perceived changes in seasonal temperature and precipitation over the last 30 years at study sites

Farmer perceptions of changes in temperatures largely corresponded with observations from the meteorological stations (Figure 10). On the plains, the perceived increase in temperatures was reflected mainly in higher observed minimum temperatures, especially during the winter months. Maximum winter temperatures seem to have actually decreased here, perhaps as a result of increased smog (Raza et al., 2021; M. Umar et al., 2021), leading to reduced visibility and limiting incoming solar radiation

(Padma Kumari, Londhe, Daniel, & Jadhav, 2007; Shao et al., 2021) (see Figure-3A1, Annex-3A). Weather data for the mid-hills site was only available after 2009, and clear trends here were lacking. However, the station representing the plains was relatively close to the mid-hills site, and farmers' perceptions of trends were similar at both locations. In the mountain valleys, the increase in observed maximum winter temperatures corresponded with farmers' perception of a shortening of the winter season. In the high mountains, not only minimum but also maximum temperatures showed a clear upward trend (*p*-value of 0 meaning a *p*-value < 0.001).

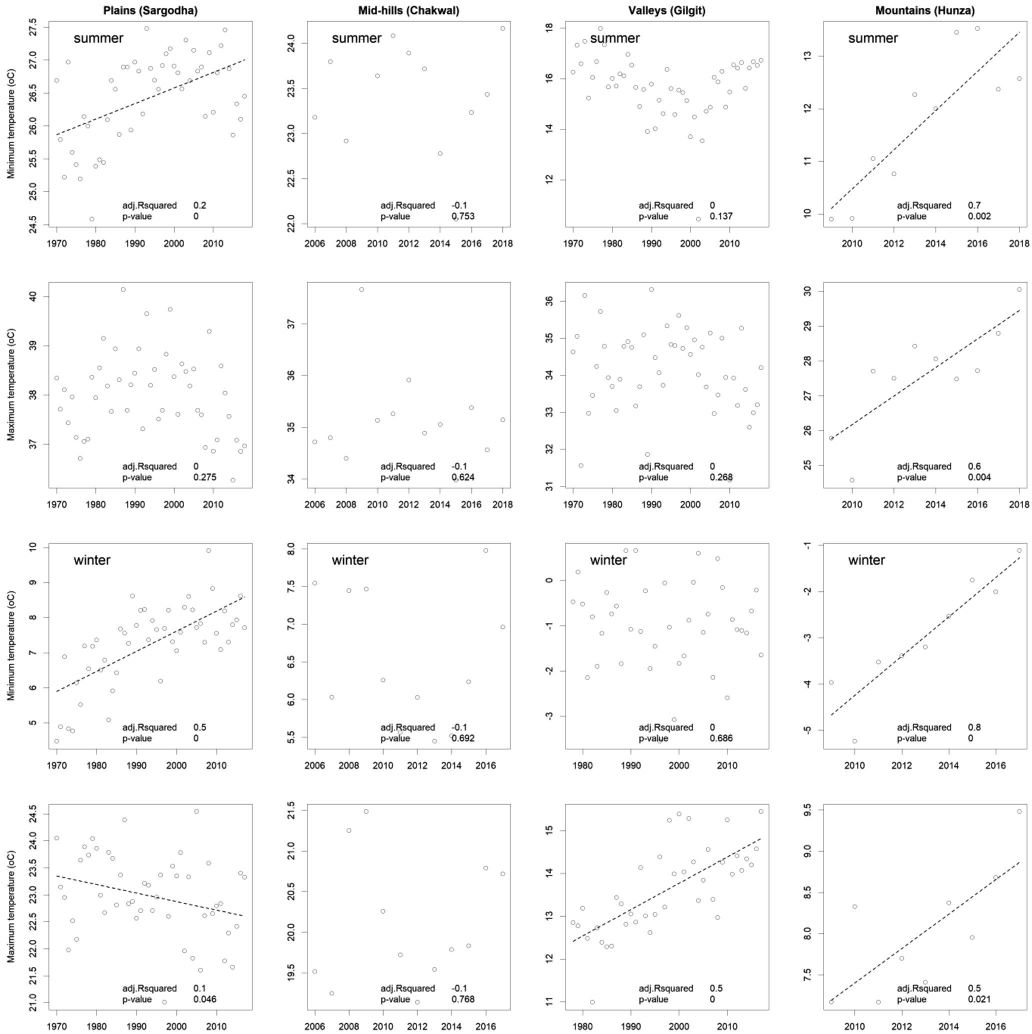


Figure 10. Min. and maxi temperature trends during summer and winter seasons at the study sites

Perceived precipitation changes were somewhat consistent with observations from the meteorological stations (Figure 11). Decreases in precipitation in the mid-hills and high mountains over the past ten years corresponded with farmer perceptions. The absence of a clear trend in the data from the mountain valley station was reflected in the mixed responses of farmers. A significant increasing long-term trend in summer precipitation for the plains went counter to farmers' experiences, but the observed trend was weak. Farmers likely had a more complex understanding of changes in precipitation, with intensity and timing of precipitation events and their complementarity to irrigation water availability being equally or more important than seasonal precipitation totals.

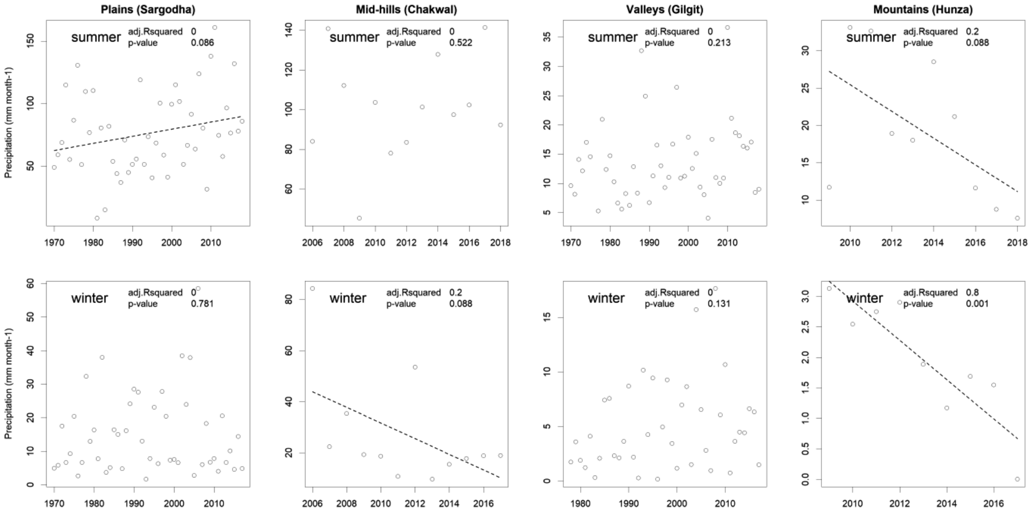


Figure 11. Precipitation trends during summer and winter seasons at the study sites

4.3.2 Adjusting farming practices to shifts in seasons

Shifts in seasons were observed at all study sites, associated mainly with changes in seasonal temperatures. Overall, farmers perceived an earlier start and later end of the summer season, resulting in longer summers and shorter winters. At the lower altitude sites, farmers' observations indicated that the summer season had lengthened by approximately five weeks; 34 and 36 days, respectively, for the plains and mid-hills over the past three decades. At the higher altitude sites, a 15 and 18 day extension in the crop season was observed, respectively, in the valleys and mountains, over the three decades. In response to the changes in crop seasons, farmers had adjusted their farming practices. At all sites, the timing of both sowing and harvesting were affected, resulting in changes in the overall growing period from both ends (Figure 12). The direction of the changes observed also varied by agroecological zone and altitude.

Changes in GDD, derived from station observations of temperature, for the start and end of growing periods matched farmers' perceptions (Table 8). In the plains, there was an increase of 10 GDD during the second half of November (the main wheat growing period) from the first decade (1989-1998) to the last decade (2009-2018) under study. For the end of the winter crop growing period, in the first half of April, a net increase of 40 GDD was observed, resulting in earlier plant maturity. With later sowing and earlier maturity, the winter crop growing period was squeezed from both ends. For the mid-hills site, we assumed similar changes in GDD for the reasons discussed earlier. In the valleys, a sharp increase in GDD at both the start and the end of the crop growing period was found in the second decade under study, which then persisted in the third decade. The early germination reported by farmers due to higher temperatures corresponds with a higher GDD during the same period. In the mountains, during the last decade, a consistent increase in five-year average GDD was observed, matching farmers' reports regarding a lengthening of the growing period here.

Table 8. Average GDD at the start and end of the growing period

Site	Plains		Valleys		Mountains		
Crop/stage	Wheat sowing	Wheat maturity	Wheat sowing	Maize maturity		Wheat sowing	Wheat maturity
Period	Nov 16-30	April 1-15	Feb 1-29	Oct 1-30		April 1-30	Sept 1-31
1989-1998	196	274	59	178	--	--	--
1999-2008	201	329	84	191	2009-13	193	351
2009-2018	207	314	84	200	2014-18	222	408

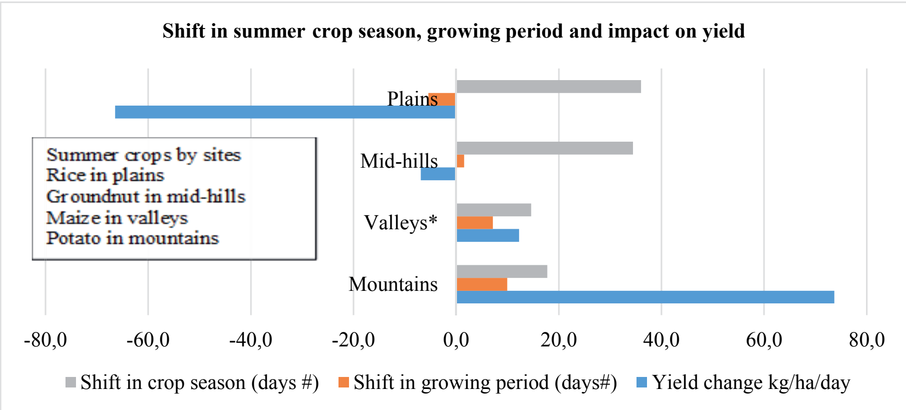
On the plains and in the mid-hills, the summer crop season had lengthened, but the actual growing period had shortened. The rice growing period had shifted to later in the year, due to later sowing. The harvest period was delayed less than sowing, due to the higher temperatures reported at plant maturity. This resulted in a net decrease in the rice growing period. We found a slight increase in the groundnut growing period in the mid-hills. This was due to an earlier start only (early sowing). But early sowing resulted in early maturity and early harvesting, which neutralized some of the gain in growing period achieved by sowing early. The time to ripening or harvesting was linked mainly to sowing date. Thus, early sown crops tended to be harvested early and late sown crops harvested late. Regarding yield, farmers reported a positive impact of early sowing on groundnut development, but they noted a negative effect of early ripening in case of higher than average temperatures, resulting in a net decrease in groundnut yield. Similarly, rice yields had declined. Hence, despite the extended summer season both on the plains and in the mid-hills the growing period for summer crops had shortened, with a negative impact on yields. Farmers attributed lower rice yields to delays in sowing and higher temperatures at maturity. The shorter winter season, starting late and ending early, meant that the wheat growing period was shorter on the plains and in the mid-hills, and farmers reported changing their sowing and harvesting practices accordingly. Farmers on the plains and in the mid-hills said that the shorter wheat growing period, resulting from both late sowing and early harvesting/maturity, led to diminished yields.

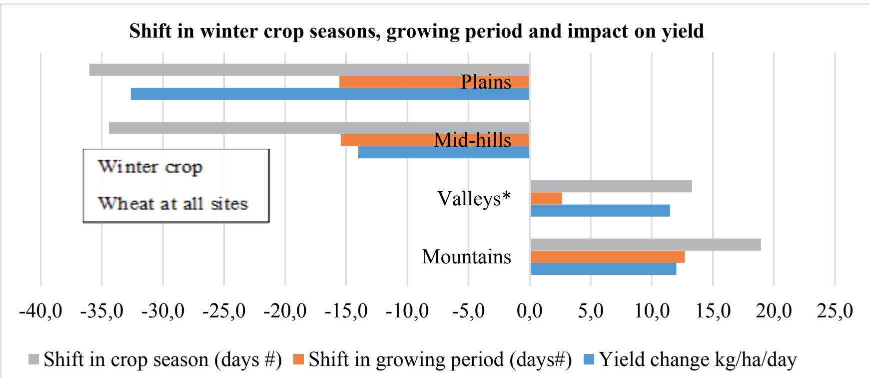
The direction of the shift in the sowing and harvesting of the winter crop at all sites was similar to the direction of the shift in season (Figure 3AI., Annex 3A2), while for summer crops at the low-altitude sites (the plains and mid-hills) the direction of the shift differed from the change in the summer season (Figure 3B, Annex 3B). Farmers here could choose to plant their summer crop earlier. Yet, despite the early start of summer, farmers on the plains opted for later rice sowing, mainly due to delayed summer rains and to avoid the cost of irrigation water, considering the higher temperatures. In the mid-hills, 75% of farmers opted for early sowing of groundnut, thus conserving moisture from winter rainfall but exposing the crop to moisture stress in case of delayed summer rains. The other 25% of farmers opted for late sowing of groundnut, despite the summer season starting early, mainly to avoid the risk of moisture stress due to delayed summer rains, especially the pre-monsoon rains.

