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HEAT STRESS

Quantification of the impacts of climate warming and crop management on canola phenology in Punjab, Pakistan

S. Ahmad[1] | G. Abbas[1] | Z. Fatima[1] | R. J. Khan[1] | M. A. Anjum[1] | M. Ahmed[2] | M. A. Khan[3] | C. H. Porter[4] | G. Hoogenboom[4]

[1]Bahauddin Zakariya University, Multan, Pakistan
[2]Pir Meher Ali Shah, Arid Agriculture University, Rawalpindi, Pakistan
[3]Extension Wing, Department of Agriculture, Government of Punjab, Chiniot, Pakistan
[4]University of Florida, Gainesville, FL, USA

Correspondence
S. Ahmad, Bahauddin Zakariya University, Multan, Pakistan.
Email: shakeelahmad@bzu.edu.pk

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Abstract
Yield is influenced by the length of the growing season, which is affected by weather conditions and management practices of a crop, including sowing dates and shifting of cultivars. It is necessary to understand the effects of agronomic management practices and weather variables on phenological stages and crop phases in order to develop strategies for adaptation of agricultural systems to changes in climatic conditions. The goal of this study was to determine the impact of warming trends on phenology of canola from 1980 to 2014 for central and southern Punjab, Pakistan. Sowing, emergence, anthesis and physiological maturity dates were delayed by an average of 6.02, 3.14, 3.31 and 1.89 days per decade, respectively. The duration of sowing to anthesis, sowing to physiological maturity and anthesis to physiological maturity phases decreased an average 2.71, 4.13 and 1.42 days per decade, respectively, for all 10 locations that were analysed in this study. The sowing, emergence, anthesis and physiological maturity dates were positively correlated with an increase in temperature by an average 2.71, 1.41, 1.49 and 0.85 days per °C, respectively. However, the phenological phases such as sowing to anthesis, anthesis to maturity and sowing to maturity were negatively correlated with an increase in temperature by an average of 1.22, 0.64 and 1.86 days per °C, respectively, for all 10 locations. Applying a process-based CSM-CROPGRO-Canola model using a standard cultivar (field tested) for all locations and years indicated that the simulated phenological stages occurred earlier due to the warming trend compared to the observed phenological stages. One-quarter of the negative effects of this thermal trend was compensated by growing new cultivars that had higher thermal time requirements. Therefore, new canola genotypes with a higher number of growing degree day requirement and high temperature tolerance should be a priority for evolving new cultivars.

KEYWORDS
anthesis date, *Brassica napus* L., climate change, CSM-CROPGRO-Canola model, cultivar shift, Decision Support System for Agrotechnology Transfer, maturity date, warming trend

1 | INTRODUCTION

Punjab is the 2nd largest province in Pakistan (796,095 square kilometres) following Baluchistan and has the highest population (99.86 million), comprising nearly 57% of the entire population of the country (Govt. of Pakistan, 2014). The climate ranges from arid subtropical with an average temperature of 17.5–30.4°C and rainfall 150–200 mm in southern Punjab to semi-arid tropical with an average temperature of 10.5–24.4 °C and rainfall 315–600 mm in central Punjab. The majority of the rain occurs during the monsoon season (July–September) in Punjab (Ahmad et al., 2014).

Canola (*Brassica napus* L.) is an important oilseed crop in South Asia and Pakistan (Noreen, Noor, Ahmad, Bibi, & Hasanuzzaman, 2016). However, climate change has had a negative effect on the phenology of canola resulting in low seed yield (average 950 kg ha^{-1}) in Punjab, Pakistan. During year 2013–2014, Pakistan imported 2.63 M ton of edible oil at a cost of $2.50 billion compared with the local edible oil production of 0.57 M ton in Pakistan (Govt. of Pakistan 2015).

Climate change has been shown to be a severe menace to the agricultural production systems of developing countries, as has been illustrated in many recent global climate change studies (IPCC 2014). The global mean surface temperature has increased by 0.8°C since the industrial revolution; the warmest decade on record was the 2001–2010 and the warmest year so far has been 2014 (IPCC 2014). This thermal trend has been observed during three decades beginning in the 1980s and predominantly in the 2000s in Punjab, Pakistan (Wang, Davies, Huang, & Gillies, 2011). The mean surface temperature has shown a slow annual increase that has impacted the socio-economic sector of Pakistan (Akram & Hamid, 2015). The observed mean temperature in Punjab, Pakistan, has increased by 0.78–1.5°C for the past three decades and is expected to increase from 2 to 4°C by the end of 21 century, which could have a significant impact on agricultural production (Ahmad et al., 2015; Mueller, Gray, & Kosec, 2014; Rasul, Mahmood, Sadiq, & Khan, 2012).

