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Quantification of the effects of climate warming and crop management on sugarcane phenology

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ABSTRACT: Crop phenology influences the partitioning of assimilates, crop yield and agronomic management under a changing climate. It is critical to quantify the interaction between climate warming and crop management on sugarcane phenology to understand the adaptation of crop to climate change. Similarly, in crop modeling, parameterizing the phenology of new crop varieties is a major challenge. Historical changes between 1980 and 2014 in spring and autumn sugarcane phenology have been observed in Punjab, Pakistan. Planting, emergence, stalk elongation, peak population and harvest dates advanced by a mean of 2.87, 2.63, 4.47, 5.01 and 6.41 d decade^{-1}, respectively for spring sugarcane, and were delayed by 6.59, 6.21, 4.38, 3.13 and 2.17 d decade^{-1}, respectively for autumn sugarcane. Similarly, planting to stalk elongation, stalk elongation to peak population and peak population to harvesting and planting to harvesting phases were shortened by a mean of 1.60, 0.54, 1.40 and 3.54 d decade^{-1}, respectively for spring sugarcane and 2.21, 1.25, 0.96 and 4.42 d decade^{-1}, respectively for autumn sugarcane. The changes in phenological characteristics of spring and autumn sugarcane were significantly correlated with rising temperature for the period 1980–2014. Application of the CSM-CANEGRO-sugarcane model to simulate sugarcane phenology for a single cultivar at each site across years revealed that simulated phenological characteristics of sugarcane were accelerated with climate warming. We conclude that, during 1980 to 2014, advancement of planting date for spring sugarcane and delay in planting autumn sugarcane, together with adoption by farmers of new cultivars with higher total growing degree-day requirements, have partially mitigated the negative influence of climate-change induced thermal trends on phenological characteristics of spring and autumn sugarcane.

KEY WORDS: Sugarcane phenology · Climate change · Thermal trend · Cultivar shift · Punjab · CSM-CANEGRO-Sugarcane model

1. INTRODUCTION

Punjab is the most populated (99.93 million) province of Pakistan, with almost 59% of the total population. Punjab has the second largest area (205 345 km^2) among provinces in Pakistan after Baluchistan (GOP 2015). The dominant climate of central and southern Punjab is tropical semiarid (mean temperature 16.2 to 25.6 °C and rainfall 250 to 750 mm) and subtropical arid (mean temperature 19.4 to 28.6°C and rainfall 50 to 300 mm), respectively. The monsoon season is mid-July to the end of September in central and southern Punjab (Ahmad et al. 2014).

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Sugarcane is a very important cash crop in Pakistan, where it is grown in both spring and autumn. Pakistan ranks fifth position in the world with respect to sugarcane sowing area and production (Nazir et al. 2013). The contribution of spring and autumn sugarcane to Pakistan's gross domestic product (GDP) is 3.1% and 0.6%, respectively. Total cane production is 62.65×10^6 t with a mean cane yield of 54 910 kg ha^{-1}, on 1.41×10^6 ha (GOP 2015).

There is now universal agreement among scientists that global warming will significantly impact agriculture in the current and upcoming decades, a trend confirmed by numerous climate change studies at local, regional, continental and global scales. The mean air temperature at the Earth's surface has increased by 0.78°C since the beginning of the industrial revolution. The warmest decade since records began was the 2000s and the hottest year was 2014 (IPCC 2014). The mean annual temperature rose during the previous 3 decades and especially in the 2000s in Punjab, Pakistan (S. Y. Wang et al. 2011). The mean surface air temperature is increasing continuously, which has a negative socioeconomic impact on Pakistan (Farooqi et al. 2005, Akram & Hamid 2015). The mean thermal trend in central and southern Punjab ranges from 0.72 to 1.2°C for the previous 3 decades and it could rise from 2 to 4 °C in the future, which would be dangerous for agriculture, especially for arid regions (Rasul et al. 2012, Mueller et al. 2014). In Australia, Park et al. (2012) predict that due to climate warming sugarcane yield losses will be up to 47%. However, in Brazil the impact of climate change on sugarcane yields will be positive due to the increase in CO_2 levels (Marin et al. 2013). In Pakistan, Siddiqui et al. (2012) concluded sugarcane yields would decrease by 13.56 and 40% in response to temperature rises of 1 and 2°C, respectively. Furthermore, Afghan & Ijaz (2015) indicated that sugarcane production will decline due to both the increase in temperature (by 10% for every 1°C rise) and the reduction of rainy days. Such conditions will increase evapotranspiration, reducing availability of soil water, increasing irrigation demands and making sugarcane cultivation logistically difficult in many places.