At the high-altitude sites (the mountain valleys and mountains), the growing period for summer crops (maize and potato) was reportedly 7–10 days longer than in the past, while for the winter crop (wheat), the growing period was about 12 days longer in the mountains and only 2–3 days longer in the mountain valleys. The change in the growing period at both high-altitude sites was in line with the direction of the shift in crop season. Farmers here tended to sow early and harvest late, with the extended summer season providing more time for crop management at the sowing and harvesting stages. Shorter winter dormant periods were also observed; that is, the period in which the soil was frozen and snow covered. This resulted in a longer wheat growing period, mainly due to early sowing, with the earlier onset of spring. Farmers considered the extension of both the summer and winter growing periods beneficial in terms of yields and grain quality, as better ripening was reported under the higher temperatures at both high-altitude sites.

Despite the fact that an early end of winter meant an early start of the wheat crop season, with the possibility of early sowing/germination and late harvesting, only up to half of the farmers had changed their growing practices at the high mountain site. In the mountains, those farmers who had not shifted to earlier sowing mentioned the risk of crop failure due to a sudden drop in temperature at the early germination stage. Farmers in the mountain valleys planted wheat during the dormant period in winter. Thus, no significant change in sowing time was reported here. However, mountain valley farmers did report earlier wheat germination due to the shift in season, which had a positive impact on wheat yields (Figure 12).

Thus, the change in growing period (based on farmers' sowing and harvesting practices) was less marked than the shift in the summer and winter crop seasons at all sites. The reported changes in both crop seasons and growing periods were more marked at the two low-altitude sites than at the high-altitude sites. The direction and magnitude of the shift in sowing and harvesting practices, and the respective impacts on yields of summer and winter crops at the four sites, are presented in Annex 3C and 3D.





* At this site, the change in yield was due to a change in germination date (ending the winter dormant period), hence the impact on yield was calculated using the shift in season (days).

Figure 12. Shift in crop seasons & growing period and impact on yield for summer & winter crops.

4.3.3 Complementary adaptations

Farmers at the low-altitude sites had to do more than just adjust sowing dates to maintain their yields. They adopted a number of complementary measures to mitigate yield losses. Two main strategies were switching varieties (to short duration and heat tolerant varieties) and greater application of inputs (seed and fertilizer). Farmers on the plains reported using larger amounts of seed and fertilizer, as their access to irrigation water gave them more flexibility in application of these inputs. Such flexibility was lacking in the mid-hills, where farmers were dependent on rainfall. On the plains, farmers adopted both complementary strategies, usually in combination, while most mid-hill farmers (74%) adopted these separately. Some 54% of mid-hill respondent farmers indicated having switched varieties, and 20% used a higher seeding rate. Crop diversification, that is, allocating some farm area to other crops, in combination with the aforementioned adaptation strategies, was reported by 3% of the respondent farmers on the plains and 11% of those in the mid-hills.

Complementary adaptation brought additional costs. Among the adaptation strategies practiced, a higher seeding rate was the one with the lowest cost, followed by switching varieties and using additional fertilizer (Table 9). Farmers also applied various combinations of these, with the cost of combinations ranging from 2,400 to 5,800 PKR/ha for wheat and 1,600 to 7,600 PKR/ha for rice. Cost depended on the price of the inputs and the quantities used. For wheat, farmers in the mid-hills spent less on adaptation than those on the plains, as mid-hill farmers used smaller additional quantities of inputs (seed and fertilizer) considering the moisture limitations there.

Table 9. Cost of complementary adaptation strategies for the shortened growing period (PKR/ha)

Adaptations	Plains (wheat)		Plains (rice)		Mid-hills (wheat)	
	Cost (PKR/ha)	Response (%)	Cost (PKR/ha)	Response (%)	Cost (PKR/ha)	Response (%)
Switch varieties	1,285 (±207)	8	680 (±87)	8	1,339 (±470)	54
Increase fertilizer dose	3,855 (±2,079)	8	3,707 (±3,495)	8		
Raise seeding rate	791 (±271)	8			659 (±231)	20
Switch varieties and increase fertilizer dose	4,201 (±1,503)	8	1,606 (±1,223)	8		
Increase fertilizer dose and seeding rate	4,744 (±1,691)	15	4,374 (±2,054)	38		
Switch varieties, increase fertilizer dose and increase seeding rate	5,830 (±1,596)	47	7,660 (±3,643)	15	3,354 (±620)	15
Switch varieties, increase seeding rate and diversify crops	3,707 (±1,747)	3	4,654 (±981)	23	2,422 (±442)	11
Increase fertilizer dose, increase seeding rate and apply additional irrigation	7,042 (±524)	3				
Total	4,639 (±2,246)		4,396 (±2,709)		1,630 (±981)	

Note: The figures in parenthesis are standard deviations.

4.3.4 Adapting to future shifts

In the future, farmers at all sites expected shifts in seasons and changes in growing periods similar to those experienced in recent decades. At the low-altitude sites, farmers expected a further shortening of the growing period for rice and wheat, with negative impacts on yields. On the plains, only 25% of farmers expected a further shortening of the rice growing season, attributed mainly to delays in rice transplanting due to increased temperatures and changes in rainfall patterns. Farmers in the mid-hills did not expect further major changes in the groundnut growing period. However, both on the plains and in the mid-hills, farmers expected increasing temperatures to negatively impact summer crop yields. Farmers at these sites also expected a further shortening of the winter crop season. On the plains, 82% of respondent farmers expected further delays in wheat sowing, and 42% expected an early start of harvesting. In the mid-hills, 78% of farmers expected further delays in the start of wheat sowing, and 52% expected an early start of harvesting.

At the high-altitude sites, farmers expected a further lengthening of both crop seasons and growing periods due to shorter winters (dormant/frost period) along with further increases in temperatures. In the mountain valleys, 33% of respondent farmers expected an extension of the wheat and maize growing period, with the possibility of earlier sowing in the future. In the mountains, 64% of respondent farmers expected an earlier start of sowing, and 24% expected later wheat harvesting. Regarding potato, 58% of respondent farmers expected a longer potato growing period, mainly due to earlier sowing. Farmers at the high-altitude sites considered this shift beneficial and expected improvements in crop yields and quality due to better ripening and more flexibility in crop management under the extended growing periods of the future.

Figure 13 presents the shift in wheat sowing periods and expected sowing limits. The recommended sowing time for wheat on the plains used to be prior to mid-November, but this had changed to a more spread period extending from the first week of November to mid-December. A constraint here was conflicts with late-maturing rice varieties and operational issues like the difficulty of cultivating land with rice stubbles and too wet or too dry fields causing delays in wheat sowing (M. Aslam, Majid, Hobbs, Hashmi, & Byerlee, 1989; Byerlee, Sheikh, Aslam, & Hobbs, 1984; Sheikh, Byerlee, & Azeem, 1988). At the time of our research, the sowing period on the plains started in the second week of November, but the spread was large, as sowing continued through to the end of December. In the mid-hills, wheat sowing had started in mid-October in the past and was completed by the first week of November. This had already shifted by about two weeks.

Farmers expected limits to further postponement of wheat sowing. The median week for the maximum possible shift in wheat sowing on the plains was considered to be the end of December; in the mid-hills this was mid-December (see Annex 3E). Moreover, farmers expected that no further delay in wheat sowing would be feasible, because sufficient time was needed for crop stand establishment, and higher temperatures were known to compromise grain development. The limits observed varied between the plains and mid-hills due to differences in their agroecologies and cropping systems. Farmers on the plains estimated the limit to wheat sowing as two weeks later than mid-hill farmers, mainly due to the former's flexibility to mitigate potential yield losses by using higher levels of inputs and irrigation.

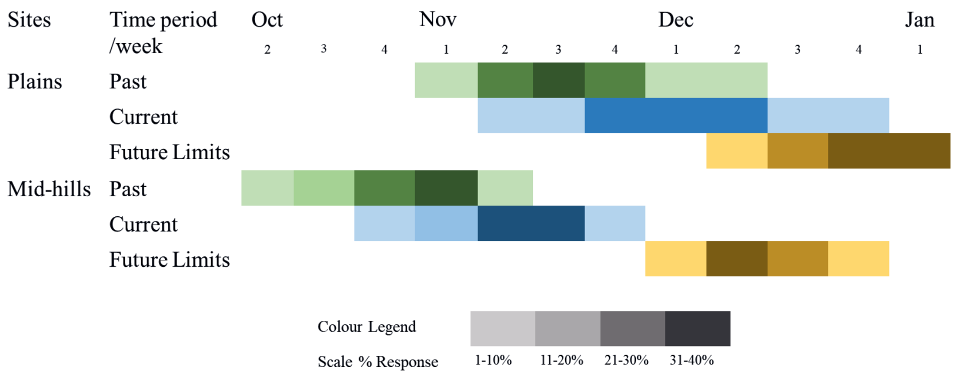


Figure 13. Changes in wheat sowing period and future limits with expected seasonal shifts, according to farmers' responses (*n*=142)

To adapt to shorter growing periods with continued seasonal shifts, farmers expected to rely on crop management practices as well as to switch to enterprises other than crop farming. Rice and wheat farmers at the low-altitude sites mentioned adaptation by using improved seed varieties (shorter duration, more stress tolerant varieties); higher input applications (seeding rate and fertilizer); crop diversification, particularly switching some of their wheat and rice area to other crops; investments in new irrigation sources; and soil and water conservation (Figure 14). Another strategy mentioned was optimization of irrigation scheduling and management at the plot level by adjusting the timing, frequency and quantity of water delivery – though this was reported by very few respondents (<5%). For groundnut, farmers mentioned only one possible adaptation: adjusting sowing times in line with moisture availability within the extended summer season. Farmers in the mid-hills said they planned to invest in high-efficiency irrigation systems and in water conservation and harvesting, and also to adopt soil and moisture conservation technologies such as intercropping, improved tillage and drainage. At the high-altitude sites, farmers reported plans to switch varieties and crop mixes to harness the opportunities presented by an extended growing period. Regarding other enterprises, shifts to non-farm activities, horticulture and livestock operations were mentioned, with some differences between the sites. Regarding agricultural enterprises, farmers at the mountain sites were more inclined towards horticulture crops, mainly fruits, while farmers in the mid-hills and on the plains indicated the possibility of expanding livestock operations. Relatively larger numbers of farmers at the high-altitude sites mentioned shifting away from farm activities entirely as a future adaptation option, compared to farmers at the sites in the mid-hills (rainfed) and plains (irrigated).

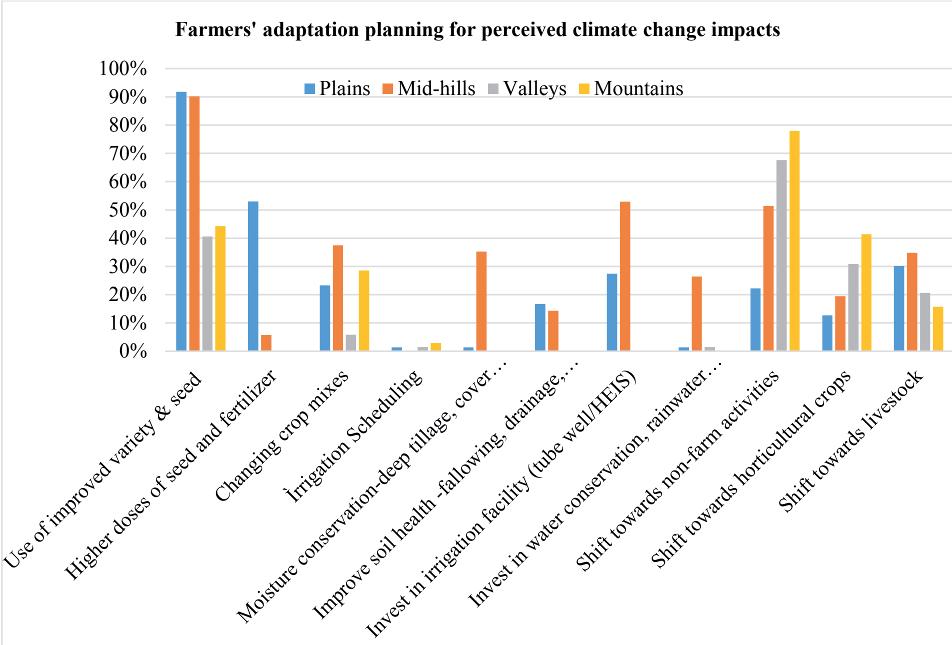


Figure 14. Farmers’ adaptation strategies for climate change impacts

4.4 Discussion

We explored farmers’ perceptions of changes in temperatures and precipitation and their associated adjustments in crop growing periods, using household survey data from four agroecological zones of the Indus Basin, Pakistan. Farmers’ perceptions of temperature trends over the past 30 years generally matched well with station observations. Perceived changes in precipitation were more mixed, with station observations indicating no uniform trends. Our findings on changes in both the start and end dates of crop seasons correspond with those reported by Yasmeen, Basra, Ahmad, & Wahid (2012) and M. A. Aslam et al. (2017), and the resulting yield losses are consistent with those reported by S. A. Bhutto et al. (2019). Our results furthermore are in line with the review by Linderholm (2006), which found a lengthening of the summer crop season over the previous three decades, with an earlier onset of summer being the most prominent change.