Phenology of all crops is impacted by weather and agronomic management practices, including sowing date and cultivar selection (Ahmad et al., 2016; Craufurd & Wheeler, 2009; Qaderi, Basraon, Chinnappa, & Reid, 2010; Qaderi, Kurepin, & Reid, 2006; Slauenwhite & Qaderi, 2013). Consistent changes in sowing date and introduction of new cultivars have made it difficult to assess the long-term response of crop phenology to warming trends (Ahmad et al., 2017; Chmielewski, Muller, & Bruns, 2004; Estrella, Sparks, & Menzel, 2007). Crop growth and development rates are accelerated with an increase in temperature for most environments (Ahmad et al., 2016; Faraji, Latifi, Soltani, & Rad, 2009). This increase in temperature has a direct effect on the duration of the phenological phases and ultimately impacts seed yield (Sommer et al., 2013; Tao et al., 2014; Xiao & Tao, 2014). Therefore, it is necessary to understand the phenological responses of a crop due to changes in local temperature in order to be able to develop better adaptation strategies, such as improved agronomic management practices and improved cultivars that can alleviate the potential negative impact of climate change (Ahmad et al., 2016; Anwar et al., 2015; Ismaili, Salavati, & Mohammadi, 2014). Advancement of the phenological stages and a decrease in the duration of the phenological phases of crop cycles may occur due to an increase in temperature. These effects could be reduced by adopting later sowing dates and introducing new cultivars with a longer thermal time requirement (Li et al., 2016; Rezaei, Siebert, & Ewert, 2015). The correlation between environmental changes, agronomical management practices and shifting of cultivars cannot be explained by statistical models because of the complex interaction between genetics, environment and management. However, the use of process-based crop growth models such as APSIM (Keating et al., 2003) and DSSAT (Jones et al., 2003) can explain some of these complex interactions (Boote, Jones, Hoogenboom, & White, 2010; Zhao, Bryan, & Song, 2014) by allowing researchers to examine either the impacts of a single factor at a time or the interactions among multiple factors (White, Hoogenboom, & Hunt, 2005; Liu, Wang, Yang, & Wang, 2010; Liu et al. 2012, Wang, Wang, Feng, Yin, & Yu, 2013).

The objectives of this study were as follows: (i) to examine the observed trends of phenological stages and phases of canola between 1980 and 2014 in central and southern Punjab, Pakistan; (ii) to correlate the observed phenological stages and phases with temperature trends for the same period; and (iii) to understand the interacting effects of thermal trends and agronomic management practices on the phenology of canola crop.

2 | MATERIALS AND METHODS

2.1 | The study area, weather and canola phenological data

Canola is the third most important oilseed crop in Punjab, Pakistan, after cotton and sunflower. The locations were selected for this

TABLE 1 Canola cultivars grown at the different locations (coordinates and elevation) of Punjab, Pakistan

Locations	Coordinates and elevation	Cultivars
Sialkot	32.49°N; 74.53°E and 256 m	Westar[a], Dunkeld, Tarnab-III
Gujranwala	31.42°N; 73.08°E and 226 m	Shiralee, Rainbow[a], Sultan canola
Hafizabad	32.07°N; 73.69°E and 207 m	CON-I, Oscar, Pakola[a]
Sheikhupura	31.72°N; 73.98°E and 236 m	Pakola, 19-H, Punjab sarsoon[a]
Nankana Sahib	31.45°N; 73.70°E and 187 m	Canola raya, Hyola-420[a], Rainbow
Multan	30.19°N; 71.47°E and 122 m	Faisal Canola[a], Hyola-308
Lodhran	29.54°N; 71.63°E and 112 m	CON-II, Hyola-401[a]
Bahawalpur	29.39°N; 71.68°E and 461 m	CON-III, Pioneer-45J21[a]
Bahawalnagar	29.99°N; 73.25°E and 163 m	PARC Canola[a], Tarnab-I
Rahim Yar Khan	28.42°N; 70.29°E and 081 m	Hyola[a], Tarnab-II

[a]Cultivars calibrated for respective location.

research representing approximately 50% of the total production of canola in Punjab. Thirty-five years of observed weather data from 1980 to 2014 were obtained from the Pakistan Metrological Department (PMD). Phenological stages of canola were recorded by the Extension wing of the Department of Agriculture, Government of Punjab, Pakistan, at the district level for the 10 selected locations from 1980 to 2014. The phenological stages that were recorded for canola included sowing dates and the dates for emergence, anthesis and physiological maturity. Using the phenological stages, three phenological phases were computed, including sowing to anthesis (S–A), sowing to physiological maturity (S–M) and anthesis to physiological maturity (A–M). The canola cultivars grown at the ten selected locations are presented in Table 1. The agronomic management practices for canola production were obtained from the local farmers. The local farming community determines crop management practices, and approximately every 6–8 years, the canola growers change to a new canola cultivar with different growing degree day requirements for the key phenological phases. The change in cultivars was due to an increase in the photo-thermal time required to maintain the same actual number of days for the growing season. The average daily temperature during S–A, A–M and S–M was measured for the observed sowing date to the anthesis date, from the anthesis date to the maturity date and from the sowing date to physiological maturity date, respectively, for each year.

2.2 | Analysis of observed data

A linear regression analysis was conducted to correlate the trends in observed phenological stages and phases of canola with the average temperature (Ahmad et al., 2016; He et al., 2015). Using the observed longest phenological stage for each location, time windows were determined for calculating the warming trends. For instance, the time window for the canola growing season, that is S–M, was calculated by determining the duration from the earliest sowing date to the latest physiological maturity for the period of study for each location. Using this procedure, the calculated warming trend was not dependent on the variability in the phenological stages and phases.

