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Limitations to adjusting growing periods in different agroecological zones of Pakistan

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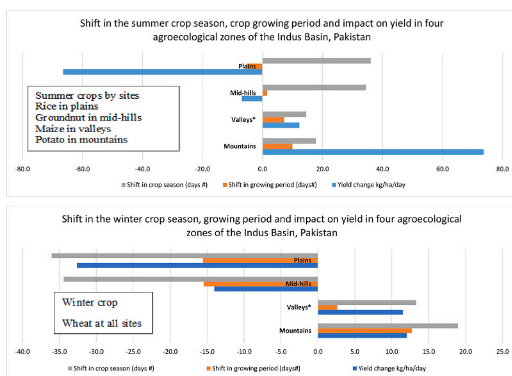
HIGHLIGHTS

- There are limitations to adjust growing period parallel to the shift in seasons.
- Impacts and limitations vary by cropping systems and agroecologies.
- Low altitude agroecologies in the Indo-Gigantic Plains are negatively impacted.
- Farmers invest in complementary adaptations to mitigate negative yield losses.
- Scope for further delay in wheat sowing is limited in low altitude agroecologies.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: 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.
OBJECTIVE: 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.
METHODS: 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.
RESULTS AND CONCLUSIONS: 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

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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.

SIGNIFICANCE: 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.

1. Introduction

Shifts in onset dates and length of cropping seasons are a main manifestation of climate change (Allen and Sheridan, 2016; Dong et al., 2010; Dwyer et al., 2012; Kutta and Hubbart, 2016; Linderholm, 2006). Changes have been documented in many seasonal parameters (Kutta and Hubbart, 2016; Linderholm, 2006). Key among these are changing temperatures, combined with shifting rainfall patterns (timing and amounts) (Bhatti et al., 2018; 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 et al., 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 (Ahmad et al., 2017; Nelson et al., 2010; Paymard et al., 2018; Sultana et al., 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 et al., 2016; Bhutto et al., 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 (Matthews et al., 1997; Shimono and Okada, 2013; Wang et al., 2015). Such impacts are also dependent on the prevailing mean local climate (Kutta and 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 climatic 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 and Lall, 2013; Kabir et al., 2017; Shah et al., 2020b). 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 (Ahmad et al., 2019; Bhatti et al., 2018; Nendel et al., 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 and Hubbart, 2016; Linderholm, 2006; Sparks and 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 et al., 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 et al., 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; Biemans et al., 2019; Yu et al., 2013).

2. Methodology

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 et al., 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 climatic 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 1). To check the consistency between the climatic 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.

Table 1
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	1600–1800	2500–3000
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.

To guide the interviews, critical moments were identified at which crops were deemed particularly sensitive to certain climatic 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 (Shah et al., 2020a). 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, $t-30$:

$$Scs_{ijk} = \left(\sum\nolimits_{i=1}^{n} cs_{ijkt} \Big/ n\right) - \left(\sum\nolimits_{i=1}^{n} cs_{ijkt-30} \Big/ n\right) \tag{1}$$

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:

$$Cgp_{ijk} = \left(\sum\nolimits_{i=1}^{n} gp_{ikjt} \Big/ n\right) - \left(\sum\nolimits_{i=1}^{n} gp_{ijkt-30} \Big/ n\right) \tag{2}$$

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 and Biscoe (1978):

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

where T_{base} is the base temperature, taken as 4.5 °C for wheat (Acevedo et al., 2002; Dar et al., 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) (Shah et al., 2020b). Such variation, combined with a variable climate, meant that some years were more representative of historical climatic 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:

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

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:

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

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.

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 s1). 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 (Biemans et al., 2019; Fowler and Archer, 2006; 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 (Ali et al., 2014; Government of Pakistan, 2018; Hashmi and Shafiullah, 2003; Khan and 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 (Khan and Khan, 2019). At the high-altitude sites, in the valleys (2300–3000 m), maize was grown from June to November and wheat from February to June. In the mountains (above 3000 m), wheat and potatoes were grown in a single crop season, from April to September (Ali et al., 2014; Hashmi and 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 Shah et al. (2020b).