Phenological studies such as those mentioned above, and others recommending adaptation (e.g., S. Ahmad et al., 2017; Nelson et al., 2010; Paymard et al., 2018; Sultana et al., 2009), tend to focus on temperature conditions to determine the available time windows in which farmers can adjust the growing period. However, as we demonstrated, an array of factors influences farmers’ decisions on planting and harvesting, such as the risk of extreme weather, moisture limitations, irrigation water availability, management options (especially the availability of labor and machinery) and the cost of implementing the various measures. Under controlled conditions at experimental field sites, rice phenological stages were found to have advanced, while wheat sowing could be delayed (Shakeel Ahmad et al., 2019). In practice, we found farmers delayed rice transplanting because of, for example, moisture limitations, lack of irrigation water availability and the high cost of tube well irrigation, while delayed wheat sowing was associated with higher risks at the maturity stage, particularly in the low altitudes. Farmers in the high mountains had hardly shifted their sowing of wheat and potato to take advantage of the earlier end of winter, as early sowing was perceived to bring a higher risk of crop failure, due to the possibility of a sudden drop in temperatures at the early germination stage. These factors prohibited farmers from taking advantage of the modest, or gradual, changes they perceived in mean temperatures and the resulting seasonal shifts, and they explain why farm practices do not necessarily parallel shifts in crop seasons.

By considering the limitations farmers faced in adjusting planting dates, the current study demonstrates the importance of complementary measures to compensate for potential yield losses. The generalizability of our results is obviously limited to these four agroecological zones, and their dominant cropping systems. Yet, our findings generally confirm studies reporting a potential decline of wheat yields, with all else being constant, in rice-wheat cropping systems, due to a shortening of the growing period (P. Aggarwal et al., 2000; S. M. Ahmed & Meisner, 1996; Hobbs & Morris, 1996; Ortiz-Monasterio et al., 1994). However, we found impacts on yields to vary by agroecological zone. Farmers in the low-altitude, warmer agroecological zones experienced reduced crop yields due to the shorter growing period, while farmers in the higher altitude, colder agroecological zones benefited from an extended growing period under climate change. In these latter zones, the experienced climate change has positively impacted crops in both seasons, as also reported by others (Hashmi & Shafiullah, 2003; S. S. Hussain, Mudasser, Sheikh, & Manzoor, 2005; Golam Rasul et al., 2019). This suggests that the high-altitude, colder agroecological zones could be considered 'winning' zones, compared to the low-altitude, warmer zones.

Climate change is anticipated to further increase the suitability of middle- and high-latitude areas for wheat cultivation (Yue, Zhang, & Shang, 2019). Pakistan forms a middle-latitude area, and suitability for wheat cultivation here increases from south to north with increased latitude and altitude. However, due to the limited area of arable land at higher elevations, the potential to expand wheat production remains limited (S. S. Hussain et al., 2005). Eighty percent of Pakistan's cereal production comes from the Indo-Gangetic Plain (Gupta & Seth, 2007), and maintaining production levels in this region seems crucial to meet the country's needs. As rice and wheat are already grown near their temperature threshold limits here (M. V. Sivakumar & Stefanski, 2011), the increasing trend in thermal sums during the wheat maturity period implies a rising risk of yield losses from heat stress. Possibilities to expand multiple cropping during the extended summer crop season will depend on water availability. Hence, further adaptation planning is needed to prepare farmers for shifts in crop seasons, changes in growing periods and increased seasonal variability, in order to meet future food requirements.

Complementary adaptation strategies are also needed. Our results indicate that shifting sowing practices alone is not a sufficient response to the challenges posed by climate change. Farmers on the plains and in the mid-hills had experimented with a combination of other adaptation measures to reduce the negative impacts of the shorter growing period. The additional cost of these adaptations is often overlooked, but has major implications for farm profitability (H. Shah, Hellegers, et al., 2021). Their feasibility, moreover, is often dependent on irrigation facilities and service delivery. On the plains, for example, farmers' ability to implement these adaptations was constrained by the cost and timely availability of irrigation water. Thus, recommendations of adaptation measures need to be tailor-made, considering the characteristics of each agroecological zone, as well as costs and farm profitability.

A majority of the surveyed farmers expressed concern about future limits to adjusting practices, especially in agroecological zones already negatively impacted by climate change. An often promoted alternative, the adoption of short-duration varieties, has equally been hampered by the direct relationship between crop yield and growing period (M. A. Aslam et al., 2017). We found that farmers were already looking beyond their existing cropping pattern and considering crop diversification as a potential adaptation option. This indicates their awareness that the sustainability of their current livelihood and traditional cropping system is under threat. If global warming goes unchecked, a transformation beyond incremental adjustments, such as changes in sowing and harvesting dates, seems required.

4.5 Conclusion

This study sought a contextual understanding of farmers' responses to shifts in crop seasons. It found that farmers had adjusted their growing practices in response to the risks posed by climate variability and limitations, especially by adjusting sowing dates. However, these adjustments did not necessarily parallel the shift in seasons, and they tended to fall short of the potential reported from controlled field site experiments and recommendations based on model simulations. This study highlights the importance of combining biophysical and socioeconomic insights to develop adaptation recommendations. We found that the direction of the shift in crop seasons, the changes in growing periods and impacts on yields varied by cropping systems and agroecological zones. Our results indicate shortened crop growing periods in the low-altitude, warmer agroecological zones, irrespective of the length of meteorological crop seasons. These shorter growing periods had negative impacts on crop yields. Beyond adjusting sowing dates, farmers considered complementary adaptations essential to maintain crop yields. These included use of improved varieties developed for specific agroecological zones, higher seeding rates and additional fertilizer application. Opportunities were identified in the high-altitude, colder agroecological zones to increase yields, in response to the observed shift in seasons. But these positive impacts are minor compared to the negative overall impacts of climate change on agricultural production in the Indo-Gangetic Plain, where much of Pakistan's crops are produced.

In the low-altitude agroecological zones, farmers cannot keep up with the shift in seasons. Further changes in the start of the sowing period would reduce yields such that wheat production would become unfeasible. To enable farmers to adjust their growing practices to the shift in seasons, adaptation plans need to include improved capacity to cope with climate variability, incremental adjustment of practices and complementary adaptations. Further, in the 'losing' agroecological zones, advances are needed in adaptation and mitigation pathways, as farmers are rapidly approaching limits beyond which they consider production of their current crops unfeasible. Our analysis highlights that everywhere farmers will need to adapt to shifts in seasons, even where the changes might ultimately be beneficial. Our findings also point to major challenges to productivity and greater difficulties in managing risks of climate variability. To help farmers adapt and cope with climate risks, in addition to place-based technological innovations, farmers need an active institutional support system that incorporates science-based climate information and forecasts into planning, policy and practice.

Acknowledgement

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Annexures

Annex-3A. Visibility (Sunshine hours) trend at low altitude (Sargodha) site

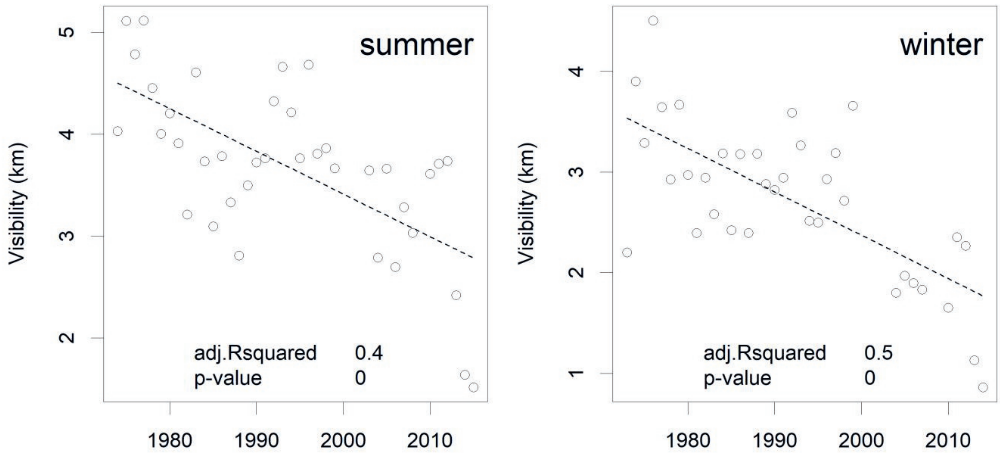

Figure 3A. Solar radiation trends during summer and winter in Pakistan

Annex-3B. Direction of the shift in season and sowing and harvesting practices of crops

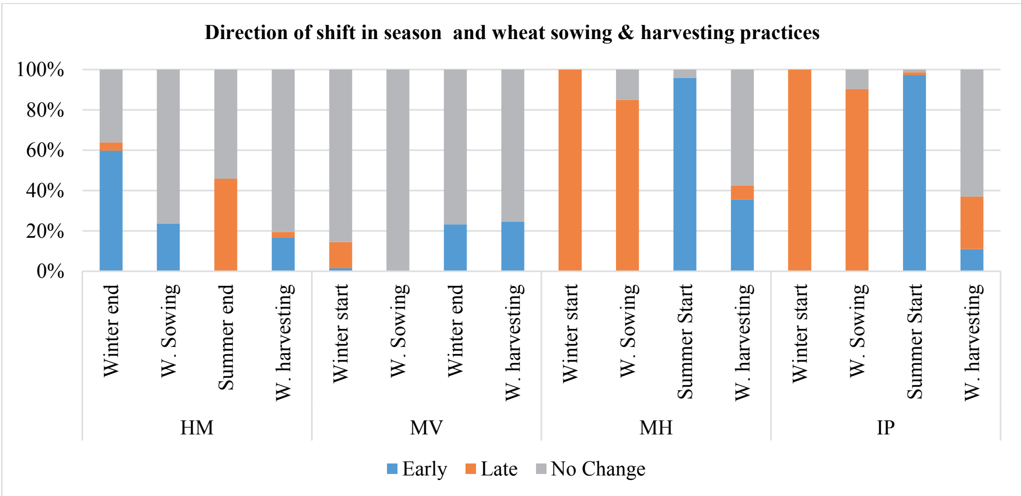

Figure 3B-I. Direction of shift in winter season and wheat sowing & harvesting practices (% Response)

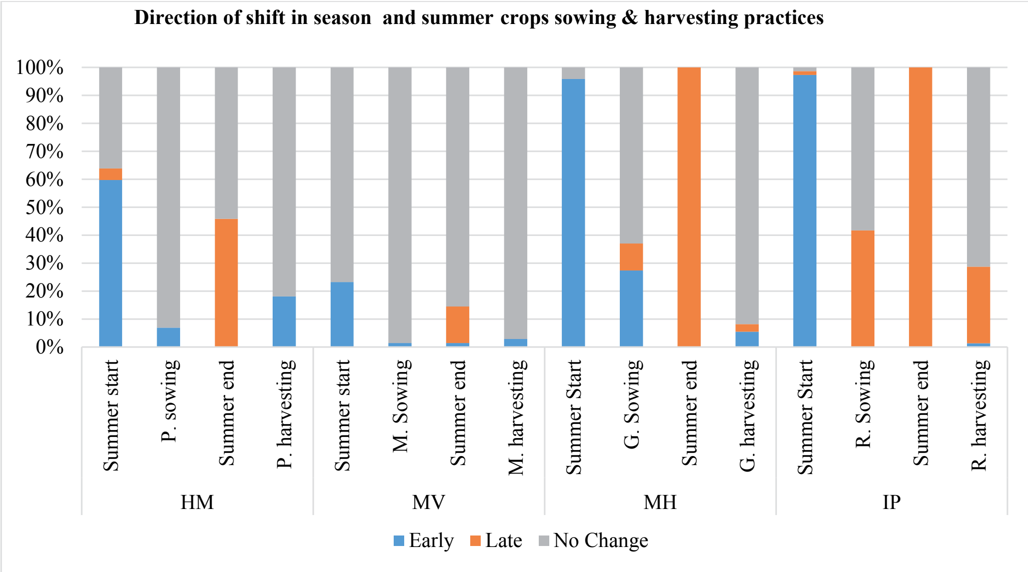

Figure 3B-II. Direction of shift in summer seasons and summer crop sowing and harvesting practices (% Response)

Annex-3C. Shift in Rabi (winter) season, crop growing period and impact

Table 3C-I. Shift in start of Rabi seasons, wheat sowing period and its impact on crop yield

	Crop season starts*				Shift in wheat sowing				Impact on crop yield			
Sites	Direction	Days#	N	St Dev	Shift	Days#	N	St Dev	Impact	T/ha	N	St Dev
Mountains	Early	11.49	47	3.07	Early	7.65	17	2.52	Positive	0.14	15	0.05
									No Change		2	
Valleys	Early	13.29	28	3.67	Early	9.80	15	2.91	Positive	0.11	15	0.05
Mid-hills	Late	20.55	73	5.77	Late	13.46	63	3.68	Negative	0.25	46	0.09
									No Change		17	
Plains	Late	21.21	73	5.61	Late	15.41	66	3.97	Negative	0.49	66	0.14

*=Starts from end of winter in mountains and valleys while from start of winter in mid-hills and plains

Table 3C-II. Shift in end of Rabi seasons, wheat harvesting period and its impact on crop yield

	Crop season Ends*				Shift in wheat harvesting				Impact on crop yield			
Sites	Direction	Days#	N	St Dev	Shift	Days#	N	St Dev	Impact	T/ha	N	St Dev
Mountains	Late	13.91	35	3.97	Late	11.57	14	2.77	Positive	0.14	10	0.06
									No Change		4	
Valleys	Early	13.29	28	3.67	Earlier	6.41	17	2.00	Positive	0.06	16	0.03
									No Change		1	
Mid-hills	Early	14.47	70	5.08	Early	7.73	26	3.26	Negative	0.14	20	0.08
									No Change		6	
					Late	8.80	5	1.64	No Change		5	
Plains	Early	15.46	71	4.76	Early	10.73	11	3.85	Negative	0.29	9	0.15
									No Change		2	
					Late	6.75	16	1.91	Positive	0.17	8	0.05
									No Change		8	

*=Ends from start of winter in mountains, and start of summer season in and valleys, mid-hills and plains

Annex-3D Shift in Kharif (summer) season, crop growing period and impact

Table-3D-I. Shift in start of Kharif seasons, Kharif crop sowing period and its impact on crop yield