The researchers used a linear regression model (Equation 1) to analyse the canola crop phenological phases with average monthly temperature during the respective month of occurrence of phases to determine the effect of temperature on the phenological phases.

$$\mathrm{OP}_{\mathrm{nt}} = a_{\mathrm{nt}} T_{\mathrm{nt}} + b_{\mathrm{nt}} + \varepsilon_{\mathrm{nt}}. \quad (1)$$

2.3 | Phenology simulation with the CSM-CROPGRO-Canola model

The Decision Support System for Agro-technology Transfer (DSSAT) is a modular framework of crop growth modelling that was originally developed by the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) Project (Hoogenboom et al., 2015; Uehara & Tsuji, 1998). In DSSAT, the CSM-CROPGRO-Canola model predicts phenological stages on the basis of photo-thermal time and one photo-thermal day is one real day under optimum growing conditions. Phenological phases were derived on the basis of predicted phenological stages. Photoperiod sensitivity affects the crop phenology prior to anthesis. Total accumulated thermal time (ATT) for S–A and A–M phases is determined by the following equation:

$$\mathrm{ATT} = \sum_{i=1}^{n} \mathrm{DTT}. \quad (2)$$

A detailed description of DSSAT CROPGRO-model is available in earlier publications (Boote, Sau, Hoogenboom, & Jones, 2008; Boote et al., 2010; Hoogenboom et al., 2015; Jing et al., 2016; Jones et al.,

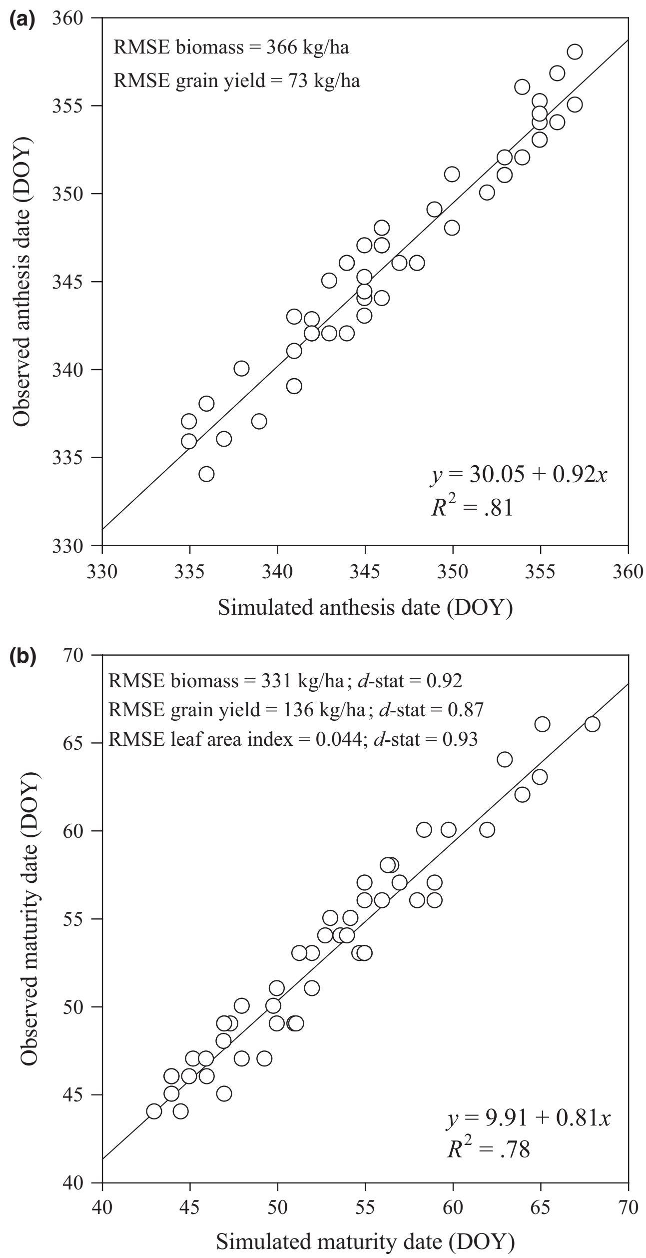

FIGURE 1 Comparison of simulated and observed anthesis dates (a) and maturity dates (b) for canola during 1983–1985 at 10 locations in Punjab, Pakistan