3. Results

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

At each study site, most farmers reported changes in climatic 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 (Fig. 1). 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 (Fig. 1). 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.

Farmer perceptions of changes in temperatures largely corresponded with observations from the meteorological stations (Fig. 2). 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; Umar et al., 2021), leading to reduced visibility and limiting incoming solar radiation (Padma Kumari et al., 2007; Shao et al., 2021) (see Fig.-I, Annex-I). Weather data for the mid-hills site was only available after 2009, and clear trends here were lacking. However, the station

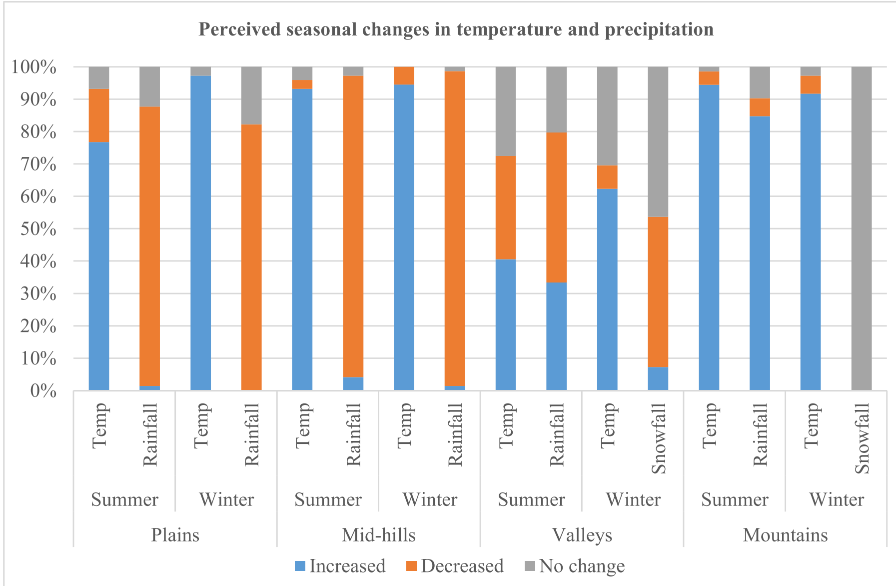

Fig. 1. Perceived changes in seasonal temperature and precipitation over the last 30 years at study sites.

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).

Perceived precipitation changes were somewhat consistent with observations from the meteorological stations (Fig. 3). 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.

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 (Fig. 4). 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 2). 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.

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 (Fig. II. A, Annex II), 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