Growth and development of crops is driven by environmental conditions, particularly total thermal time, as well as by agronomic management practices such as adoption of new cultivars and shifting planting dates, etc. (Tubiello et al. 2002, Lashkari et al. 2012, He et al. 2015), These adaptation strategies can help minimize the negative effects of climate change on growth and development of sugarcane (Singels & Bezuidenhout 2002, Zhao & Li 2015). For example, introducing new cultivars with a longer thermal time requirement could have a positive influence on growth and development and ultimately increase crop productivity in spite of a greater accumulation of heat (Araya et al. 2015). Various research studies indicate that growth and developmental stages and phases of spring and autumn sugarcane are negatively affected by climate change (Marin et al. 2013). Changes in growth and developmental stages and phases of any crop are fundamental indicators of deviations in environmental conditions (Streck et al. 2008, Li et al. 2014). Sugarcane production is also affected in various regions due to warming (Gouvêa et al. 2009, Knox et al. 2010, Biggs et al. 2013, Chandiposha 2013, Carvalho et al. 2015, Everingham et al. 2015, Melgar & Queme 2015). Phenological processes of any crop respond to variations in climatic conditions and agronomic management practices, which include planting date and selection of cultivars, etc. (Deressa et al. 2005). Climate warming could accelerate the growth and developmental stages of any crop, and high thermal-time-requirement cultivars could cause the delay of phenological stages (Moradi et al. 2013, Chen & Liu 2014, He et al. 2015, Xiao et al. 2016). Correlations among cultivar shift, crop management practices and environmental variations could not be teased apart by statistical models. Therefore, crop growth models have been used to predict the relationships among shifting of cultivars, variations and changes in climatic conditions and agronomic management practices (Marin et al. 2011, Ahmed et al. 2016). Since the influence of one factor can be separated from other factors in crop growth models (L. Liu et al. 2012, Wang et al. 2013, Zhao et al. 2014, He et al. 2015), there is keen interest in using these models to study the potential application of various adaptive management practices to develop new strategies to minimize the negative influence of climate change on crop growth and development (Gouache et al. 2012, Zhang & Huang 2013).

The main purposes of this research were as follows: (1) to assess the spatiotemporal variability in sugarcane phenology with the help of long-term chronological observed data across Punjab, Pakistan for the period 1980–2014; (2) to determine the correlation among thermal trend, sugarcane phenology, crop management and cultivar shift; and (3) to see whether changes in crop management practices and the adoption of new cultivars can compensate for the negative influence of current thermal trends on sugarcane phenology in the future.

2. MATERIALS AND METHODS

2.1. Research area, weather data and spring and autumn sugarcane phenological data

Sugarcane is the major sugar crop grown in central and lower Punjab, Pakistan. Ten sites (each has 1 local weather station) were selected for this research, which considered data for the maximum number of years for which records were available for all sites, i.e. 35 yr, from 1980 to 2014 (Table 1). During this period, phenological data for spring and autumn sugarcane were collected at the 10 sites by Department of Agriculture (Extension Wing) of the Government of Punjab. Planting, emergence, stalk elongation (50% stalk elongation), peak population (50% peak population) and physiological maturity dates were recorded for spring and autumn sugarcane. From the observed phenological data, 4 phenological phases were calculated, namely planting to stalk elongation, stalk elongation to peak population, peak population to harvest and planting to physiological maturity. On average, 4 different cultivars were grown on each site and every 7 to 9 years farmers introduced new, recently developed cultivars with higher total thermal time requirements. Weather data (daily maximum and minimum temperature, rainfall and solar radiation) for the 10 locations were obtained from local weather observatories of Pakistan Meteorological Department (PMD), Islamabad for the period 1980–2014.