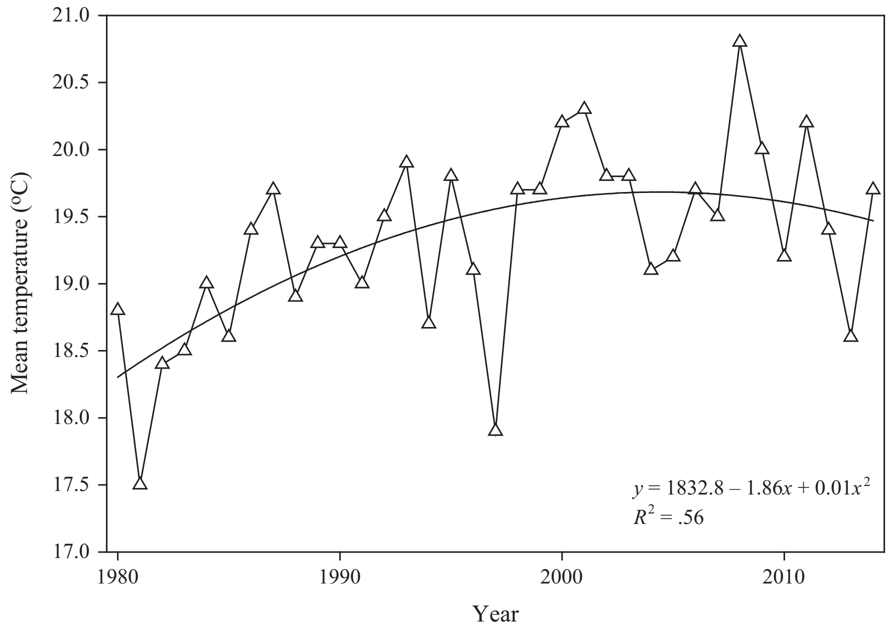

FIGURE 2 Mean temperature trend from 1980 to 2014 for Punjab, Pakistan

2003). The CSM-CROPGRO-Canola model of DSSAT Version 4.6.1 was used to determine the impact of agronomic management practices, cultivar and temperature on the phenology of canola crop (Hoogenboom et al., 2015). For each individual year from 1980 to 2014 and for each individual location the anthesis, physiological maturity dates and S–M phases were predicted. For each location, the predominant cultivar grown in that location was calibrated for 1980, 1981 and 1982 resulting in 10 different calibrated cultivars. The observed data for 1983, 1984 and 1985 were used for model evaluation. The CSM-CROPGRO-Canola model was then used to predict the phenological stages from 1980 to 2014 using the same cultivar and agronomic management practices for each individual year. The impact of temperature on the model predicted crop phenological stages and derived phases, including S–A, A–M and S–M, was computed using the following linear regression equation:

$$SP_{nt} = C_{nt}T_{nt} + d_{nt} + \varepsilon_{nt}. \tag{3}$$

A comparison between the predicted and observed anthesis and physiological maturity dates for 1983–1985 for the ten locations is shown in Figure 1a,b. The difference between the simulated and observed anthesis and physiological maturity dates was 1 and 0 days, respectively. The simulated LAI ranged from 2.23 to 2.49, compared to observed values ranging from 2.18 to 2.47. There was little variation between simulated (13,285 kg ha^{-1}) and observed (12,919 kg ha^{-1}) above-ground biomass. Finally, the model simulated (2804 kg ha^{-1}) and observed (2731 kg ha^{-1}) canola grain yield showed a little variation. The root-mean-square error (RMSE) was 366, 73 kg ha^{-1} and 0.03 for biomass, grain yield and LAI, respectively. Overall, the CSM-CROPGRO-Canola model performed well for these locations as indicated by a slope of 0.92, and R^2 of .81, and $p < .01$ for anthesis and slope of 0.81, and R^2 of .78, and $p < .01$ for physiological maturity.

3 | RESULTS

3.1 | Temperature trend

From 1980 through 2014, there was a slight increase in temperature at all 10 locations (Figure 2). The historical temperature trends for S–A, S–M and A–M were between 0.74–1.05, 0.73–1.02 and 0.88–1.05°**C** per decade, respectively (Figure 3a–c). The average for all 10 locations was 0.91°C per decade for S–A, 0.86°C per decade for S–M and 0.99°C per decade for all ten locations in Punjab.

3.2 | The impact of temperature on observed phenological stages

Canola is planted at the end of September through the end of October in the study areas of Punjab, Pakistan (Table 2). The spatial trends of canola sowing dates are shown in Figure 4. Sowing was delayed each year during the period from 1980 to 2014 at all the locations (Figure 5). The recorded sowing dates of canola showed a delay of 4.8–7.6 days per decade and with an average delay of 6.0 days per decade. This delay was statistically significant ($p < .05$) for nine locations. A delay in emergence dates was observed for all ten locations, with ranges of 2.3–4.4 days per decade. An average delay in emergence date of 3.14 days per decade was observed. The delay in emergence date was significant ($p < .05$) at eight locations.

Anthesis of canola in the study areas generally occurs from the end of November to the end of December. The anthesis dates were delayed by 2.1–4.5 days per decade for all locations with an average change of 3.31 days per decade. The delay in anthesis dates was significant ($p < .05$) at seven locations. Physiologically, maturity dates of canola were also delayed at all locations, ranging from 1.1 to 3.2 days per decade. On an average, physiological maturity dates

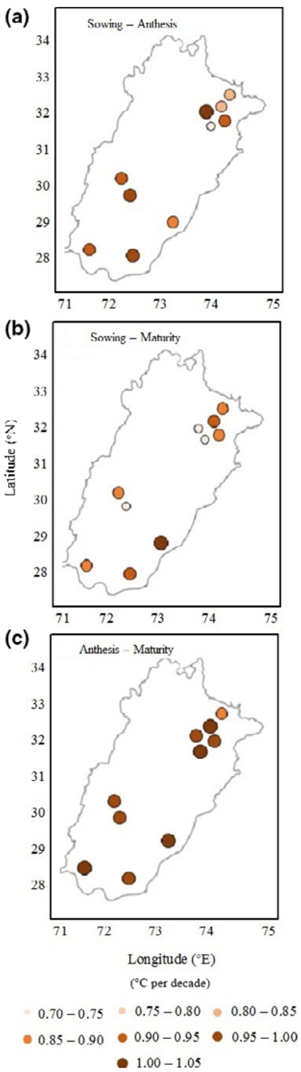

FIGURE 3 Observed trend in mean temperature (°C per decade) during phenological phases (a) Sowing to Anthesis, (b) Sowing to Maturity, (c) Anthesis to Maturity of canola in Punjab, Pakistan, during 1980–2014. [Colour figure can be viewed at wileyonlinelibrary.com]

were delayed by 1.89 days per decade. This delay in physiological maturity dates was significant ($p < .05$) at eight locations.

3.3 | The impact of temperature on observed phenological phases

The period from sowing to physiological maturity decreased by 3.5–5.2 days per decade (Figure 6a) due to more of delay in sowing and less delay in physiological maturity, with an average decrease of 4.13 days per decade. The shortening of the total growing season (S–M) was statistically significant ($p < .05$) for eight locations. S–A phase was reduced by 2.2–3.6 days per decade at all locations (Figure 6b), which was statistically significant ($p < .05$) for seven locations. On average, the decrease of the S–A phase was 2.71 days per decade. The A–M phase (Figure 6c) was reduced by an average of 1.42 days per decade, and this reduction was statistically significant ($p < .05$) for all ten locations.