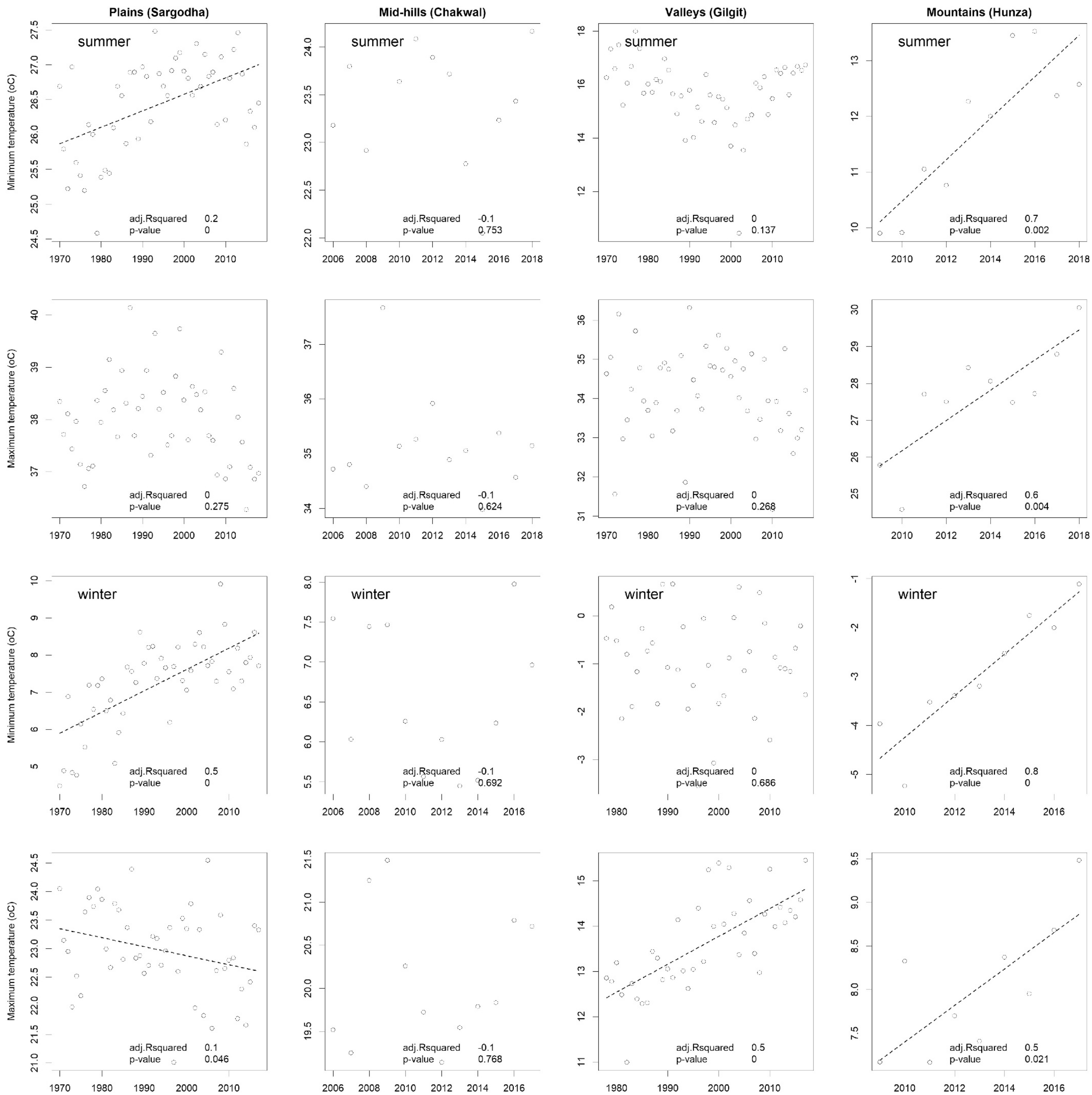

Fig. 2. Minimum and maximum temperature trends during summer and winter seasons at the study sites.

summer season (Fig. II·B, Annex II). 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