2.2. Analysis of observed data

Linear regression was used to determine the trends in observed phenological stages and phases of spring and autumn sugarcane in response to mean temperature. By examining maximum date ranges (earliest onset to latest conclusion) of the phenological stages at each location, time windows for measuring thermal trends were obtained. For example, the time window for the phenological phase planting to harvesting, was from the earliest planting date to the latest harvest over the study period at each site. With this procedure, the measured warming tendency was not dependent on the corresponding changes in phenology

Correlation of planting dates with the mean temperature during the month when planting occurred was calculated to assess whether planting dates were driven by temperature. For this, the following linear regression equation was used to determine the responses of spring and autumn sugarcane phenology to temperature:

$$OP_{nt} = a_t\ T_{nt} + b_{nt} \tag{1}$$

where OP_{nt} is the observed phenological phase (d) or phenological event (day of the year, DOY) for the nth station in year t, a_{nt} is slope , i.e. the coefficient of the corresponding phenology response to temperature (d °C^{-1}) for the nth station, T_{nt} is the mean daily temperature (°C) during the corresponding development stage for the nth station in year 't', and b_{nt} represents the intercept for each station (He et al. 2015).

2.3. Phenology simulation with CSM-CANEGRO-sugarcane model and calculation of total thermal time requirement

We applied the CSM-CANEGRO-sugarcane model to simulate sugarcane phenology, using a single cultivar for each site, the same management practices

Table 1. Study sites for investigation of the effects of climate warming and crop management on sugarcane phenology in Punjab, Pakistan, showing site number, site name (coordinates and elevation [m a.s.l.]) and sugarcane cultivars grown at each site during the study period, 1980–2014

Site No.	Site name	Cultivars
1	Sialkot (32.49° N; 74.53° E and 256 m)	CP-77-400, HSF-242, GS-1-7, SPF-213, PR-1000
2	Gujranwala (31.42° N; 73.08° E and 226 m)	CP-72-2086, CPF-243, S-2000, COL-54
3	Hafizabad (32.07° N; 73.69° E and 207 m)	PF-237, CP-82-1172, US-133, CO-1148
4	Sheikhupura (31.72° N; 73.9° E and 236 m)	HSF-240, CP-81-1254, US-162, COL-29
5	Nankana Sahib (31.45° N; 73.70° E and 187 m)	SPSG-26, CP-85-1491, SPF-244, BL-116
6	Multan (30.19° N; 71.47° E and 710 m)	SPF-245, S-96, HSF-240, BL-118
7	Lodhran (29.54° N; 71.63° E and 112 m)	COJ-84, SP-1215, HSF-242, CPF-238
8	Bahawalpur (29.39° N; 71.68° E and 461 m)	BL-4, S-98, CP-43-33, BF-164
9	Bahawalnagar (29.99° N; 73.25° E and 163 m)	BF-162, SP-108, CPF-237, Triton
10	Rahim Yar Khan (28.42° N; 70.29° E and 81 m)	SPF-234, SP-302, SPF-245, BL-19

across years, to simulate the stalk elongation, peak population and harvest dates from 1980 to 2014 across all 10 sites, in order to separate the effects of temperature, crop management, and cultivars on spring and autumn sugarcane phenology. Decision support system for agro-technology transfer (DSSAT, see http://dssat.net for a detailed description) is a modular framework for crop growth modeling which was originally developed with the help of the international scientific study organization, International Benchmark Sites Network for Agro-technology transfer (IBSNAT). We used DSSAT model version 4.6 6 to quantify the impact of climate warming on crop phenology and draw up climate change adaptation strategies.

The CSM-CANEGRO-sugarcane model requires the following minimum data sets for simulation or prediction growth and yield: (1) daily weather data for crop season or period, i.e. (T_{max}), minimum temperature (T_{min}), rainfall and sunshine hours/solar radiation, (2) soil profile data (physical and chemical), (3) crop management data and (4) cultivar genetic information or cultivar coefficients.