	Crop season starts				Shift in Kharif crop sowing				Impact on crop yield			
Sites	Direction	Days#	N	St Dev		Days#	N	St Dev	Impact	T/ha	N	St Dev
	Early	11.49	47	3.07	Earlier	7.24	25	1.94	Positive	0.57	25	0.29
Mountains												
	Early	13.29	28	3.67	Earlier	6.41	17	2.00	Positive	0.11	11	0.06
Valleys	Late							2.00	No Change		6	
	Early	14.47	70	5.08	Earlier	8.45	20	2.80	Positive	0.14	7	0.05
Mid-hills									No Change		13	
					Later	14.71	7	5.38	Negative	0.28	4	0.09
									No Change		3	
	Early	15.46	71	4.76	Later	14.79	33	5.00	Negative	0.44	26	0.19
Plains									No Change		7	

Table-3D-II. Shift in end of Kharif seasons, Kharif crop harvesting period and its impact on crop yield

Sites	Kharif crop season ends				Kharif crop harvesting				Impact on crop yield			
	Direction	Days#	N	St Dev		Days#	N	St Dev	Impact	T/ha	N	St Dev
Mountains	Late	13.91	35	3.97	Later	12.08	13	3.57	Positive	0.83	13	0.49
Valleys	Early	10.00	1	-								
	Late	11.67	9	2.50	Later	10.00	2	-	Positive	0.20	2	-
Mid-hills	Late	20.55	73	5.77	Earlier	10.00	3	-	Negative	0.20	1	-
									No Change		2	-
					Later	10.00	1	-	No Change		1	-
Plains	Late	21.21	73	5.61	Later	14.10	20	3.75	Negative	0.19	12	0.09
									No Change		8	

Table-3D-III. Over time change in wheat sowing period and limits under expected shift in seasons (Farmers responses %)

Sites	Time period Month/week	Oct			Nov				Dec				Jan
		2	3	4	1	2	3	4	1	2	3	4	1
Mid-hills	Past	1.59	19.05	26.98	41.27	11.11							
	Current			6.85	16.44	36.99	35.62	4.11					
	Future Limits								18.00	34.40	27.90	19.70	
Plains	Past				5.88	26.47	32.35	26.47	5.88	2.94			
	Current					6.85	8.22	23.29	26.03	24.66	8.22	2.74	
	Future Limits									14.50	21.00	33.90	30.60

Note: On an average farmers in mid-hills reported 13.46 days delay in sowing and in plains 15.41 delay in sowing. Almost 2 weeks shift in sowing is reported for the both

Chapter 5

5. Synthesis

5.1 Recap on climate hazards and critical moments

Changes in climate, both its mean state and variability, pose challenges to sustainable crop production (Ashok & Sasikala, 2012; Cyr et al., 2010; Katz & Brown, 1992; Panday et al., 2015; Schär et al., 2004). Up to now, research has tended to focus on the impacts of the most extreme climate events, bypassing the impacts of lower intensity but higher frequency climate risks. Nonetheless, climate events that are not considered extreme in a statistical sense can still result in extreme impacts, for example, if they coincide with a critical crop stage, if thresholds are exceeded or if impacts are compounded over time. Such hazards result not only in reduced crop production, but can also affect the quality of agricultural produce. Even if yield losses can be largely averted through coping mechanisms, the need for coping measures raises the cost of production, eroding farm income. In addition to bringing additional costs, coping strategies seldom lead to full yield loss recovery. Furthermore, farmers face multiple barriers in coping with in-season hazards. In some cases, no coping options may be available, or the time window to respond may be too short to act.

The current research sought to enhance understanding of the way farmers cope with climate hazards that threaten crop production. Specifically, it developed a categorization of critical moments (CMs), defined as periods of heightened risk during the crop season when farm households are particularly vulnerable to specific climate hazards. Use of the CM concept shed light on the effectiveness of strategies for coping with in-season climate hazards, while also pointing to barriers to enacting such coping in different agro-ecological zones and cropping systems of Pakistan. It also indicated the limits of coping as perceived by farmers in the face of ongoing changes in climate.

Chapter 2 and 3 identified particular in-season hazards and farm-level coping strategies both from the literature and within the given conditions of three agro-ecological zones in the Indus Basin of Pakistan. Ex ante coping was found only for hazards occurring at the pre-sowing stage and affecting the crop sowing period. Chapter 4 considered adaptation; that is, autonomous or planned changes in anticipation of, or in response to, gradual changes as perceived over the long term by farmers. At the case study sites, coping and adaptation strategies were found linked to climate variability and climate change. The case study of past and potential future shifts in cropping seasons and farm-level adjustments in crop growing periods differed in the four agro-ecological systems considered. The hazards examined in the current study were similar to the moderate extremes referenced by the IPCC (2001) in its typology of climate extremes; these mainly being local weather variables exceeding critical thresholds, like high or low temperatures, high or low rainfall and extreme winds.

The research presented in this thesis centered on a single overarching question: “When, within a crop production cycle, are farming communities most vulnerable to climate hazards?” To answer this question, the research developed the integrative concept of “critical moments” (CMs) covering the different dimensions of hazard vulnerability – these being type of hazard, the time dimension by crop stage, pathways causing losses and potential coping strategies. Four sub-questions were defined, each contributing evidence with which to answer the main research question. The investigation started with development of the CM concept, which underscores the time dimension of the occurrence of hazards and farmers’ ability to cope. A review of the literature was followed by collection of evidence from the field on each of these aspects. A conceptual framework was developed, distinguishing three types of CMs according to the “when” of their impact, in order to structure the evidence on CMs. The conceptual framework aided in the development of inclusion and exclusion criteria for evidence from the literature. Specifically, the literature on climate modelling, agronomy and socio-economics was examined. From these, examples were compiled on CMs related to weed growth, disease incidence, quality and workability issues.

Field evidence on CMs was derived from a farm-level household survey conducted in three agro-ecological zones of Pakistan, spanning four cropping systems. One of the aims of the survey was to map hazards by crop stage, impacts and coping strategies, including full cause-and-effect pathways to losses. This mapping exercise was completed for each of the four studied cropping systems. The coping strategies were appraised in regard to their cost and their effectiveness in terms of yield loss recovery, while also being assessed in monetary terms as well. Because multi-crop systems were most common at the study sites – as in much of the world – the coping possibilities and limitations were explored from a system perspective. Weather, climate variability and climate change were found to be intertwined, as were strategies to cope and adapt. This research was interested in points of convergence, these being foremost times at which farmers must cope with climate variability risks within the new mean climate setting. Similarities and differences in shifts of seasons versus changes in growing periods, both in direction and magnitude, were explored from farmers' perspective.

5.2 Return to the research questions

5.2.1 What types of climate risks can be differentiated?

To capture different vulnerability aspects and underscore the time dimension, the current research developed the concept of critical moments (CMs), defined as "periods of risk during which livelihoods are vulnerable to specific climate hazards". The classification of hazards' impacts and pathways to losses by time window was considered valuable to support identification of appropriate coping interventions to improve farm-level resilience. A review of the three strands of literature led to identification of three types of CMs, distinguished by the "when" of their impact; that is, CMs resulting from hazards with immediate impact (iCM), CMs resulting from compound hazards (cCM) and CMs resulting from hazards in which the impact was shifted to the next period in the crop rotation in a multi-crop system (sCM). Hence, the question of "when" with respect to risk relates not to a single hazard incidence or crop phenology; rather, it is multifaceted, encompassing a time window in which a climate hazard may occur, alongside the extent of crop exposure and the possibility for a farmer to implement a coping response.

In terms of complexity, most CMs identified in the literature were of the immediate type, followed by the compound type. Previous studies report the reproductive stage as a particularly high-risk period for agriculture. Most of the iCMs identified were related to heat and moisture stress and most commonly affected wheat among the studied crops. CMs at early growth stages were also reported relatively more frequently, especially CMs in which the impacts are compound (cCM) or shifted (sCMs). At the early crop production stage, however, a variety of coping options are still considered feasible. Looking at geographical spread, more complex CMs with shifted impacts are reported in only a few studies, often focused on Europe and to a lesser extent on South and East Asia. Few examples of such impacts were found from South America and Africa. In terms of geographical representation in the literature, the Middle East and Central Asia region are underrepresented, but because wheat is such a major crop here, many global modelling studies have focused on wheat in this region.

The CM concept covers the overall effects of individual and multiple hazards by crop stage, allowing estimates to be derived of the cost of coping. A weather hazard, for example, affects more than just the volumetric yield of a crop; it often also affects yield quality, which can render a crop unmarketable. Workability issues are common as well. For example, overly wet or cool weather can cause lodging and difficulty in harvesting a crop.

5.2.2 How effective are available strategies to cope with in-season climate hazards?

Without coping, in-season climate hazards can result in heavy losses for farmers. The four studied cropping systems in the three agro-ecological zones of Pakistan were no exception. Losses here were in the 10–30% range for 43% of the in-season hazards and the 31–50% range for another 39% reported cases, as presented in Chapter 3. A multitude of moderate hazards affected each of the cropping systems studied, with their frequency of occurrence ranging from once in five years to once in two years. Furthermore, the findings demonstrate that the same hazard occurring at different crop stages can cause losses through different pathways, with coping options also differing for each impact pathway. The farm-level survey uncovered compound-impact CMs not reported in literature, especially where a single hazard affected crops via multiple impact pathways at the same crop stage. An example of such a compound-impact CM is losses due to insect infestation (and the additional cost of insecticide) combined with reduced yield due to a seasonal dry spell at the reproductive stage of a rainfed groundnut crop in the Pothwar region of Pakistan. For the rice-wheat cropping system on the irrigated plains of Punjab, Pakistan, exposure of rice to high temperatures at the reproductive and grain formation stages caused losses from insect infestation as well as reduced grain setting due to impairment of pollen formation. Compounding impacts were also identified for crops growing side by side in the high mountains, where the previously rare combination of hot and humid weather was found to cause losses in wheat and potato, grown simultaneously during the single cropping season. Shifted CMs were found mostly on intensively farmed lands, characterized by multi-crop rotations. Thus, unseasonal rains at the rice harvesting stage delayed the harvesting operation, triggering a delay in wheat sowing on the same plot in the sequential crop rotation, pushing wheat to later maturity and higher risk of heat stress. Beside yield impacts, this increased operational complexity, leading to higher production costs which affected profitability.

In-season coping, when possible, was generally very effective in terms of yield loss recovery, though outcomes did vary, as application of coping strategies resulted in a yield recovery of 40–95%. Still, average yield loss after implementing a coping strategy was high at 23%. Coping also brought additional costs, varying from 4% to 34% of the recovered yield value, the average being 19% of the recovered yield value.

5.2.3 What barriers hinder farmers' ability to cope with in-season climate hazards?

The main barrier hindering farmers' ability to cope is whether there was a coping option available. No coping option was available for 22–45% of the events identified across the different study sites. Events for which no coping option was available included hazards at later crop stages causing lodging, disturbed pollination, damaged spikes or shrivelled grains, as well as wilting due to moisture stress at early crop stages in the rainfed agro-ecologies. Possibilities for coping were further constrained by limited time windows in which to respond to in-season hazards and/or timely availability of resources to cope. With regard to the latter, land, labour and machinery conflicts frequently arose due to overlaps in necessary operations in multi-crop systems. Where coping options were available, farmers differed in their propensity to adopt these, ranging from 60% in the mountain valley to 86% on the irrigated plains. Furthermore, a timely response was found to improve the effectiveness of the coping option. However, timeliness often proved difficult. Even when financial resources were available, this did not guarantee that farmers could arrange the required labour, for example, to fill in gaps left when rice seedlings were uprooted by rain and wind. Nor were additional nursery plants of same variety and age always available. Using seedlings of different age and variety affected the quality of the produce. In the valleys and high mountains, farmers' inability to repair water channels in a timely manner after these had been destroyed by a flash flood exacerbated losses. In this case labour shortage delayed the work. With their water supply limited, farmers faced a trade-off between growing potato and saving losses in wheat. Reserving water for wheat meant leaving fallow some of the lands they would otherwise devote to potato cultivation. A purely crop-based analysis would obscure the complexity of the multi-crop rotations that dominate Pakistan's agriculture, while also masking complications arising from shifted CMs impacts. By adopting a cropping system perspective focused on CMs categorized by the temporal aspect of their impact, the assessment carried out in the current research revealed time, land and workability conflicts that arose due to hazards identified as having shifted impacts.

The time window, underscored by the CM concept, is key to understand the incidence of a hazard, the varying pathways to losses, the time limits to respond effectively, operational difficulties and the potential of incurring additional costs due to overlaps in farm operations at certain periods of time. As such, the “when” within the CM concept is multifaceted, encompassing the time window in which a climate hazard may occur, alongside the extent of crop exposure and the possibility for a farmer to implement a coping strategy.

5.2.4 What is the scope for further adapting to changing climate conditions?

Changes in crop growing periods at the farm level do not necessarily parallel shifts in meteorological seasons. Longer summers and shorter winters were observed at all study sites, associated with an increasing mean temperature over the past three decades. Farmers had prioritized modest adjustments to planting dates, maintaining their capacity to cope with known weather hazards, especially during sowing periods. The high altitude sites, characterized by colder temperatures, especially in winter and at night, can be viewed as “winning” ecologies due to the expected increases in crop yields there; thanks to an extended crop growing period. Low altitude ecologies, however, with their higher mean temperatures, are set to be “losing” ecologies, as yields here are likely to diminish due to shorter growing periods. Indeed, at the low altitudes, both mean climate changes and increased climate variability threaten cropping systems. However, even in the winning ecologies climate variability brings additional risks that at present hold farmers back from taking full advantage of the longer growing period.