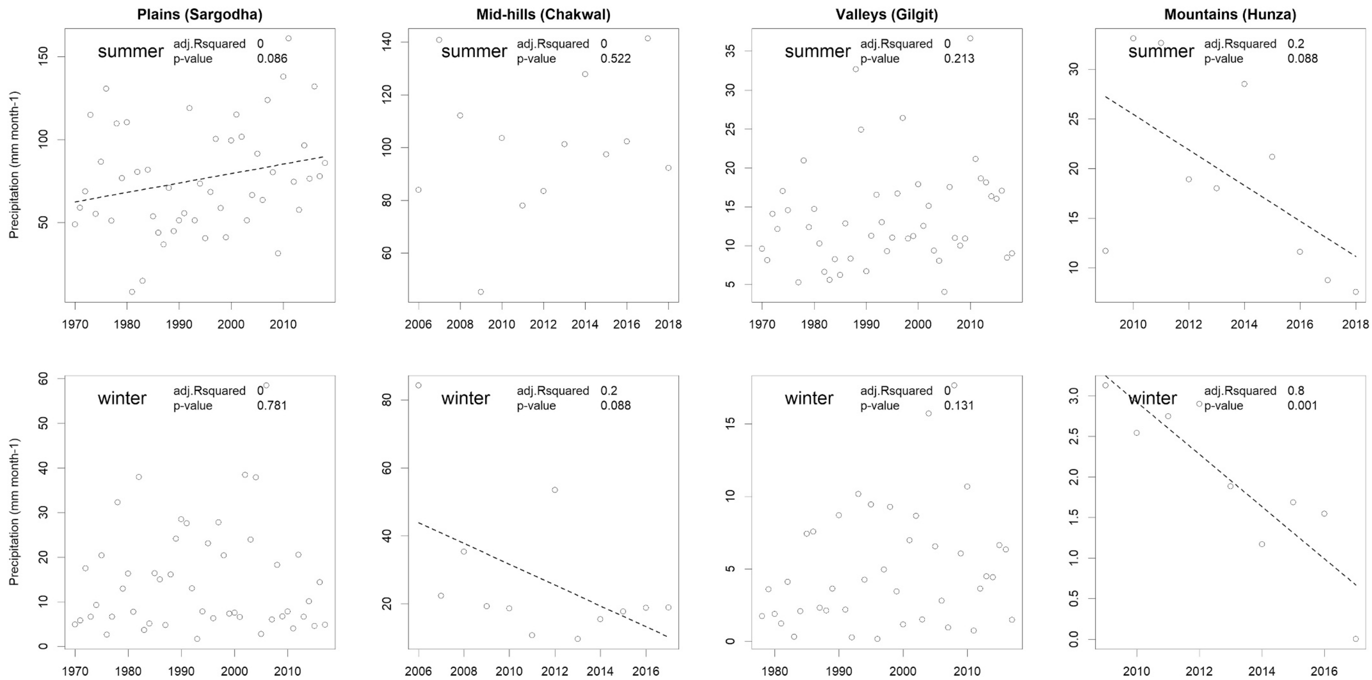

Fig. 3. Precipitation trends during summer and winter seasons at the study sites.