In the model, spring and autumn sugarcane phenology is indexed to the accumulation of thermal time (ATT), since sugarcane is sensitive to photoperiod. The total growing period in degree days (°D) for planting to stalk elongation and for stalk elongation to peak population is calculated as:

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

where DTT is daily thermal time and n is the duration (d) of the phenological stages. The CSM-CANEGRO-sugarcane model utilizes daily weather data (Hoogenboom et al. 2015) which include maximum and minimum temperature, rainfall and solar radiation. Daily maximum and minimum temperatures are used to determine DTT:

$$\text{DTT} = \frac{(T\,\text{max} + T\,\text{min})}{2} T_{\text{base}} \quad (3)$$

where, T_{base} is the base temperature, which is taken to be 10 °C (Singels et al. 2008).

Only the most common cultivar for the period 1980–1982 at each site was utilized for calibration of CSM-CANEGRO-Sugarcane model. Hence, for overall calibration of CSM-CANEGRO-Sugarcane model at 10 sites, 10 cultivars were utilized. After calibration, observed spring and autumn phenological data from 1983 to 1985 were used for validation of the model. The model was then utilized to simulate spring and autumn sugarcane phenology from 1980 to 2014 using the same variety and crop agronomic management practices each year. The impact of temperature on simulated phenological phases for spring and autumn sugarcane (planting to stalk elongation, stalk elongation to peak population, peak population to harvest and planting to harvesting) was assessed using linear regression analysis:

$$\text{SP}_{nt} = c_n\, T_{nt} + d_n \quad (4)$$

where SP_{nt} stands for simulated phenological length (d) for the n^{th} station in year t, c_{nt} is the coefficient of phenology responses to temperature (d °C^{-1}) for the n^{th} station, T_{nt} is the phenological phase mean temperature (°C) for the n^{th} station in year t, and d_{nt} is the intercept. For validation, a comparison of the simulated and observed phenological stages of stalk elongation and peak population dates in years 1983 to 1985 at 10 sites is illustrated in Fig. 1. The CSM-CANEGRO-sugarcane model performed well at all sites, with R^2 being >0.72 in all cases.

2.4. Observed and simulated response to temperature

In Eq. (1), a_{nt} is the regression coefficient representing the response of spring and autumn sugarcane phenological characteristics to changing cultivars, planting date and temperature. Whereas in Eq. (4) only the impact of temperature on simulated crop phenology is reflected in c_{nt}. If the difference between regression coefficients ($a_{nt} - c_{nt}$) is negative, then local farmers planted cultivars with short thermal time requirements in previous years. If '$a_{nt} - c_{nt}$' is positive, then the local farming community changed to higher total thermal time requirement cultivars for the previous years (1980–2014). A paired *t*-test was applied to determine whether the difference between regression coefficients was significant ($p < 0.01$).

3. RESULTS

3.1. Temperature trends in spring and autumn

A thermal trend was observed throughout both spring and autumn seasons. More warming was observed during autumn than in spring. The mean temperature rise during planting to stalk elongation ranged from 0.45 to 0.87 and 0.52 to 0.90°C decade^{-1} during spring and autumn, respectively, with a mean rise of 0.68 and 0.71°C decade^{-1} in spring and autumn, respectively (Fig. 2). Mean warming during stalk elongation to peak population ranged from 0.63