As an adaptation strategy, in the losing ecologies changing sowing dates was only somewhat effective in preventing yield losses. The direction of farmers’ adaptations in sowing and harvesting was similar to the direction of the observed seasonal shifts at all sites except for the summer crop on the irrigated plains. In the face of a longer summer season, farmers here opted for later rice sowing rather than planting earlier, mainly to avoid the cost of irrigation water in case summer rains were delayed, as farmers’ experience suggested a substantial risk of such delay. Though farmers adopted complementary strategies to avoid yield losses under the shorter growing period in the losing ecologies, these brought additional costs. Switching plant varieties and using additional inputs in various combinations were the main strategies. The cost of these depended on the price of inputs and the combinations and quantities used.

Limited scope was found for further adjustments in growing period under future climate change in the low altitude ecologies. Farmers expected temperatures to continue to rise, resulting in further shifts in crop growing seasons. Already, farmers delayed wheat sowing almost by two weeks compared to the situation three decades ago. A majority of the surveyed farmers expressed concern that they might be nearing a threshold beyond which wheat planting would no longer be feasible. In the mid-hills, in the rainfed zone, farmers’ expectations were mixed. Some indicated that the sowing period was approaching a critical threshold. Other, however, were looking beyond their existing cropping pattern, and considering diversification as a potential adaptation option. This indicates their acute awareness of the extent of the sustainability threat to the traditional cropping system in the losing ecologies.

5.3 Discussion on data and methods

A detailed survey instrument, informed by the CM concept, was used to generate field data on the range of coping strategies available in the studied cropping systems. Within-site differences were minimized by selecting a cluster of villages having similar crop growing seasons and crop management practices as well as similar climate conditions. The generalizability of our results is obviously limited to the three agro-ecological zones and four cropping systems examined. These, however, can be considered representative of the majority of cropping systems in the Pakistani part of the Indus Basin, and more widely across the Indo-Gangetic Plain. Variations between the studied agro-ecological zones provided interesting comparisons. Indeed, distinct “winning” and “losing” ecologies could be identified.

As the range of moderate climate hazards, impacts and coping strategies is very wide, development of the questionnaire investigating less extreme and less immediate CMs required trade-offs to be made between comprehensiveness and time and staff constraints. In this regard, earlier experiences of the survey team in collecting data on the selected cropping systems and ecologies proved invaluable for guiding the data collection effort. Daily field observations by the survey team were cross-checked every evening during the data collection period. Two approaches greatly helped reduce the time required to administer the questionnaires. First, work done in the pre-testing phase proved critical for identifying, and limiting the range of hazard-coping-impact options to be incorporated into the questionnaire. Second, in cases where two or more hazards were reported for the same crop stage by the same respondent, details on costs and yields were included only for the most recent hazard in the survey. In this regard, the procedures and experiences from the current research in surveying CMs can provide a valuable addition to the contemporary literature on farm livelihood and adaptation surveys.

A considerable level of co-design and engagement is essential for development of a meaningful CM survey instrument. As hazards' pathways to losses and coping strategies vary by ecology and cropping systems, the survey team had to possess a contextual understanding in order to capture location-specific CMs. In the current research, this was promoted by focus group discussions at each site, which provided key learning moments and starting points for probing in further detail with individual respondents during the formal survey. Backed by the insights obtained during the focus groups, informal discussions with sample respondents helped us to identify risks, impacts and limitations to coping related to individual CMs within particular socioeconomic and biophysical contexts. These discussions were also helpful in identifying the compound risk of simultaneous events (e.g., drought coupled with heat) or single events generating compound impacts and causing losses through different pathways simultaneously (e.g., drought causing loss due to moisture stress and by favouring pest infestation), as well as resource conflicts that limited farmers' ability to cope.

Data triangulation was also important. In addition to consistency checks, the climate changes reported by farmers were compared to observation data from nearby meteorological stations, obtained from the Pakistan Meteorological Department. Though the overall change patterns matched, not all perceived trends in precipitation were confirmed. More local meteorological station data might serve to validate farmers' perceptions, as meteorological observations at a specific station may not reflect conditions at all nearby villages and farms. Farmers' perceptions may also be influenced by their more in-depth understanding of the critical situations posed by particular combinations of meteorological conditions.

Yield impacts were estimated based on memory recollection, though this can produce widely ranging results. An alternative would be to conduct on-farm experiments. However, time and resource constraints combined with the multitude of hazard-impact pathways of interest in any given cropping system, beside the existence of multiple cropping systems across different agro-ecological zones, limited the applicability of this approach. Farmers were used to facing different situations in terms of climate conditions and had gained knowledge over the years on magnitudes of yield gains and losses associated with different weather conditions. Indeed, the surveyed farmers proved well aware of the impact of changes in sowing and harvesting periods and the potential for yield loss recovery under different coping strategies. Findings from the agronomic literature, moreover, confirm the yield losses reported.

The time to impact and limitations to coping due to amounts of time to respond are two interesting areas for further analysis, particularly, integrated with on-farm experiments to verify and validate potential new coping options. The methodology used in the current research to measure yield recovery, and its effectiveness, is a further promising avenue for experimental research.

The current research confirmed that an analysis focused on a single crop obscures the complexities of the multi-crop rotations found in much of the world. Compounding impacts from multiple hazards or via multiple pathways, as well as cascading effects in interconnected multi-crop systems, need to be studied from a system perspective. As yet, assessments of the impact of climate hazards at the regional and national level have tended to be difficult due to the multitude of agro-ecological zones and diversity of cropping systems in use. With a system perspective, we can better capture shifted impacts of CMs and related management and operational conflicts, which may be overlooked using a single-crop focus.

Conflicts due to overlaps in harvesting and sowing periods, for example, either due to limitations of land and labour or other operational issues, were found to be of particular importance in the current research. But such conflicts are not confined to Pakistan's agricultural systems. Many of the world's most densely populated food-producing regions, especially those in Asia, are characterized by a high intensity of land use. In all such areas, these kinds of conflicts are crucial to consider. The CM approach can support larger scale planning in such diversified and interlinked environments.

The present study targeted CMs at the farm level and focused on in-season coping strategies. It therefore did not examine impacts of climate hazards in regional production figures, market supplies and prices at the production system level. However, weather hazards accumulated at larger scale do affect market supplies and impact prices. Changes in production at a larger, regional scale also affect trade. The moderate climate hazards associated with the CMs investigated will thus also affect commodity supply chains and, together with changes in production level, affect prices and farm incomes in connected parts of the world. In this regard, the methodology presented in the current research could be applied to conduct a wider mapping and monitoring of risks along commodity value chains. Such a mapping would provide invaluable support for informed decision-making and for managing supplies towards food security.

5.4 Scientific contribution

The current research bridges disciplinary silos by synthesizing and further extending evidence on CMs. In it, the CM concept was approached as an integrated notion of risk, in which the incidence of hazards (which are the focus of many climate modelling studies) at different sensitive time windows during the crop cycle (the domain of agronomic research), were linked to crop income estimates (applying concepts from socio-economic research). In so doing, the research shed light on less-reported pathways that nonetheless contribute to vulnerability.

In addition to linking coping strategies to specific pathways to losses and covering both direct and indirect impacts of climate hazards, the CM framework integrates the impacts of combinations of hazards and compound effects due to hazards that occur simultaneously or sequentially. A specific, underreported case is when two loss-causing pathways are generated simultaneously from a single hazard. By taking a farming systems perspective, the research design helped to reveal vulnerabilities due to hazards occurring in one crop season but having impacts in another season. For example, a hazard may cause land and operational conflicts in connected multi-crop systems (Schaap et al., 2013).

Much of the climate change literature focuses on large-scale changes and extremes in temperature and precipitation, as well as impacts such as accelerating glacial melt. There has been substantially less attention to how farmers cope and how their coping might influence future adaptation to ongoing climate change (Q.-u.-A. Ahmad, Biemans, Moors, Shaheen, & Masih, 2021; H. Biemans et al., 2019). Similarly, most surveys conducted or supported by governments, the Asian Development Bank and the World Bank – or other international agencies for that matter – strongly focus either on climate impacts or on people's adaptive capacity, with the latter assessed by indicators such as income or assets (Munir Ahmad, Iqbal, & Khan, 2013; World Bank, 2011, 2015). Though such surveys can provide important guidance, they generally miss the place- and context-specific solutions by which farmers address the complexity of agriculture under highly variable conditions. As indicated by the IPCC (2012), there is no point in preparing for future hazards if we cannot cope with present-day risks. Yet, preparation for future hazards could be strengthened by better linking knowledge on local coping practices with climate modelling results (Reidsma et al., 2015; Ruane et al., 2018). An example of such an initiative is the Agricultural Model Intercomparison and Improvement Project (Antle et al., 2015). In a similar vein, IPCC (2022), indicates substantial consensus on the role of adaptation in reducing climate risk for food systems. The survey instrument developed and applied in the current research to assess CMs under today's and expected future shifts in growing seasons, can contribute to bridging these gaps.

Only a few studies, primarily limited to Europe (Gobin, 2018; Reidsma et al., 2015; Schaap et al., 2013), have done a complete, in-depth cause-effect analysis, considering impact pathways by time window and covering both coping and adaptation. The research presented in this thesis expands the scope of this pioneering research to different production systems, in a different region, South Asia. This thesis sheds light on an important but underreported component of coping – the in-season strategies that farmers employ to manage risk and the impact mitigation strategies applied in multi-crop production systems. The research provides insights into the decisions farmers make in allocating resources and their crop practices, which could contribute to climate risk management strategies at the national level.

There are limitations to coping too, as this research points out. In addition to a lack of resources, the possibility to cope is often constrained by the short time window in which to respond. Moreover, this research found that farmers adapted, but only to a certain extent. Farmers adapted to changing growing conditions by adjusting sowing dates, a finding which corresponds to other literature (Waha et al., 2013). However, these adjustments did not necessarily parallel the shift in seasons, because of additional risks emerging within the altered climate. Insight into the variety of strategies farmers used to cope with climate risks across the different cropping systems supports the need for place-specific planning and implementation of climate-resilient agriculture in the face of both current and future climate change (White et al., 2011). This nuances future adaptation potential and provides important new insights for climate risk management.

This scientific contribution points to five key recommendations emanating from the current work. *First*, there is a need to investigate CMs in other regions and other ecologies where production systems are subjected to similar hazards, to characterize the impacts of these hazards, alongside possibilities for coping and adaptation. Especially, compound risks and operational conflicts in multi-crop systems need to be better understood. Integrating the assessment of risks in particular time windows with risks associated with mean climate changes that also affect shifts in crop growing periods in different regions can help to reveal future risks and the extent to which farmers may be able to further adapt.

Second, the concept of CMs merits widening to include production systems other than crops. In Pakistan, for example, there are mixed crop-livestock farming systems, as well as a thriving horticultural sector. These, too, are subjected to similar risks as field crops, or the risks may be even greater. Other economic sectors, such as transport, tourism and health, also have critical moments (Groot et al., 2018). More insight on these would contribute to better adaptation planning overall.

Third, some 22–45% of the farmers in the four studied cropping systems expressed an inability to cope with in-season hazards due to the lack of any coping option. A better understanding of the effectiveness of current and alternative coping options for different CMs, may point to viable, cropping-system compatible coping options. With seasonal shifts already observable and changes in the growing period well underway, farmers need alternative solutions, both in the losing ecologies, where current cropping systems are threatened by shorter growing periods, and in the winning ecologies, to harness the opportunities presented by extended growing periods. The analysis of pathways to losses presented in the current research challenges all areas of agricultural research to search for answers, especially where farmers see no coping strategy available. Farm advisory support services could provide a vital link in this regard, to help farmers respond to emerging challenges. To fulfil this function, however, requires integrated and multidisciplinary planning and implementation, strong R&D and effective farm service institutions.

Fourth, more attention to response times is needed, not only for tailored advice on the optimum level of additional inputs, but also on the optimum time of application and effectiveness under non-optimum conditions. This could improve the efficacy of coping options and adaptive capacity. Furthermore, coping strategies and their cost and effectiveness need to be integrated into assessments of the net impact of climate hazards. Attention is also needed for coping flexibility, keeping in mind the availability of certain coping options and the time window for an effective response.

Finally, the adaptive capacity of affected communities should be explored beyond a basic assessment of assets, capacities and barriers. Specifically, farmers' experiences regarding response times need to be taken into consideration, as well as their concerns about limitations therein and priorities to support adaptation planning. This points to the need for further analysis of the functioning and adaptive capacity of the institutional and policy support system.

5.5 Policy implications

The concept of CMs and the methodologies presented in this thesis can contribute to the mapping and monitoring of climate risks and the development of the requisite coping strategies to support sustainable crop production beyond the few cropping systems and agro-ecological zones studied. Viewing climate risk through a CMs lens supports greater interdisciplinary engagement, both to identify vulnerabilities specific to particular places and times and to develop user-relevant climate risk metrics and climate services conducive to effective coping and adaptation. Interdisciplinary engagement will also be crucial to develop the required coping options and support mechanisms to reduce vulnerabilities. To this end, the risks and vulnerabilities encountered by members of farm communities at the receiving end of climate change need to be incorporated into the development plans of policymakers (A. Pandey, Prakash, & Werners, 2021).

The research presented in this thesis addresses farm-level risks, coping strategies and adaptations in multi-crop systems in different agro-ecological zones of Pakistan. Farmers were found to have adjusted sowing dates, in order to adapt to mean changes in the climate over time; however, having done so they have also contend with hazards and CMs arising from climate variability within the newly established seasons. These in-season hazards form a barrier to further adaptations in recommended planting dates under the expected future changes in climate conditions. The CM concept shed light on differences in pathways to losses, as well as limitations to coping and ways to prepare for the challenges ahead. Use of the concept indicates the need to integrate coping with adaptation planning and for conscious effort to promote climate-resilient agriculture.