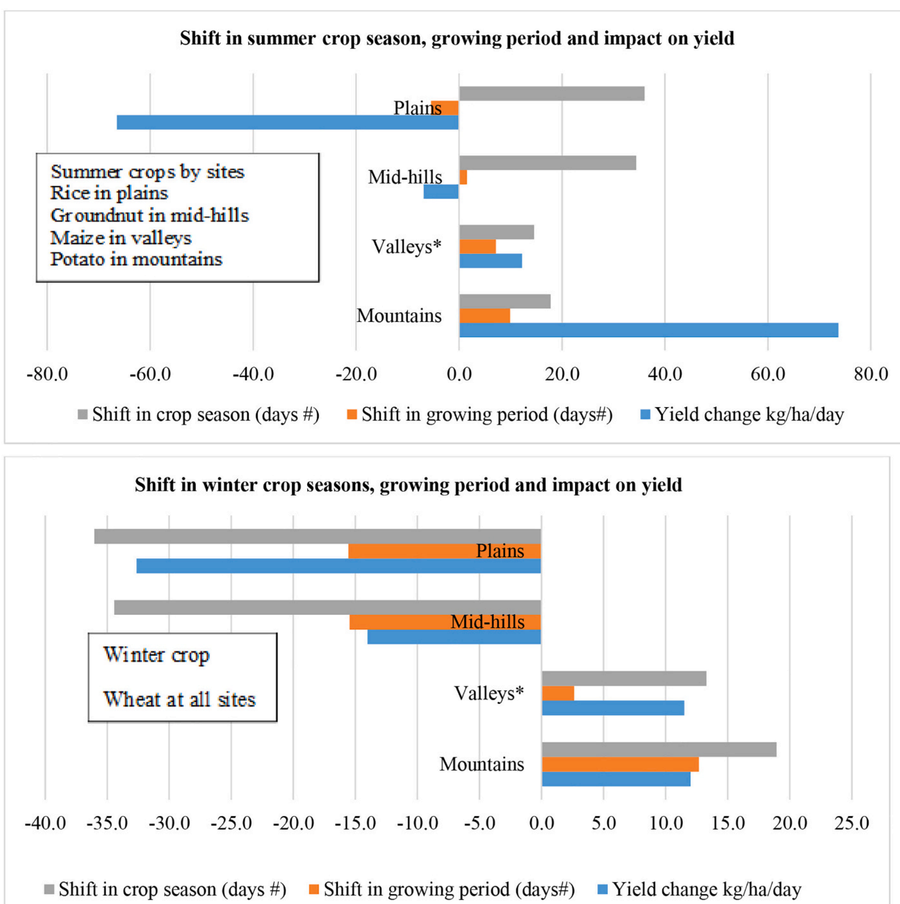

Fig. 4. Shift in crop season and growing period and impact on yield for summer crops.
*At this site, the change in yield was due to a change in germination date (ending the winter dormant period), hence the impact on yield was calculated using the shift in season (days).

Table 2
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

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 (Fig. 4).

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 III and IV.

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 3). Farmers also applied various combinations of these, with the cost of combinations ranging from 2400 to 5800 PKR/ha for wheat and 1600 to 7600 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.

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

Table 3
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	1285 (±207)	8	680 (±87)	8	1339 (±470)	54
Increase fertilizer dose	3855 (±2079)	8	3707 (±3495)	8		
Raise seeding rate	791 (±271)	8			659 (±231)	20
Switch varieties and increase fertilizer dose	4201 (±1503)	8	1606 (±1223)	8		
Increase fertilizer dose and seeding rate	4744 (±1691)	15	4374 (±2054)	38		
Switch varieties, increase fertilizer dose and increase seeding rate	5830 (±1596)	47	7660 (±3643)	15	3354 (±620)	15
Switch varieties, increase seeding rate and diversify crops	3707 (±1747)	3	4654 (±981)	23	2422 (±442)	11
Increase fertilizer dose, increase seeding rate and apply additional irrigation	7042 (±524)	3				
Total	4639 (±2246)		4396 (±2709)		1630 (±981)	

Note: The figures in parenthesis are standard deviations.

the future.

Fig. 5 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 (Aslam et al., 1989; Byerlee et al., 1984; Sheikh et al., 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 V). 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 agro-ecologies 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 flexibility to mitigate potential yield losses by using higher levels of inputs and irrigation.

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 (Fig. 6). 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).

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 et al. (2012) and Aslam et al. (2017), and the resulting yield losses are consistent with those reported by 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., 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 (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

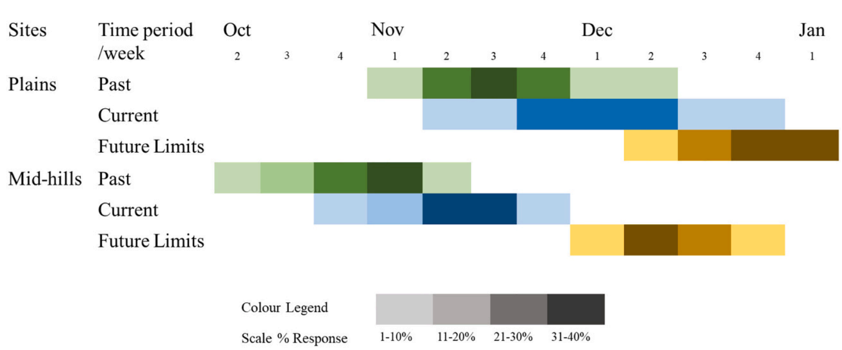

Fig. 5. Changes in wheat sowing period and future limits with expected seasonal shifts, according to farmers' responses ($n = 142$).