3.4 | Spatial and temporal variability of the thermal characteristics of local canola cultivars

The photo-thermal time requirement of the cultivars for the S–A phase increased at all ten locations, ranging from 65 to 88°C d per decade, and it was statistically significant ($p < .05$) for five locations (Figure 7). Similarly, the photo-thermal time requirement for A–M also increased ranging from 60 to 74°C d per decade, with an average of 67°C d per decade and was statistically significant ($p < .05$) for five locations.

3.5 | Correlation of model predicted phenology to temperature

A negative relationship was found between three phenological phases simulated with the CSM-CROPGRO-Canola model and temperature (Table 3 and Figure 8). The S–A phase was shortened ranging from 1.31 to 2.94 days, with an average of 1.82 days °C^{-1}. This reduction

TABLE 2 Average observed phenology of canola in Punjab, Pakistan, during the period of 1980–2014

Locations	S (DOY)	E (DOY)	A[a] (DOY)	M[b] (DOY)	S–A (days)	A–M (days)	S–M (days)
Sialkot	282 ± 6.0	286 ± 5.5	338 ± 8.4	84 ± 8.1	56 ± 8.6	111 ± 6.4	161 ± 6.3
Gujranwala	280 ± 6.6	284 ± 6.2	336 ± 7.6	80 ± 6.7	54 ± 7.3	112 ± 4.7	165 ± 5.5
Hafizabad	284 ± 5.7	288 ± 5.1	338 ± 5.7	85 ± 7.0	55 ± 5.7	111 ± 4.8	163 ± 5.2
Sheikhupura	286 ± 6.2	290 ± 6.0	340 ± 8.6	87 ± 7.5	54 ± 8.1	101 ± 5.5	156 ± 7.5
Nankana Sahib	287 ± 6.9	291 ± 6.4	351 ± 7.3	84 ± 8.3	64 ± 7.2	98 ± 4.9	162 ± 5.8
Multan	289 ± 6.4	293 ± 6.1	342 ± 9.0	83 ± 8.8	54 ± 5.7	105 ± 2.9	159 ± 6.1
Lodhran	271 ± 5.6	275 ± 5.3	344 ± 8.2	88 ± 9.4	65 ± 9.8	86 ± 6.0	152 ± 7.3
Bahawalpur	294 ± 6.9	298 ± 6.6	343 ± 10.2	80 ± 9.1	66 ± 10.2	85 ± 4.9	151 ± 9.6
Bahawalnagar	284 ± 6.7	288 ± 5.2	339 ± 11.5	86 ± 13.2	60 ± 8.9	89 ± 6.2	150 ± 8.4
Rahim Yar khan	276 ± 6.1	280 ± 5.8	354 ± 7.6	92 ± 13.8	76 ± 13.7	84 ± 12.1	161 ± 5.4

DOY, day of year; S, sowing; E, emergence; A, anthesis; M, maturity.
[a]50% Anthesis.
[b]Physiological maturity.