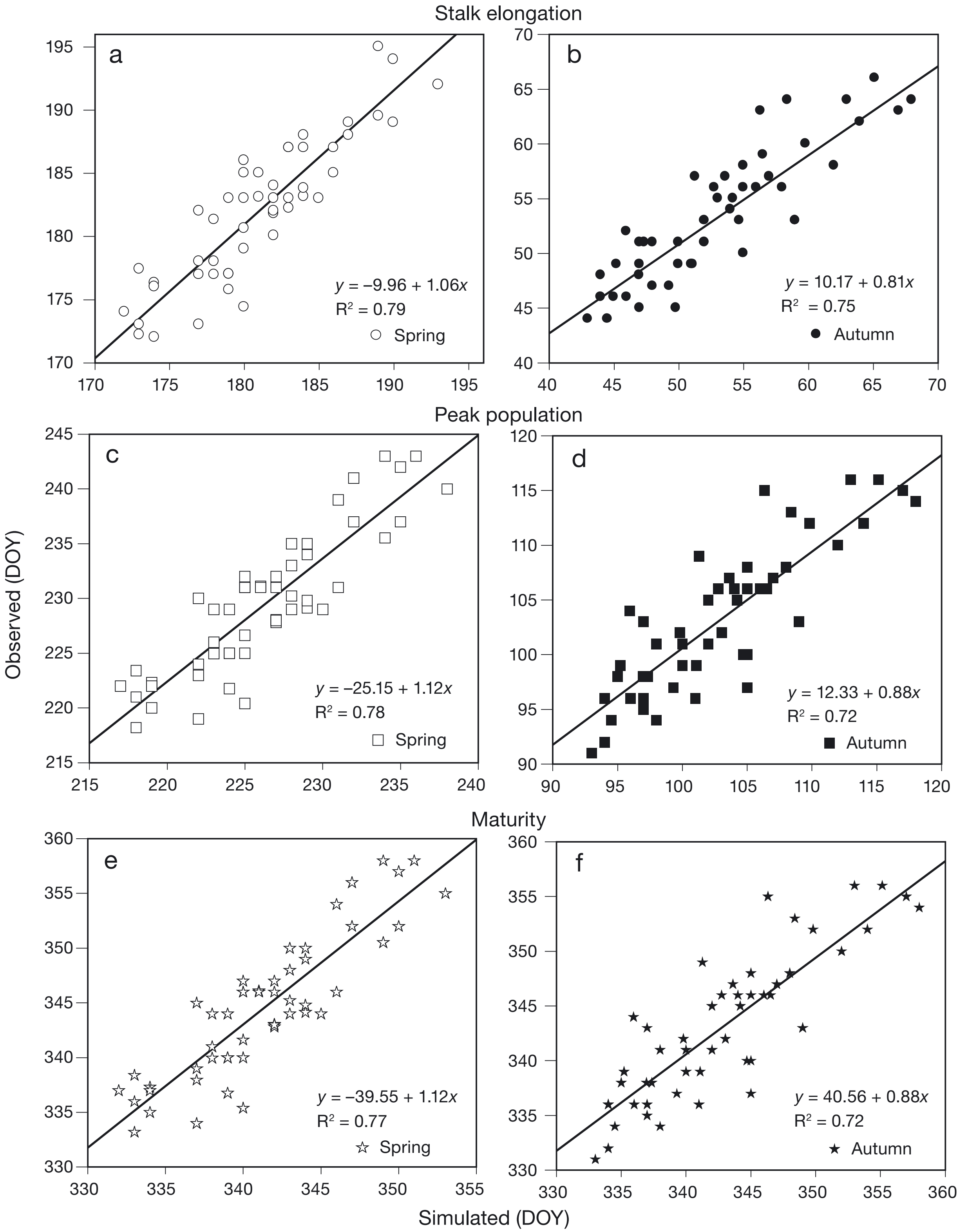

Fig. 1. Simulated and observed dates of onset of phenological stages for spring (left panels) and autumn (right panels) sugarcane in Punjab, Pakistan, during 1983–1985: (a,b) stalk elongation, (b,c) peak population and (d,e) maturity. DOY: day of the year

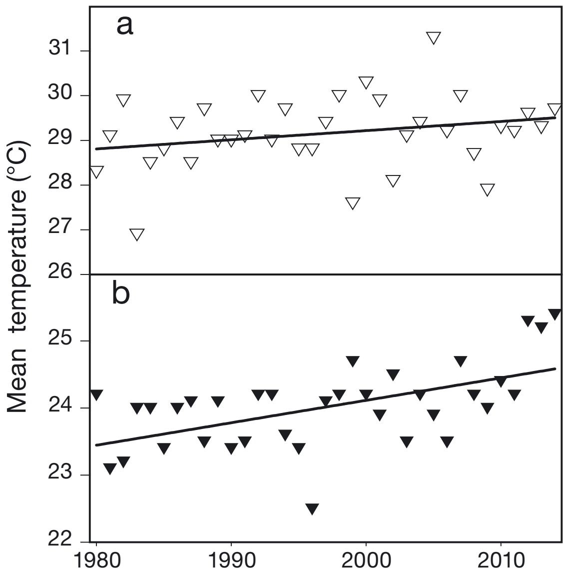

Fig. 2. Mean temperatures during the growing seasons of (a) spring and (b) autumn season planted sugarcane from 1980 to 2014, based on data from weather stations at 10 sites (Table 1) in Punjab, Pakistan