Pakistani policies are cognizant of the implications of climate science (Government of Pakistan, 2012, 2018a). Thus the government has sought to support and promote sustainable food production systems through climate-resilient agriculture. However, recommendations and policy initiatives up to now have focused mainly on disaster risk management, covering extreme events, primarily large-scale flooding and droughts. The risks of less extreme local weather variability are largely overlooked, as these are less obvious and dramatic and affect production at different stages throughout the growing season. Similarly overlooked are vulnerabilities and damages incurred by farmers due to the increased risk of in-season hazards, such as heavy rains, flooding, drought and pest infestation (like locust), though these lead to crop losses or even failure without production loans being covered by appropriate insurance. Banks do have an insurance coverage for crop and livestock production loans in case of calamities, but only for the event declared as a calamity by the responsible provincial revenue authority (State Bank of Pakistan, 2014). In other South Asian countries, too, financial inclusion of rural peoples is typically low, with those engaged in agriculture especially likely to be excluded from formal financial services (F. A. Malik, Yadav, Lone, & Adam, 2021).

Agricultural production systems in developing countries in sub-Saharan Africa and South Asia, where rural poverty and hunger are already concentrated, will bear a heavy burden in satisfying their rapidly growing populations' burgeoning demand for food. As they simultaneously face the daunting risks of climate change and climate variability, effective adaptation will require enabling policy and a supportive technical, infrastructural and informational environment. Though since the Green Revolution, the world's agricultural research and education systems have largely shifted from a productivity enhancement focus to a focus on sustainable use of natural resources, the uptake of improved technologies and management practices that reduce environmental damage has been disappointing, particularly in intensively farmed areas in developing countries (P. K. Thornton & Herrero, 2014). Among the developing world's many agricultural research and education institutions only a few have a specific mandate to address climate change. Despite the realization that climate change is real and that the projected changes will have grave impacts, developing countries remain unprepared. Given their current still underdeveloped status, the agriculture sector in developing countries still has significant potential to contribute to economic growth and food supply. Yet, achieving this aim requires sustainable production strategies that are resilient to an erratic climate (M. I. Ahmad & Ma, 2020; Pingali, 2007; Shafqat, Maqbool, Eqani, Ahmad, & Ahmed, 2016).

The current research points to eight policy areas in which developing country governments, particularly those in Pakistan and South Asia, can support appropriate responses to climate risks.

Mapping and monitoring. CMs can be used to map and monitor climate risks, thus providing the basis for developing the required coping strategies to support climate-resilient agriculture under current and future climate conditions. The pathway analysis methodology presented in this thesis provides evidence of the many indirect impacts of climate hazards, especially the emergence of weeds, insect infestations and disease incidence, under certain weather conditions. Mapping and monitoring such changes not only supports place-based coping, but also helps control further spread and avoid outbreaks at larger scales. As climate change is a continuous process, there is need to map and monitor the climate risk as a continuing process.

Coordination. The diversity of hazards and pathways demands action emanating from diverse disciplines. Beyond other needs, effective coping requires timely responses. These can be made possible by well-coordinated rapid response systems housed in relevant institutions to ensure timely provision of the required financial, technical, advisory and input supply services.

Early warning, advisory systems and market services. Weather forecasts connected to early warning, advisory systems and market services can help farmers avert potential threats during the crop production season. While different departments working in isolation are unlikely to be able to provide such support, institutional integration – at least for purposes of collaborative planning and implementation – could fill the gap in the short run. The possible solution is that coping with climate variability be considered a key element in planning adaptations to climate change. Furthermore, place-based planning for individual agro-ecological zones is needed to harness potential opportunities in the winning ecologies and to support farmers to adapt in the losing ecologies. The diversity found within agro-ecosystems and in climate conditions generally further necessitates tailored-made farm-level support on technical aspects of coping and adaptation. There is need to extend the supporting effective in-season coping services beyond the farm level, however. Broader support and investment policy are needed at the regional and national level, not least, improved weather and early warning information, technical guidance and rapid access to production inputs and finance through functioning market services.

Response time. Agricultural production against the backdrop of climate change entails a heightened livelihood risk and need to be able to rapidly respond to save crops from permanent damage (e.g., due to wilting) or ensure farmer sustenance when combined CMs generate extreme impacts. Delayed responses in such situations can reduce the effectiveness of coping and may render coping fruitless or unfeasible. Like the provision of real-time weather information and market services, supply mechanisms for technology, inputs and finance need to consider the required time window for effective coping and adaptation. Rapid response will in many cases require cooperative actions from financial, technical, R&D and community stakeholders.

Subsidies and insurance. Even moderate hazards, by climate standards, can generate extreme impacts, as demonstrated by this research's analysis using the CM concept. Yet, financial support mechanisms are not in place, and complexities are seldom taken into account when preparing for climate change impacts. Regarding ex post coping strategies, too, better real-time analysis of in-season hazards will support proactive planning. A comprehensive financial framework is required for climate risk management, especially for agrarian economies dominated by smallholder farms.

Coping actions and transitional planning. Dealing with changing climate conditions requires action in the short run while simultaneously planning for a transition in the long run. Integrated transdisciplinary actions and transitional planning need to be carried out on a continual basis in order to successfully implement the structural changes needed.

Policies and their implementation. In Pakistan, as in neighbouring countries, there is a well-established agricultural advisory and support system with clear policy guidelines, but nonetheless struggling with implementation due to the multitude of challenges and demands. Coping with in-season hazards is thereby easily overlooked, or seen as the sole responsibility of farmers. There is a lack of action and implementation of policy on this front. However, the impact of smaller hazards is large due to their frequent occurrence and wide spatial extent. This warrants rapid response mechanisms similar in scale to those for large-scale extreme events. In addition to help to cope with in-season hazards, farmers need ex post livelihood support services for when in-season coping fails or when extreme impacts are generated from multiple hazards during the production period. Furthermore, implementation of such actions need to ensure inclusiveness of smallholders, who as yet are often excluded from incentives and support services. To help farmers adapt and cope with climate risks, in addition to place-based technological innovations, farmers need an active institutional support system that incorporates science-based climate information and forecasts into planning, policy and practice.

Farmer and community coping responses. Farmers do act to cope with in-season hazards, as long as they perceive a possibility to cope and have the resources to do so within the required window of time. They also seek ways to adapt to climate change in the longer term. However, they are clear on the limits to adjustment. Some at the study sites indicated being on the lookout for alternative crops that they could switch to if critical thresholds were crossed. Development of technological packages for coping and adaptation alone will not suffice for uptake of new production avenues. Allied service delivery mechanisms are required to be put in place to support new packages in the new agro-climatic setting. The diversity of agro-ecological zones, and the differing climate impacts within "winning" and "losing" ecologies, identified in the current research as, respectively, the high and low altitude study sites, demand site-specific support. Within winning ecologies communities require new production packages and services that fit in with their traditional production systems, as well as support mechanisms to cope with new challenges posed by the more erratic climate conditions. The losing ecologies would benefit from a rethinking of livelihoods and support for sustainability of traditional production systems, as well as reducing barriers to a smooth transition to alternatives.

6. References

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Annex I Full questionnaire on exploration of critical moments during a crop calendar

Questionnaire No. to be used for data entry

Part-1. Questionnaire identification and site classification

Module 1: Location (Identification and classification by agroecology and farming system)

Date of interview		Village	
Tehsil		District	
Name of enumerator		Start Time	

Module 2: Household Demographic Information

2.1. Respondent information

Name of Respondent		Contact # of Respondent	
Education of the Respondent (Years)		Age of respondent	
Farming experience of the Respondent (years)		Present involvement in farming 1=full time 2=part time	
Respond. Relation to H.H. Head[a]		Education of HH Head (years)	

(a) 1=Self 2= Brother, 3=Son, 4=Uncle, 5= Father, 6=Other (specify/spy)

2.2 Family type, size and employment

Type of farm family 1=Joint family, 2=Single family		Total family size (no)	

2.3 Family employment (Adult Family Members)

	Adult (16-60)	
	Male	Female
Working on farm full time (#)		
Working on-farm part time		
Working off-farm full time (job, labour, or business) (#)		
Working off Farm part time		
Off-farm income contributed to family of **all** persons working off-farm (part time + full time) (Rs./Month)		
Working Abroad (#)		
Remittances (Rs./Year)		
Retired from govt. services (#)		
Sum of pension of all retired persons (Rs./Month)		

Income of HH from other sources not mentioned above (rent of tractor/building etc.) (Rs./Year)____________

Permanent **Hired Farm Labor** #_______ @ _______ Rs./month (including all in- kind benefits)

Module 3. Household and farm assets owned by the HH*

Assets	Number	Assets	Number	Assets	Number
Tractor		Refrigerator		Car/Jeep	
Drill/ Ridger/Bed planter		Washing Machine		Motorcycle	
Trolly		Computer		Cycle	

*(for adaptive capacity differential by asset endowment)

Module 4: Land Resource and its Management (land utilization, allocation, output and income)

4.1. Land owned and cultivated (in Acre), put '0' if no and 'X' if not relevant**)**

Total Own Land (acres)	Own Cultivated	Own Uncultivated
Leased in/ Share in	Leased out/ Shared out	Lease **Rate** Rs./acre/year
Operational Land Holding	Operational Rainfed	Operational Irrigated

Irrigation sources 1=tube well/Turbine for underground water 2=pumped from pond/mini dam/stream 3=surface supply from canal 4=surface supply from stream/pond/dam 5=Other specify

Power source for irrigation system 1=Electric motor 2=Peter engine 3=Tractor 4=Solar 5=Other -

** Not in use for crop/forest farming (gravel, saline, waterlogged)

4.2 Utilization of irrigated and un-irrigated land resources for crops production (Cropping Pattern, Intensity)

Rabi crops 2015-16 (name season if different)	**Area (acre)**		**Kharif crops (2016) (name season if different)**	**Area (acre)**	
	Irrigated	**Rainfed**		**Irrigated**	**Rainfed**
Wheat			Rice		
Mustard/sarsoon/ canola			Maize (grain)		
Berseem			Sorghum/Millet /maize (fodder)		
Oat			Groundnut		
Lentil			Guar		
Gram			Potato		
Vegetables*			Vegetables*		
Orchard (area or plant #)			Orchard		
Other crop (specify)			Other (specify)		
Other (specify)			Other (specify)		
Fallow**			Fallow		

*(H. Consumption +commercial) ** Land kept fallow for 4-6 months other than non-intercropped orchard area

Note: Give names and period of crop season if different than rabi/kharif in plains

4.3 Income from Horticulture, sale of tress and livestock (milk or animal sale**) (ON AN AVERAGE)**

Source	Income Rs./Year	Source	Income Rs./Year
Vegetables Production (Rs/year)		Orchard/Fruits (Rs/year)	
Sale of Trees		Any other	

4.4. Livestock Animals

Large ruminants/Dairy Animals (young stock + adult) #		Small Ruminants #	
Ave. Monthly income from Milk (Rs./Month)		Annual Income from sale of animals (Rs./Year)	

Module 5. Farmers' Perceptions about Climate Change

5.1. Temperature pattern has changed due to climate change. What do think about the followings?

(During the about last 10-20 years what is your observation about changes in temperature in your area?)

Overall temperature has 1=increased 2=decreased 3=no change			
Summer temperature now as compared to that it used to be 20 years ago	1=More hot, 2=Less hot, 3=Same	**Winter temperature** now as compared to that it used to be 20 years ago	1=More cold, 2=Less cold, 3=Same
i) Summer season is		i) Winter season is	
ii) Summer days are		ii) Winter days are	
iii) Summer nights are		iii) Winter night are	
Summer stresses (Intra-seasonal)	1=Increased, 2=Decreased, 3= No change	**Winter stresses (Intra-seasonal)**	1=Increased, 2=Decreased, 3= No change
i. Number of extremely hot days in summer has		i. Number of extremely cold days in winter has	
ii. Number of extremely hot nights in summer has		ii. Number of extremely cold nights in winter has	
iii. Windstorm in summer		iii. Frost nights in winter	
iv. Hailstorms		iv. Hailstorms	
v. Any other		v. Foggy days has	
vi. Any other		vi. Any other	

5.2. Experience shows that seasons have changed. What do you think about the followings?

i. Summer season:	1=Early, 2=Late, 3=No change	**No of days (0,1,2,...)**	**ii. Winter season:**	Early=1; Late=2; No change=3	No of days (0,1,2,...)
1) Summer starts*			1) Winter starts**		
2) Summer ends**			2) Winter ends*		