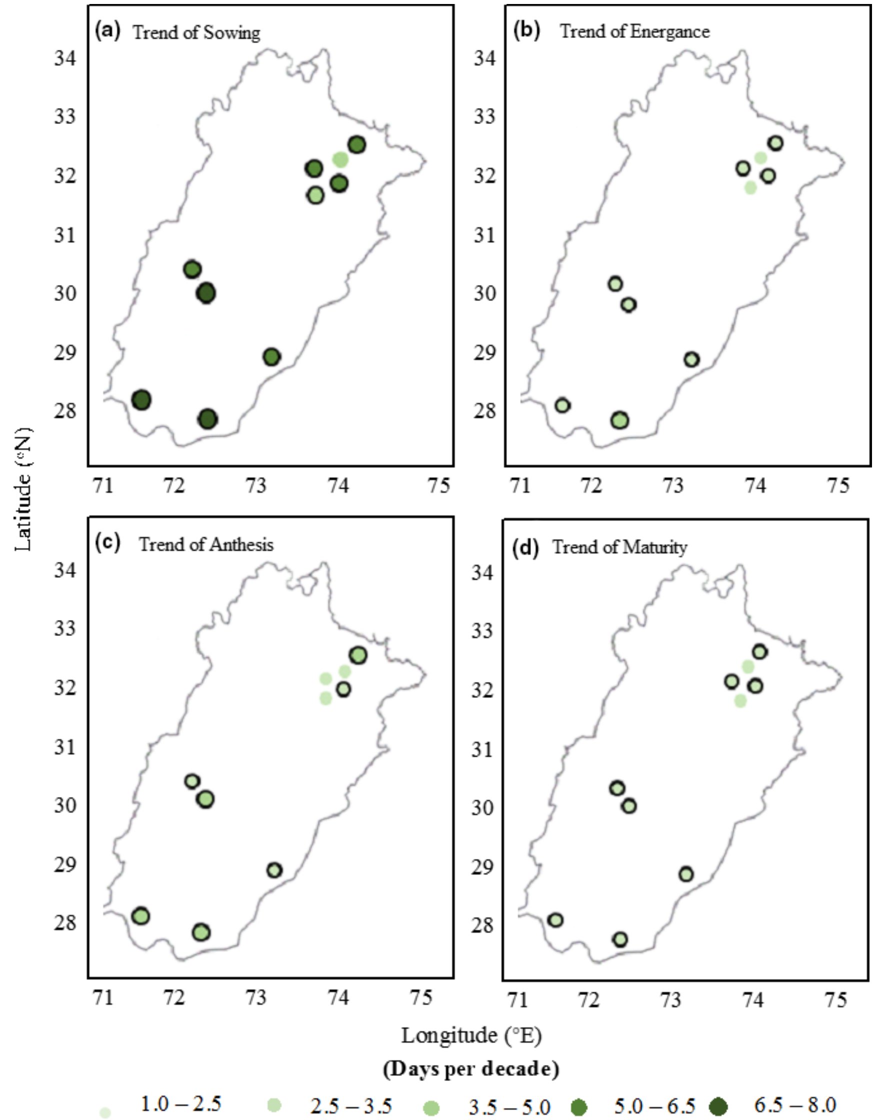

FIGURE 4 Observed trends in phenological stages (days per decade), (a) trend of sowing, (b) trend of emergence, (c) trend of anthesis, and (d) trend of maturity for canola in Punjab, Pakistan, during 1980–2014. [Colour figure can be viewed at wileyonlinelibrary.com]

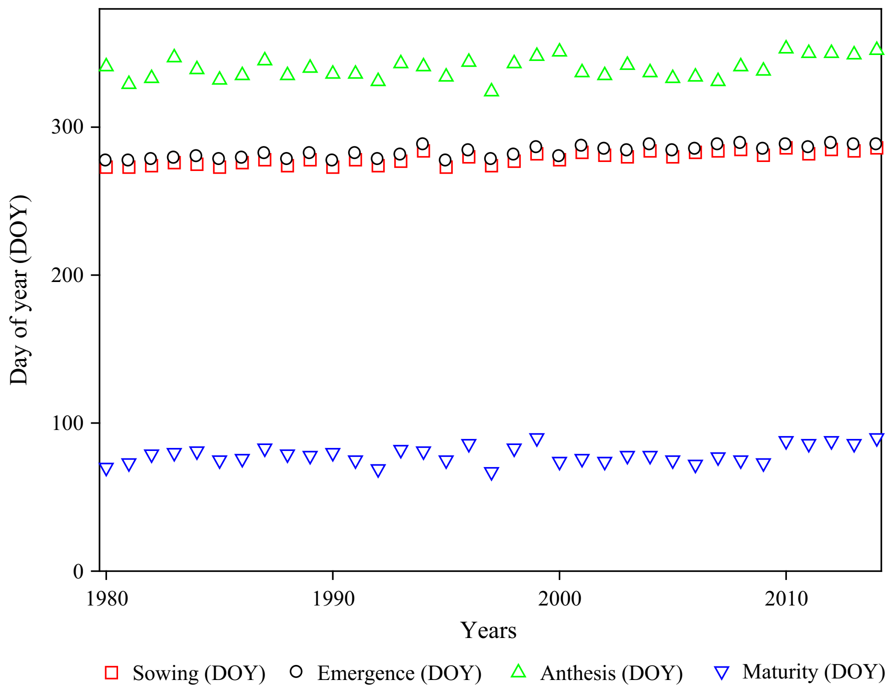

FIGURE 5 Farmers' annual sowing, emergence, anthesis and maturity dates for canola in Punjab, Pakistan. [Colour figure can be viewed at wileyonlinelibrary.com]

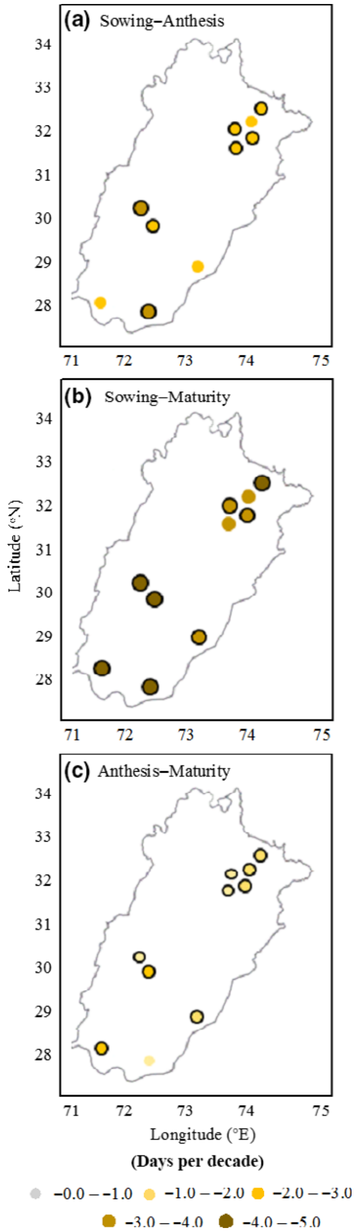

FIGURE 6 Observed trends in phenology phases (days per decade), (a) sowing-anthesis, (b) sowing-maturity, and (c) anthesis-maturity of canola in Punjab, Pakistan, during 1980–2014. [Colour figure can be viewed at wileyonlinelibrary.com]

was found to be statistically significant ($p < .05$) for nine locations. The reduction for the simulated A–M phase ranged from 0.52 to 2.0 days °C^{-1} with an average of 1.20 days °C^{-1}; it was significant ($p < .05$) for all 10 locations. The S–M phase was reduced by an average of 2.45 days °C^{-1} with values ranging from 1.96 to 3.31 days °C^{-1}. These values were significant ($p < .05$) at all 10 locations.