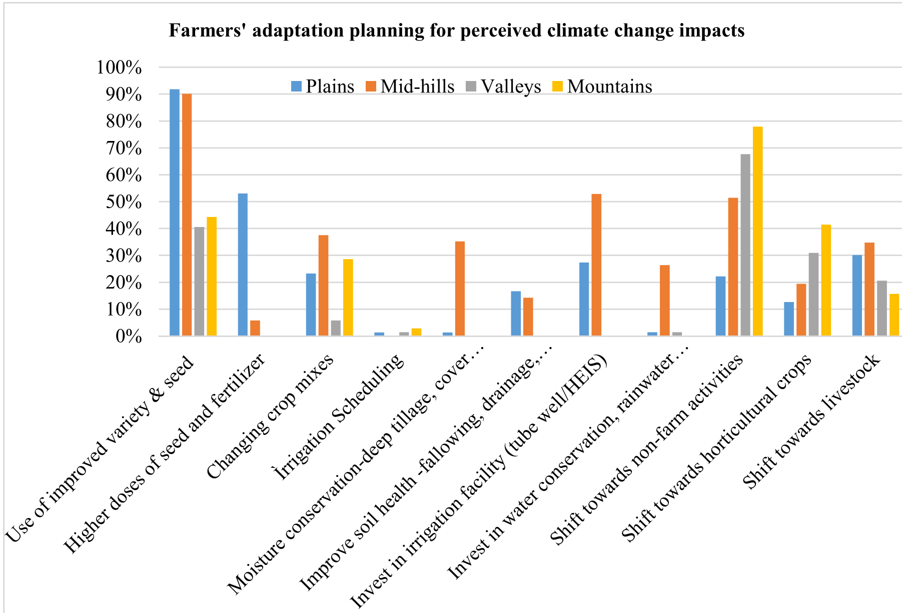

Fig. 6. Farmers' adaptation strategies for climate change impacts.

constant, in rice-wheat cropping systems, due to a shortening of the growing period (Aggarwal et al., 2000; Ahmed and Meisner, 1996; Hobbs and 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 and Shafiullah, 2003; Hussain et al., 2005; 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 et al., 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 (Hussain et al., 2005). Eighty percent of Pakistan's cereal production comes from the Indo-Gangetic Plain (Gupta and 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 (Sivakumar and 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 (Shah et al., 2020a). 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 (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.

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 socio-economic 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 agro-ecological 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.

Disclaimer

The views expressed in this work are those of the creators and do not necessarily represent those of the UK Government's Department for International Development, the International Development Research Centre, Canada or its Board of Governors.

Declaration of Competing Interest

None.

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Annexure.