*/** Coincide with each other

Write notes and reasoning for any unusual responses ———————————————————————

———————————————————————————————————

———————————————————————————————————

5.3 What have you noticed about the changes in rainfall pattern due to climate change over last 20 years?

Summer/monsoon rains:		**Winter rains:**	
Shift observed in onset of rainy season 1=Early, 2=Late, 3 =No change		Shift observed in onset of winter rainy season 1=Early, 2=Late, 3= No change	
Shift observed in occurrence of pre-moon soon rains 1=Early, 2=Late, 3 =No change			
Frequency of rains 1=Increased 2=Decreased 3=No change		Frequency of rains 1=Increased 2=Decreased 3=No change	
Number of **heavy** rainfall events has 1=Increased 2=Decreased 3=No change		Number of **heavy** rainfall events has 1=Increased 2=Decreased 3=No change	
Number of **light** rainfall events has 1=Increased 2=Decreased 3=No change		Number of **light** rainfall events has 1=Increased 2=Decreased 3=No change	
Events of untimely rains has 1=Increased 2=Decreased 3=No change		Events of untimely rains 1=Increased 2=Decreased 3=No change	
Total rainfall (quantity of water) has 1=Increased 2=Decreased 3=No change		Total rainfall (quantity of water) has 1=Increased 2=Decreased 3=No change	
Events of continuous rainy days (*jharri*) has 1=Increased 2=Decreased 3=No change		Events of continuous rainy days (*jharri*) has 1=Increased 2=Decreased 3=No change	
Canal/stream water supply has 1=Increased 2=Decreased 3=No change		Canal/stream water supply has 1=Increased 2=Decreased 3=No change	
Ground water table has 1=Increased 2=Decreased 3=No change		How much water table has change (ft)	
Under ground water quality has 1=deteriorated 2=improved 3=no change		Reason for change in quality --------	
Over time soils has become 1=more saline 2=less saline 3=no change		Reasons for this change in salinity -------	
Over time soils has become 1=more waterlogged 2=less waterlogged 3=no change		Reasons for this change in water logging -----------	

Write NA (Not Applicable) if not relevant to concerned farm/site

5.4 Rank following climate change aspects in terms of increasing challenge for crop production c (Ranke 1 as most serious and 4 less as an inter comparison among the four options)

Climate change issues	**Rank 1 to 4**
Increase in temperature (**Global warming**) overall as compared to 10-20 years ago	
Decrease in **rainfall** as compared to 10-20 years ago	
Unpredictable weather (temperature and rain) at different crop stages	
Extreme climate events (floods, droughts)	

Do you consider the following seasons in terms of weather as: **1=normal 2=good 3=bad**

Winter 2015-16 _________ Summer (Kharif) 2016 ___________ Winter 2016-17 ___________

Has Crop Yield increase over last 20 years 1=increased 2=no change 3= Decreased_________

Has crop yield increased over last 5 years 1=increased 2=no change 3= Decreased________

Ground water table ------Ft. Soil condition: 1=normal 2=Slightly saline 3=saline ------

Field condition: 1=Well drained 2=low drained ------

Soil Type 1=loam, 2=sandy loam 3=clay 4=clay loam 5=sandy --------

Module 6 Critical stress periods (What is your opinion on the effects of any experienced stresses due to clime change?)

6.1: Shift in weather and changes in cropping seasons (if both crops overlap write period with months name eg April-Oct)

	Rabi (Winter) –Period mm-mm---------		**Kharif (Summer) period mm-mm------**	
Crops (For major/common cropping practices)	**Wheat**		1=Potato (Hunza) 2=Groundnut (Pothwar) **3=Rice (irrigated Plains) 4=Maize (hunza)**	
The sowing (as per your common practice) starts from (wk/mm)	**Week# ________ Month#_______**		**Week# ________ Month#_______**	
The sowing (as per your practice) completes (wk/mm)	**Week# ________ Month#_______**		**Week# ________ Month#_______**	
The harvesting (as per your practice) starts from (wk/mm)	**Week# ________ Month#_______**		**Week# ________ Month#_______**	
The harvesting (as per your practice) completes (wk/mm)	**Week# ________ Month#_______**		**Week# ________ Month#_______**	
Major area of this crop planted after 1=Fallowing 2=---------Name of crop				
Stages	**Sowing**	**Harvesting**	**Sowing**	**Harvesting**
Is there shift in sowing/harvesting stage due to changes in seasonal patterns as compared to **10 years or more 1=yes 2no**				
If answer above is (1) **yes** it is shifted to earlier or late **1=earlier 2= later**				
How many days it has shifted				
Impact of this shift in sowing/harvesting stage on crop yield (in case of no adaptation or change of variety 1=Positive 2=Negative 3=no change				
If answer of above is 1 or 2: How much change in yield is observed (mds/acre) due to this shift				
If shift has negative impact on yield; what are your adaptation practices to avoid yield loss due to shifts: 1=change variety 2=increase fertilizer doses 3=partial shift to some other crop 4=higher seed rate 5=did nothing 6=adopted short duration variety 7= other (specify) ------				
Cost of above adaptation strategy(s) (Rs./Acre)				
Looking at past CC trend in which direction season will move (Future expectations for shift in season. (1=season will start early 2=start late 3=end early 4=end late 5=no change/ further shift)				
How will you adjust to this expected shift 1=Change variety 2=change crop 3=high fert 4=no other viable option except to continue same practices 5=high seed rate 6=other				
What are the constraints to adapt for the above expected shifts (specify)				
If farmer identify that shift in season will continue: upto what time he may adjust sowing and harvesting as compared to present practice (after that threshold reaches and has to switch some other crop).	**Wk#_____Month#________**	**Wk#_____Mh#____**	**Wk#_____Mh#_______**	**Wk#_____Mh#______**
Is this shift creates conflicts with inputs required and next cropping season? If so please identify **A- Inputs (shortage of labour, machinery, seed tec) B=Shortage of Water or moisture evaporation ; C- Delay in next crop D- Other (specify)** ----				
Describe the details of conflicts				

6.2. Critical Stress Period: occurrence of stresses and impact by stages

	Rabi (Winter) (Period -----------)						
Crops	**Wheat**						
Crop stages	**Pre-sowing (1)**	**Sowing (2)**	**Germination (3)**	**Tillering & Veg. growth (4)**	**Reproductive (5)**	**Grain formation (6)**	**Harvesting (7)**
6.2.1 Main unusual weather changes experienced by stage (during last 10 years) that results in change in yield (give # from below list) ---option may be more than 1.							
1=Higher temperature than normal season 2=Lower temperature than normal season 3=Increase in frost days 4=Decrease in frost days 5=Increase in foggy days 6=Decrease in foggy days 7=Heavy rain 8=Light rain 9=No rains (seasonal drought) 10=Delayed rains (after critical stage)- 11=Early rains 12=Decrease in surface water supply 13=Windstorms 14=Hailstorms 15=Short heat spikes (heat stress) 16=Low Moisture 17=less rains (less than required) 18=others							
6.2.2 Most common weather stress at each stage (if answer is more than one in 6.2.1) (give details for most recent in case frequency of two CP is same)							
Frequency of occurrence of most common weather change at each stage (during last 10 years)							
PART-A BIOPHYSICAL IMPACTS: (for most common) **Impact on crop yield 1=Positive 2=Negative 3=no change**							
Minimum change in yield experiences (mds/acre) *in case lower intensity (if frequency more than 1)during last 10 years*							
Maximum change in yield experienced (mds/acre) in case higher intensity of weather change during last 10 years							
Year of occurrence of last stress event by stage (write as season as 2015-16 or 2011-12)							
Decrease in yield during last stress event (Mds/acre)							
Normal season yield Mds/acre – if no stress during the season							
PART-B Pathways causing yield loss/increase 1=more weed infestation 2=insect attack 3=disease 4=less germination 5=crust formation (poor germination) 6=decrease in tillering 7=flowering/reproduction disturbed 8=grain shrivelling due to heat stress 9=lodging 10=reduced time period for grain formation (small grains) 11=delay in sowing 12=additional moisture 13=wetting of grains/crop 14=harvesting/threshing losses 15=other – (Ref of CP 6.2.2)							
Share of produce (grain+straw) that was affected by quality (%) (0 if no effect on quality)							
If it affected quality what was the effect observed: 1=change in taste 2=change in color 3=decrease grain size 4=other (specify)							
Decrease in prices of grain due of quality deterioration (%)							
Decrease in prices of straw due of quality deterioration (%)							
Area Affected during last event (%)							
Area Left Unsown during last event (%)							
---PART-C ADAPTATION adopted to avoid losses from such weather hazards: Adaptations options given below (may be more than one for a stress)							

Adaptation options to avoid/reduce expected losses: 1=Re-sowing of same crop 2=Sowing of alternate crop 3=High seed rate 4=Low seed rate 5=Adopted heat/ moisture stress tolerant new variety 6=Planted old/traditional variety 7=Supplemental/additional irrigation 8=Changed cropping pattern (adjusted new crop) 9=Changed sowing method 10=Additional/higher dose of inputs/fertilizer 11=Grow low input crop (taramera/pulses) 12=Introduced intercropping 13=Changed crop rotation 14=early sowing 15=late sowing 16=Left land fallow 17= Improved crop production practices 18= Started planting trees at boundaries for supplemental income 19=Shifting from crop to livestock 20=Diversification towards HVA 21=Check/follow weather forecasts for adjusting production practices 22= ploughed fields to prepare land for early sowing of next crop 23=availed insurance 24=use of weedicide 25=supplemental irrigation 26=Bar harrow/light cultivator to break crust 27=Drying of harvested crop 28=no sowing at all 29=Planted old variety 30=Any other specify							
Which of above you adapted (most often or last one)							
Cost of this adaptations (Rs./acre) (combine cost if more than one adaptation opted at one stage)							
How much was this adaptation effective % (recover % income or reduce loss compared if not opted this adaptation)							
What are your expectations for future regarding such stresses by stage (1=increase 2=decrease 3=no change 4=no response							
If frequency of stresses increases in future, How you will cope with it? 1=current adaptations are sufficient 2=drastically change farming practices 3=stop sowing this crop 4=had no option except to continue current practice/crop 4=other							

PART-D Did you opt any of the coping strategy to sustain livelihood due to severe losses from CP during last 10 years	
List of coping/ adaptation strategy 1=Sold livestock animals 2=Improve food storage facility 3=Sold part of land for alternative business 4=Leased /out part of land for alternative income 5=use of savings 6= Sold other assets 7=Sold trees 8=Started off farm labor/Employment in local area 9=Some family member migrate out for other employment to supplement family income 10=Support from existing Non-farm business 11=Other (specify)	
What would be possible adaptation strategies to sustain your livelihood/food security against increasing climate stresses 1=Crop diversification 2=Increase livestock 3=Shift to HVA 4=Off/non-farm activity 5=water source development (tube well) 6= Any other (specify----)	
What are the major constraints to adapt to stresses as discussed at different stages under CC 1=financial 2=technical (technology and knowledge) 3=other	
PART E: Supply demand aspect; Do the losses from weather hazards result in changes in overall production (supply side variability) significantly that also affect prices 1=yes 2=no	
If yes; How much this prices increase (due to low production/supply) compensate for the yield loss to balance net income 1=Not at all 2=Partial 3=Fully	
How often you have to purchase this commodity for your household consumption during last ten years due to losses from critical period (#)	

6.3 Critical Stress Period: occurrence of stresses and impact by stages

	Kharif (Summer)						
Crops (encircle)	**1=Potato (Hunza valley) 4= Maize** 2=Groundnut (Pothwar) 3=Rice (irrigated Plains)						
Crop stages	**Pre-sowing (1)**	**Sowing (2)**	**Germination (3)**	**Tillering & Veg. growth (4)**	**Reproductive (5)**	**Grain formation (6)**	**Harvesting (7)**
6.3.1 Main unusual weather changes experienced by stage (during last 10 years) that results in change in yield (give # from below list) ---							
1=Higher temperature than normal season 2=Lower temperature than normal season 3=Increase in frost days 4=Decrease in frost days 5=Increase in foggy days 6=Decrease in foggy days 7=Heavy rain 8=Light rain 9=No rains (seasonal drought) 10=Delayed rains (after critical stage)- 11=Early rains 12=Decrease in surface water supply 13=Windstorms 14=Hailstorms 15=Short heat spikes (heat stress) 16=Low Moisture 17=other							
6.3.2 Most common weather stress at each stage (if answer above is more than 1)							
Frequency of occurrence of most common weather change at each stage (during last 10 years)							
PART-A BIOPHYSICAL IMPACTS: (for most common) Impact on crop yield 1=Positive 2=Negative 3=no change							
Minimum change in yield experiences (mds/acre) *in case lower intensity (if frequency more than 1)during last 10 years*							
Maximum change in yield experienced (mds/acre) in case higher intensity of weather change during last 10 years							
Year of occurrence of last stress event by stage							
Decrease in yield during last stress event (Mds/acre)							
Normal season yield Mds/acre – if no stress during the season							
PART-B Pathways causing yield loss/increase 1=more weed infestation 2=insect attack 3=disease 4=less germination 5=crust formation (poor germination) 6=decrease in tillering 7=flowering/reproduction disturbed 8=grain shrivelling due to heat stress 9=lodging 10=reduced time period for grain formation (small grains) 11=delay in sowing 12=additional moisture 13=wetting of grains/crop 14=harvesting/threshing losses 15=other – (Ref of CP 6.3.2) (stress may be more than one at one stage							
Share of produce that was affected by quality (%) (0 if no effect on quality)							
If it affected quality what was the effect observed: 1=change in taste 2=change in color 3=decrease grain size 4=other (specify)							
Decrease in prices due of quality deterioration (%)							
Decrease in prices of straw due of quality deterioration (%)							
Area Affected during last event (%)							
Area Left Unsown during last event (%)							