3.6 | Simulated and observed canola phenology

The sensitivity to the warmer temperatures was higher for the simulated phenological phases as compared to the observed phenological phases (Table 4 and Figure 8). The difference between model simulation and observed data for phenological phases was 0.60, 0.59 and 0.56 days °C^{-1} for S–A, S–M and A–M, respectively, which were all significant ($p < .01$). The difference between the simulated and observed changes in phenological phases with an increase in temperature indicated that a number of new cultivars that were sown during the last decades had an increase in photo-thermal time to reach the key phenological stages.

4 | DISCUSSION

Temperature had an immense impact on phenology of crops in many regions. The observed changes in canola phenology in Punjab, Pakistan, between 1980 and 2014 were likely caused by increase in temperature. However, other agricultural management decisions included were the variability in sowing dates and the selection of new cultivars (Estrella et al., 2007) that had a larger thermal time (growing degree days) requirement. The new cultivars and sowing dates are normally determined by the local farmers, whose choices regarding cultivars and sowing dates are adaptation strategies in response to climate warming trends in Punjab, Pakistan (Ahmad et al., 2017). However, rainfall and residual soil moisture during sowing months could also influence the sowing date decisions in this area as well. The delayed emergence, anthesis and maturity dates were due to the delayed sowing, but certain phenology trends were due to differences in observed temperature trends (He et al., 2015; Hu, Weiss, Feng, & Baenziger, 2005). A similar trend of delayed sowing of winter wheat because of climate warming has been reported in the North China Plain (Xiao et al., 2013).

Breeders constantly develop new cultivars through various breeding methods that are introduced to the local farmers following extensive evaluation (Noreen et al., 2016). Often, these new cultivars are adapted for local conditions, including observed warming trends. Scientists also have reported new phenological characteristics in improved canola cultivars (Ahmad et al., 2017; Iljkic, Kovacevic, & Varga, 2014; Liu et al., 2010; Martín, Olesen, & Porter, 2014; Noreen et al., 2016). In this study, the researchers separated the impact of the introduction of new cultivars for the 10 selected locations from the observed changes through simulating the phenology of canola using the same cultivar for the duration of the study period. This simulation allowed for the separation of the interaction of temperature and improved cultivar response. The temperature sensitivity of the simulations was higher as compared to the observed phenological data, indicating that about 28.53% (Table 4) of the direct negative impact of the warming trend was mitigated with the introduction of new canola cultivars that required more photo-thermal time to reach the different phenological stages. A similar trend of introducing new cultivars that are adapted to a warming trend was found for other crops across the globe, including winter wheat for the Loess Plateau region of China (He et al., 2015; Liu et al., 2010), maize in the U.S.A. (Sacks & Kucharik, 2011), rice in China

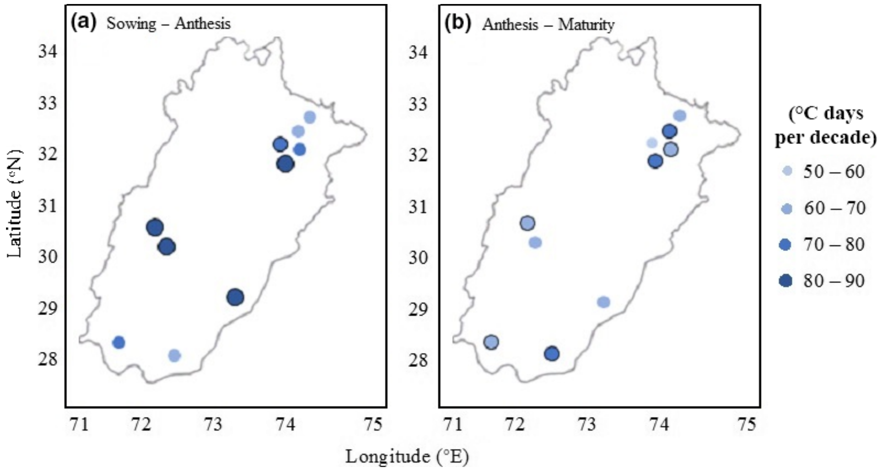

FIGURE 7 Observed trend in thermal time (°C day per decade) requires of canola cultivars (a) sowing-anthesis, and (b) anthesis-maturity in Punjab, Pakistan, during 1980–2014. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 3 Summary of the observed and simulated phenological responses to the increase in temperature for canola in Punjab, Pakistan, for 1980–2014

Phenology	No. neg.[a]	No. pos.[b]	No. sig. neg.[c]	No. sig. pos.[d]	Reg. mean[e] (days $°C^{-1}$)
Observed stages					
Sowing	0	10	0	9	2.71
Emergence	10	0	0	8	1.41
Anthesis	10	0	0	7	1.49
Maturity	10	0	0	8	0.85
Observed phases					
Sowing–Anthesis	10	0	7	0	−1.22
Sowing–Maturity	10	0	8	0	−1.86
Anthesis–Maturity	10	0	9	0	−0.64
Simulated phases					
Sowing–Anthesis	10	0	9	0	−1.82
Sowing–Maturity	10	0	10	0	−2.45
Anthesis–Maturity	10	0	10	0	−1.20

[a]Number of locations with negative regression coefficients.
[b]Number of locations with positive regression coefficients.
[c]Number of locations with significant negative regression coefficients.
[d]Number of locations with significant positive regression coefficients.
[e]Mean of regression coefficients.