to 0.97 and 0.68 to 1.0°C decade^{-1}, with mean values of 0.78 and 0.82°C decade^{-1}, in spring and autumn, respectively. Mean temperature rises ranged from 0.54 to 0.86 and 0.58 to 0.90°C decade^{-1} and 0.66 and 0.73°C decade^{-1} during peak population to harvesting phase in spring and autumn, respectively (Fig. 3a,b). The mean temperature rise during planting to harvesting ranged from 0.69 to 1.0 and 0.78 to 1.0°C decade^{-1} in spring and autumn, respectively, with mean values of 0.82 and 0.86°C decade^{-1} in spring and autumn, respectively.

3.2. Phenological variation

Spring and autumn sugarcane is generally planted in Punjab from the first week of February to mid March and from the end of August to the end of September, respectively (Table 2, Fig. 4). Planting dates of spring sugarcane advanced by 1.4 to 4.2 d decade^{-1} (statistically significant at 8 sites), with a mean of 2.87 d decade^{-1}, while planting dates were de-

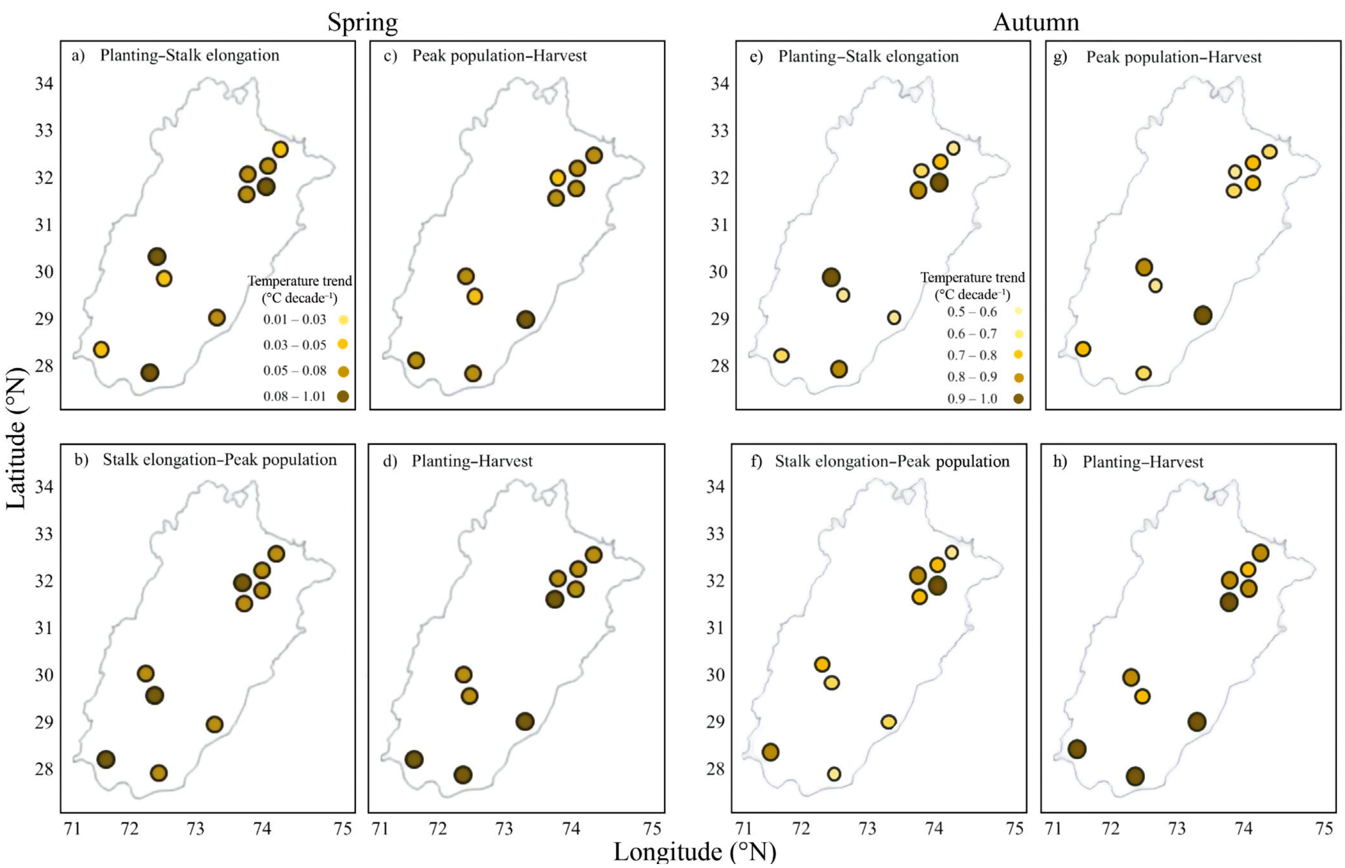

Fig. 3. Observed trends in mean temperature during the phenological phases (a,e) planting–stalk elongation, (b,f) stalk elongation–peak population, (c,g) peak population–harvest and (d,h) planting–harvest for spring (left panels) and autumn (right panels) planted sugarcane from 1980 to 2014 at 10 sites (Table 1) iin Punjab, Pakistan