Crop stages	Pre-sowing (1)	Sowing (2)	Germination (3)	Tillering & Veg. Growth (4)	Reproductive (5)	Grain formation (6)	Harvesting (7)
PART-C ADAPTATION adopted to avoid losses from such weather hazards: Adaptations options given below (may be more than one for a stress)							
Adaptation options to avoid/reduce expected losses: 1=Re-sowing of same crop 2=Sowing of alternate crop 3=High seed rate 4=Low seed rate 5=Adopted heat/ moisture stress tolerant new variety 6=Planted old/traditional variety 7=Supplemental/additional irrigation 8=Changed cropping pattern (adjusted new crop) 9=Changed sowing method 10=Additional /higher dose of inputs/fertilizer 11=Grow low input crop (taramera/pulses) 12=Introduced intercropping 13=Changed crop rotation 14=early sowing 15=late sowing 16=Left land fallow 17= Improved crop production practices 18= Started planting trees at boundaries for supplemental income 19=Shifting from crop to livestock 20=Diversification towards HVA 21=Check/follow weather forecasts for adjusting production practices 22= ploughed fields to prepare land for early sowing of next crop 23=availed insurance 24=use of weedicide 25=supplemental irrigation 26=Bar harrow/light cultivator to break crust 27=Drying of harvested crop 28=no sowing at all 29=Planted old variety 30=Any other specify							
Which of above you adapted (most often or last one)							
Cost of this adaptations (Rs./acre) (combine cost if more than one adaptation opted at one stage)							
How much was this adaptation effective % (recover % income or reduce loss compared if not opted this adaptation)							
What are your expectations for future regarding such stresses by stage (1=increase 2=decrease 3=no change 4=no response							
If frequency of stresses increases in future, How you will cope with it? 1=current adaptations are sufficient 2=drastically change farming practices 3=stop sowing this crop 4=had no option except to continue current practice/crop 4=other							
PART-D Did you opt any of the coping strategy to sustain livelihood due to severe losses from CP during last 10 years							
List of coping/ adaptation strategy 1=Sold livestock animals 2=Improve food storage facility 3=Sold part of land for alternative business 4=Leased /out part of land for alternative income 5=use of savings 6= Sold other assets 7=Sold trees 8=Started off farm labor/Employment in local area 9=Some family member migrate out for other employment to supplement family income 10=Support from existing Non-farm business 11=Other (specify)							
What would be possible adaptation strategies to sustain your livelihood/food security against increasing climate stresses 1=Crop diversification 2=Increase livestock 3=Shift to HVA 4=Off/non-farm activity 5=Any other (specify----)							
What are the major constraints to adapt to stresses as discussed at different stages under CC 1=financial 2=technical (technology and knowledge) 3=other							
PART E: Supply demand aspect; Do the losses from weather hazards result in changes in overall production (supply side variability) significantly that also affect prices 1=yes 2=no							
If yes; Do prices increase (due to low production/supply) compensate for the yield loss to balance net income 1=yes 2=no							
How often you have to purchase this commodity for your household consumption during last ten years due to losses from critical period (#)							

Module 7. Adaptive Capacity

What strategies/options (Planned) you are considering to cope with perceived weather changes for future

Options	(1=yes 2=No)		(1=yes 2=No)
Change in cropping Pattern		Use of improved seed	
Changing crop mixes		Improving soil health through fallowing/ improved tillage/drainage	
Change Irrigation management at plot level (time, qty, ferq)		Investment in water conservation and rainwater harvesting	
Change Irrigation methods		Invest in irrigation facility (tube well/HEIS)	
Improve moisture conservation –crop cover inter cropping, deep ploughing		Shift towards livestock	
Shift towards horticultural crops		Shift towards non-farm activities	

How farmer consider important the following factors to adapt to critical stress periods.
Rank as 1=Highly Important, 2=Important, 3=Neutral , 4=Less Important 5=Not important at all

Information on weather forecast	Technical guidance	Technology	Alternative crops	Crop Insurance	Other Specify

Factors that support flexibility to cope with critical stress periods at individual level

You have or can easily hire machinery (tractor, harvester etc.) if required for re-sowing or harvesting due to some critical stress period within the required time period 1=yes 2=no		You can manage (have access) additional irrigation water (own or rented tube well, pond, stream etc.) required during stress like seasonal drought or heat stress or frost 1=yes 2=no	
You can hire farm labor to do some crop management practices to avoid losses in face of some uneven weather events 1=yes 2=no		You can arrange finances for input timely to respond to weather stresses (e.g. seed, additional fertilizer, supplemental/additional irrigation, pesticides etc.) 1=yes 2=no	
Seed of possible alternate crops (sowing of alternate crop in case of crop failure due to some weather stress) is easily available to you from local market 1=yes 2=no		Required variety is also available to you from local/district level 1=yes 2=no	
Are new varieties resistant to moisture stress 1=yes 2=no		Are new varieties more resistant to heat stress 1=yes 2=no	
Are new wheat varieties of short duration 1=yes 2=no		Are new rice varieties of short duration 1=yes 2=no	
You can get credit to invest at farm or meet HH requirements from 1=relatives/friends 2=formal sources 3=commission agents /input dealers 4=private money lender 5=other (answer may be more than one)		Community members participate in collective action (in terms of labor, finances and resources) to manage common resources (irrigation, grazing lands) 1=yes 2=no	
Are you in contact with extension agent (1=yes 2=no)		If yes what type of service you get from extension staff 1=technical advice 2=literature 3=inputs 4=weather forecast 5=other (may be more than one)	
From whom did you get weather forecast most often1=relative/fellow farmer 2=extension deptt 3= TV 4=Mobile application 5=website 6=other		How often do you get weather forecasts from this source? 1=daily 2=Weekly 3=fortnightly 4=monthly 5=once or twice in a season	
Did you use any of the advice and information about when to plant crops from this source 1=yes 2=no		Is such information helpful to make adjustment in crop management to minimize risk 1=yes 2=no	
Possible adaptations/coping mechanisms are proposed for different crops along with such information 1=yes 2=no		If yes; do you consider such information for planning and implementing proposed adaptations 1=yes 2=no	
If yes; are such adaptations effective to cope with such stresses 1=yes 2=no		Is weather forecast accurate 1=yes 2=no	

If farmer is willing to spare more time please get cost of production per acre

8. Crop Management practices as per last cropping season (two to three major selected crops from each study sites)

Operations	Units	Price Rs./unit	Wheat	Rice/Potato/maize/g.nut
Previous season crop at the main plot 1=fallow 2=cropped (write name of crop)				
Name of Variety				
Land preparation				
Main power source 1=tractor 2=animal				
Deep tillage/MB plow	No./acre			
Cultivator	No./acre			
Planking (sole)	No./acre			
Rotavator/disc plough	No./acre			
Seed bed Preparation				
Cultivator	No./acre			
Planking (sole)	No./acre			
Puddling	No./acre			
Sowing method: 1=Drill, 2=Broadcast 3=Bed planting 4=Ridges 5=transplanting				
Seed rate	Kg/acre			
Seed Price	Rs./kg			
Planting cost (labour)	Rs./acre			
Planting cost (Tractor)	Rs./acre			
Seed treatment cost (Rs/acre) (0 if no treatment)				
Planting date	Week/Month			
Irrigation Total	No./acre			
Tube well/ pumped water	No/acre.			
Canal/stream	No./acre			
Conjunctive use	No./acre			
Irrigation method 1=Flood 2=Furrow 3=Other -------				
Fertilizer use: Basal dose				
DAP	(Bags/acre)			
Urea	(Bags/acre)			
Others (Specify)	(Bags/acre)			
Top dressing				
Urea	(Bags/acre)			
Others (Specify)	(Bags/acre)			
Others (Specify)	(Bags/acre)			

Operations	Units	Price Rs./Unit	Wheat	Rice/Potato/maize/g.nut
Animal FYM	(Trollies/Acre)			
Poultry manure	(Trollies/acre)			
Manual weeding	(Rs./acre)			
Chemically weeding	(Rs./Acre)			
Insecticide use	(Rs./Acre)			
Harvesting method 1=Manual 2=Reaper 3=Combine				
Harvesting cost (Machine+Labour)	Rs/acre			
Harvesting cost	Mds/are			
Threshing method 1=Manual 2=Tractor 3=Combine				
Thresher cost	(Rs/acre)			
Threshing cost	(share in % of yield)			
Threshing labour cost	Rs./acre			
Grain **yield**	(Mounds/ac)			
Grain prices	(Rs/md)			
Dry stalk/ straw production	Mds/acre			
Dry stalk prices	(Rs/ md)			
Grains kept for home consumption/seed etc (mds/year)				

Comments and field notes for important changes wrt CP and adaptations:

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Edited by: _______________ Signature _______________date______

Cross checked by: ___________________ Signature _______________date______

Data entered by: ___________________ Signature _______________date______

SENSE

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

Hassnain Shah

born on 1st November 1972 in Sargodha, Pakistan

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

Wageningen, 20 January 2023

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)

K O N I N K L I J K E N E D E R L A N D S E
A K A D E M I E V A N W E T E N S C H A P P E N

The SENSE Research School declares that Hassnain Shah has successfully fulfilled all requirements of the educational PhD programme of SENSE with a work load of 45.1 EC, including the following activities:

SENSE PhD Courses

- Basic Statistics (2015)
- Grasping Sustainability (2016)
- Environmental research in context (2016)
- SENSE Writing Week (2018)
- Research in context activity: 'Identification of climate risks to crop production: Investigation and communication of critical moments' (2022)

Other PhD and Advanced MSc Courses

- Research Methodology I: From topic to proposal, WASS graduate school (2015)
- Information Literacy including EndNote Introduction, Wageningen Graduate Schools (2015)
- Systematic approaches to reviewing literature, Wageningen Graduate Schools (2016)
- Techniques for Writing and Presenting a Scientific Paper, Wageningen Graduate Schools (2016)
- The Essentials of Scientific Writing and Presenting , Wageningen Graduate Schools (2016)
- Resilience of living systems; From fundamental concepts to interdisciplinary applications, WIAS and PE&RC (2018)
- Reviewing a Scientific Manuscript, Wageningen Graduate Schools (2019)

External training at a foreign research institute

- HI-AWARE Academy for PhD Students, ICIMOD, Nepal (2016)
- Cross-CARIAA Dialogue on Economics of adaptation: Setting agenda for incremental and transformative change. The Energy and Resource Institute, India (2017)

Oral Presentations

- *Vulnerability of agriculture to intra-annual climate variability: A synthesis to define different types of critical moments*. Water Science for Impact, 16-18 October 2018, Wageningen, The Netherlands
- *Climate Risks to Agriculture: A Critical Moment Approach.* The 3rd International Colloquium 'Challenges and opportunities of Maize Production', 18-20 May 2022, Faisalabad, Pakistan

SENSE coordinator PhD education

Dr. ir. Peter Vermeulen

Selected Publications

Shah, H., Hellegers, P., & Siderius, C. (2021). Climate risk to agriculture: A synthesis to define different types of critical moments. *Climate Risk Management*, *34*, 100378. https://doi.org/10.1016/j.crm.2021.100378

Shah, H., Siderius, C., & Hellegers, P. 2021. Limitations to Adjusting Growing Periods in different Agroecological Zones of Pakistan. Agricultural Systems, 192, 103184. https://doi.org/10.1016/j.agsy.2021.103184

Shah, H., Siderius, C., & Hellegers, P. 2020. Cost and Effectiveness of In-season Strategies for Coping with Weather Variability in Pakistan's Agriculture. *Agricultural Systems, 178*, 102746. https://doi.org/10.1016/j.agsy.2019.102746

About the Author

Hassnain Shah was born in a village named Shah Yousaf, in Sargodha, Punjab, Pakistan on November 01, 1972. The village is on the name of his grand grandfather, a great Sufi saint who came in this area some 500 years ago. He grew up in a rural agrarian culture and belongs to a farming family. He completed 8th grade schooling in the same village, 10th grade from High School No. 1, Sargodha, 12th grade from FG Sir Syed College, Rawalpindi and M.Sc. (Hons) Agriculture-Agricultural Economics in 1999 from University of Agriculture, Faisalabad. Being the son of soil, he learned the basic art and science of agriculture. During last 50 years, he witnessed rural transformation, agricultural transition from subsistence to commercial with changing agro-industry, improvement in the value chains, changing consumption patterns and crop diversification. He first opted farming, the family business as a profession. In the first two years, he succeeded to double yield of sugarcane, the cash crop at his farm. Thanks to market imperfections and exploitation of the sugar industry which pushed him to move to the present job, continuing crop and livestock farming as part time activity. Being a practicing farmer, he also bore the brunt of increasing climate risks in agriculture.

He joined Pakistan Agricultural Research Council, the apex national organization in agriculture R&D, in 2001 in scientific cadre. He contributed as national focal person and team leader for socioeconomic component in several multidisciplinary R&D projects conducted in collaboration with NARS and international R&D organizations. The important projects include SIAC 2.1, CRP Dry Land System, Maize CRP and may national multidisciplinary collaborative projects like Applied Research in BVDP, Agriculture Innovation Program, Progressive Control of FMD, Watershed Rehabilitation and Irrigation Improvement, Soil Fertility Improvement, Vertical Coordination towards High-Value Agriculture and HI-AWARE project in collaboration with USDA, FAO, CIMMYT, ICARDA, ILRI, CABI, IRRI, ICIMOD. He also contributed to preparing National Agriculture and Food Security Policy 2018, Agricultural Policy Khyber Pakhtunkhwa, A Ten-Year Perspective (2015-2025); beside conducting a few commodity and issue-based research studies and organizing capacity building trainings for agricultural scientists in economic analysis of experimental data and projects.

He started PhD research at the Water Resource Management Group of Wageningen University & Research, The Netherlands as a sandwich student in 2015. Shah has solid background in; socioeconomic backstopping to NARS&D collaborating partners in different projects, evaluation of on-farm technology validation and demonstration, moving technologies along adaption and impact pathways, benchmark and impact studies, value chain and feasibility analysis.

Shah is determined to continue his career as a researcher with the Pakistan Agricultural Research Council, the federal organization mandated to coordinate and conduct research at national level and provide opportunities to share knowledge and contribute to the agriculture R&D. At his current position he is motivated to develop projects and collaborate with other R&D agencies especially on coping with climate risks in agriculture while already supporting master and PhD students from different universities in the country.