(Tao et al., 2013) and sugarcane in Punjab, Pakistan (Ahmad et al., 2016). If the total period of growth and development of crop cultivars is short, then consequently, there is a reduction of crop production because of the shorter time for total dry matter accumulation during the vegetative phase, particularly for high input crops (Rezaei et al., 2015; Zhang & Huang, 2013). Thus, the farming community selects new cultivars that either have a higher thermal time requirement to compensate for the negative impact of the warming trend on crop duration or more efficient in utilizing the available resources with fast growth and short life cycle.

Crop growth and development are affected by temperature, which has a direct influence on the duration of the phenological phases and thus affect the final economic yield. Total dry matter accumulation is reduced with earlier anthesis and physiological maturity due to a warming trend, consequently reducing crop yield (Gan et al., 2004; Xiao & Tao, 2014). In several regions, of the world, production of various crops has been enhanced due to longer grain filling phase (A-M) caused by earlier anthesis and delayed physiological maturity (Ahmad et al., 2016; He et al., 2015; Tao, Yokozawa, Xu, Hayashi, & Zhang, 2006; Xiao et al., 2013).

It is predicted that the temperature will gradually increase in future (IPCC 2014). At the end of the present century, the average temperature is predicted to increase by 2–4°C in Punjab, Pakistan (Ahmad et al., 2015). Furthermore, severe events such as floods and droughts are predicted to be more frequent, also potentially impacting agricultural production (Rasul et al., 2012). The phenological crop phases may potentially decrease during the coming decades if the warming trend continues (Gouache et al., 2012), while at the same time in semi-arid areas with high temperatures, there is also

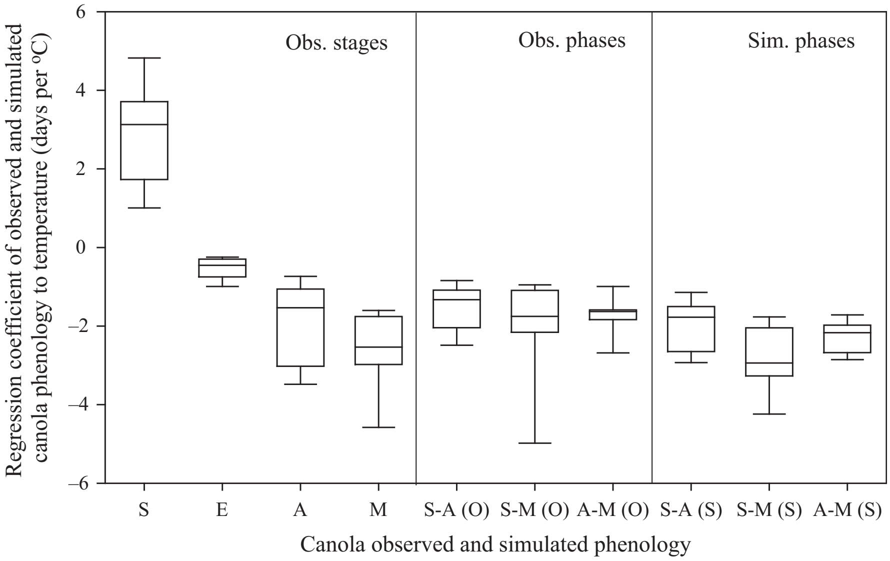

FIGURE 8 Observed phenology (stages and phases) and simulated phenology (phases) versus temperature trends using a standard canola cultivar at each location in Punjab, Pakistan, from 1980 to 2014. (S: sowing; E: emergence; A: anthesis; M: maturity; S–A: sowing–anthesis; S–M: sowing–maturity; A–M: anthesis–maturity). Horizontal line: median; box: 25th and 75th percentiles; whiskers: minimum and maximum values

TABLE 4 Comparison of the responses of canola phenology with average temperature using the observed and simulated data in Punjab, Pakistan, during 1980–2014

Phenology	Regression coefficient (days °C^{-1}) Obs. data	Regression coefficient (days °C^{-1}) Sim. data	Difference between obs. and sim. data (days °C^{-1})	t test (*p*-value)
Sowing–Anthesis	−1.22	−1.82	0.60	0.0014**
Sowing–Maturity	−1.86	−2.45	0.59	0.0017**
Anthesis–Maturity	−0.64	−1.20	0.56	0.0021**

Obs., observed; Sim., simulated.
**Significant at the 0.01 probability level.

potential for crop durations to increase if the temperatures are above the cardinal temperatures (Ainsworth & Ort, 2010; White et al., 2005). Thus, introduction and growing of new cultivars with higher total thermal time (growing degree days) requirement, temperature tolerance and sowing dates adjustments are vital to mitigate the negative impact of climate change in Punjab, Pakistan, and other regions across the world.

5 | CONCLUSION

Increasing thermal trends for the duration of 1980–2014 changed the observed phenology and delayed stages (S, E, A, and M; 6.02, 3.14, 3.31 and 1.89 days per decade, respectively) and decreased phases (S–A, S–M, and A–M; 2.71, 4.13 and 1.42 days per decade, respectively) of the canola crop in Punjab, Pakistan. The stages (S, E, A and M dates) were positively correlated and phases (S–A, S–M and A–M) were negatively correlated with an increase in temperature. The negative effect of this thermal trend on phenology of canola was partially (28.53%) compensated by growing new cultivars with higher photo-thermal time requirements and by adjusting sowing dates. Therefore, new canola cultivars should be bred to have higher photo-thermal time requirement and high temperature tolerance.

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