Table 2. Mean (±SD) observed phenology of spring and autumn planted sugarcane in the period 1980–2014 in Punjab, Pakistan. Dates are shown as day of the year

Site name	Planting	Emergence	Stalk elongation[a]	Peak population	Harvesting
Spring sugarcane					
Sialkot	34 ± 4.6	45 ± 5.8	174 ± 5.1	227 ± 6.3	357 ± 7.5
Gujranwala	40 ± 5.3	54 ± 6.1	178 ± 7.3	225 ± 6.1	354 ± 6.8
Hafizabad	38 ± 5.1	46 ± 4.8	179 ± 6.1	229 ± 7.4	361 ± 7.2
Sheikhupura	44 ± 6.4	52 ± 5.6	183 ± 7.5	236 ± 5.8	349 ± 6.6
Nankana Sahib	36 ± 4.2	47 ± 4.0	170 ± 6.1	242 ± 8.3	358 ± 9.6
Multan	47 ± 5.5	58 ± 5.3	172 ± 6.8	227 ± 6.2	362 ± 8.4
Lodhran	54 ± 6.2	67 ± 5.7	188 ± 6.1	236 ± 7.6	351 ± 7.3
Bahawalpur	48 ± 5.4	61 ± 5.1	193 ± 6.6	230 ± 6.1	347 ± 8.2
Bahawalnagar	52 ± 6.1	63 ± 5.6	192 ± 7.8	238 ± 8.1	346 ± 9.6
Rahim Yar Khan	50 ± 5.2	62 ± 5.1	186 ± 6.9	243 ± 9.4	352 ± 10.3
Autumn sugarcane					
Sialkot	252 ± 4.5	261 ± 4.8	50 ± 6.4	94 ± 5.8	350 ± 8.3
Gujranwala	246 ± 5.3	258 ± 5.1	56 ± 6.1	101 ± 6.8	353 ± 7.2
Hafizabad	260 ± 6.2	271 ± 6.1	48 ± 7.3	98 ± 7.9	348 ± 8.8
Sheikhupura	255 ± 6.7	267 ± 7.3	41 ± 5.8	103 ± 7.2	351 ± 8.2
Nankana Sahib	262 ± 5.8	270 ± 6.4	63 ± 6.7	92 ± 8.3	340 ± 9.1
Multan	259 ± 6.2	268 ± 5.7	66 ± 7.2	104 ± 9.6	357 ± 10.3
Lodhran	266 ± 5.2	279 ± 6.1	59 ± 8.4	110 ± 9.3	344 ± 8.9
Bahawalpur	261 ± 7.1	275 ± 8.2	54 ± 9.3	98 ± 8.1	349 ± 10.5
Bahawalnagar	256 ± 6.6	267 ± 7.1	65 ± 8.2	97 ± 9.3	342 ± 9.2
Rahim Yar Khan	250 ± 5.8	263 ± 6.4	68 ± 8.8	102 ± 7.5	353 ± 6.2