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

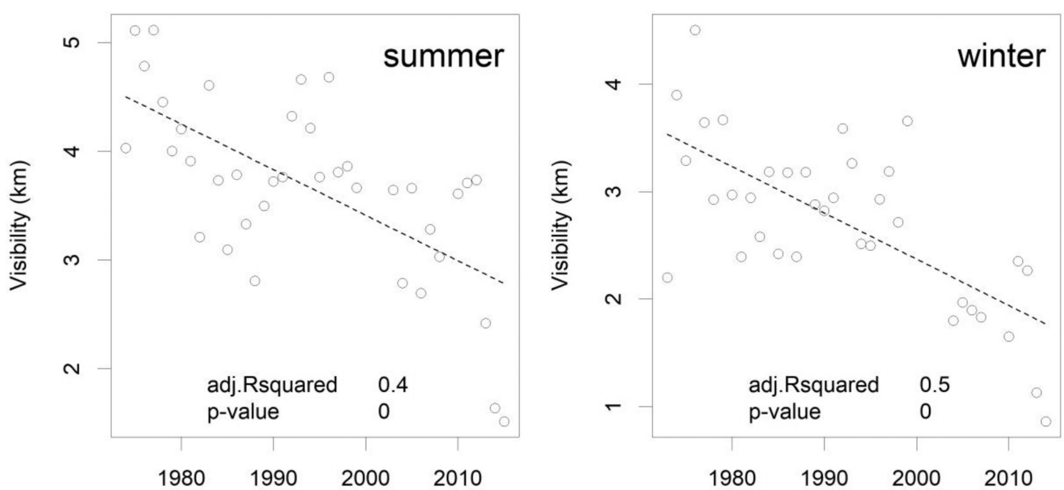

Figure 1. Solar radiation trends during summer and winter in Pakistan

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

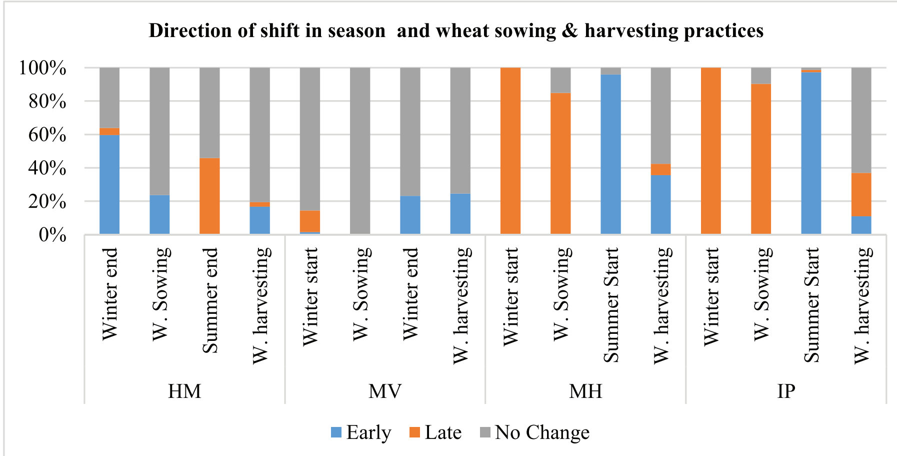

Figure II-A. Direction of shift in winter season and wheat sowing & harvesting practices (% Response)

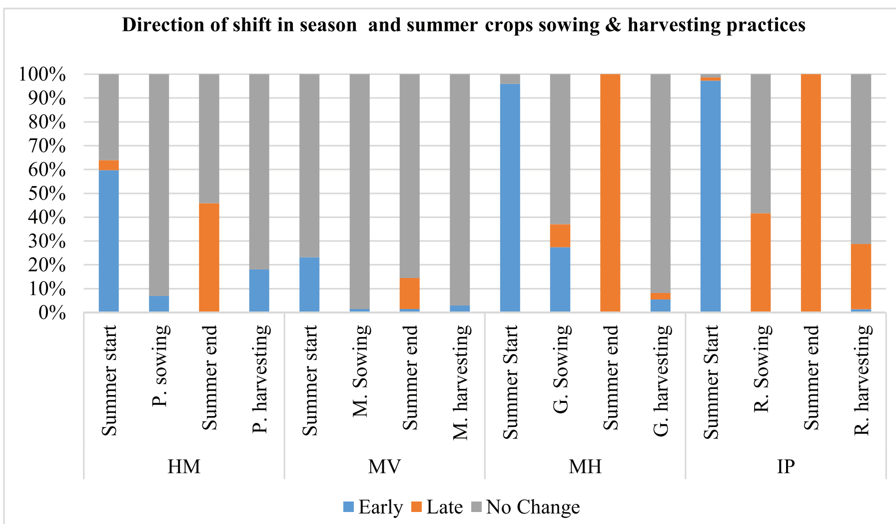

Figure II-B. Direction of shift in summer seasons and summer crop sowing and harvesting practices (% Response)

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

Table III.A
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			
	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

Table III.B
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			
	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	

Annex-IV. Shift in Kharif (summer) season, crop growing period and impact

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

Annex-IV.B
Shift in end of Kharif seasons, Kharif crop harvesting period and its impact on crop yield

	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	

Annex-V

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

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