[a]50 % Stalk elongation, peak population

layed for autumn sugarcane by 4.4 to 8.4 d decade^{-1} (statistically significant at 9 sites), with a mean of 6.59 d decade^{-1} (Fig. 4). The trends of emergence dates were similar to planting dates for both spring and autumn sugarcane, because emergence dates were directly related to planting dates (Fig. 5). Advancement of emergence dates ranged from 1.1 to 4.0 d decade^{-1} (statistically significant at 7 sites), with a mean of 2.63 d decade^{-1}, for spring sugarcane. Emergence dates of autumn sugarcane were delayed by 4.1 to 8.1 d decade^{-1} (statistically significant at 9 sites), with a mean of 6.21 d decade^{-1}. Stalk elongation of spring and autumn sugarcane generally occurred from mid-May to mid-June and from mid-February to mid-March, respectively. Stalk elongation dates advanced by 2.9 to 5.6 d decade^{-1} (statistically significant at 9 sites), with a mean of 4.47 d decade^{-1}, for spring sugarcane. Stalk elongation dates were delayed by 2.6 to 6.4 d

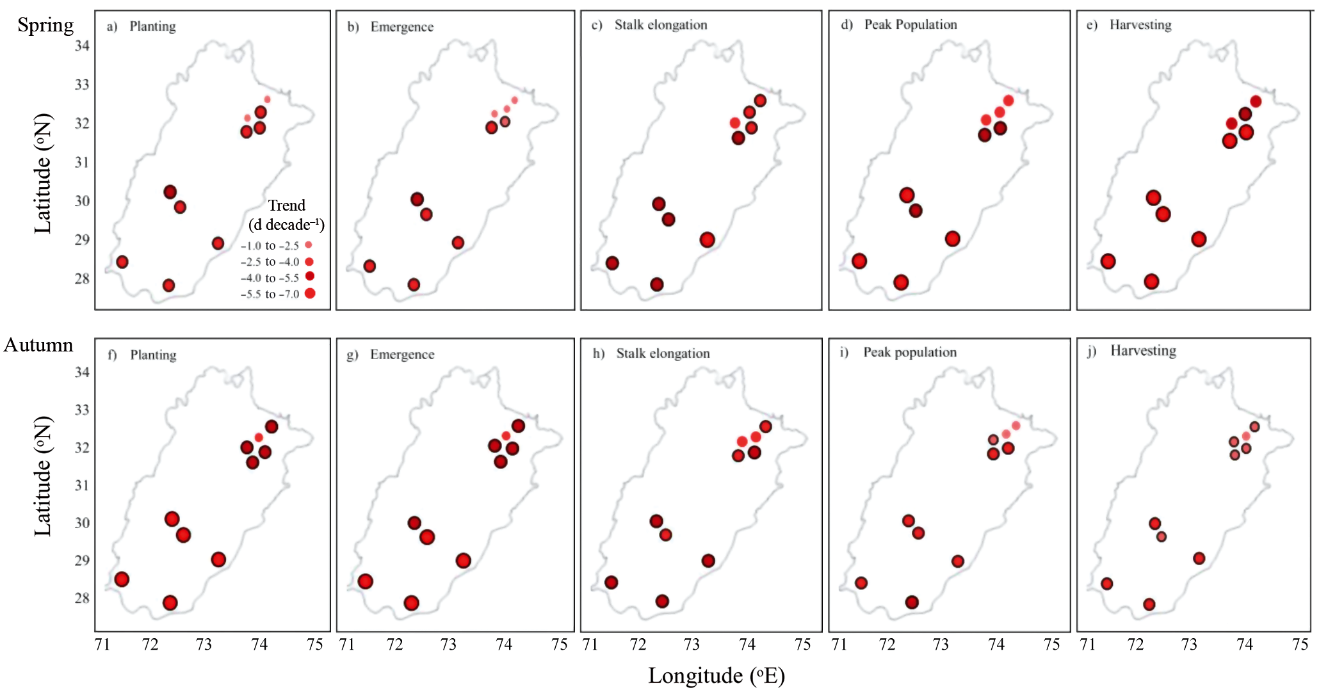

Fig. 4. Observed trends in phenological stages of spring (upper panels) and autumn (lower panels) planted sugarcane from 1980 to 2014 in Punjab, Pakistan: (a,f) planting, (b,g) emergence, (c,h) stalk elongation, (d,i) peak population and (e,j) harvesting. Circles with black border indicate statistically significant trends at p = 0.05 probability level

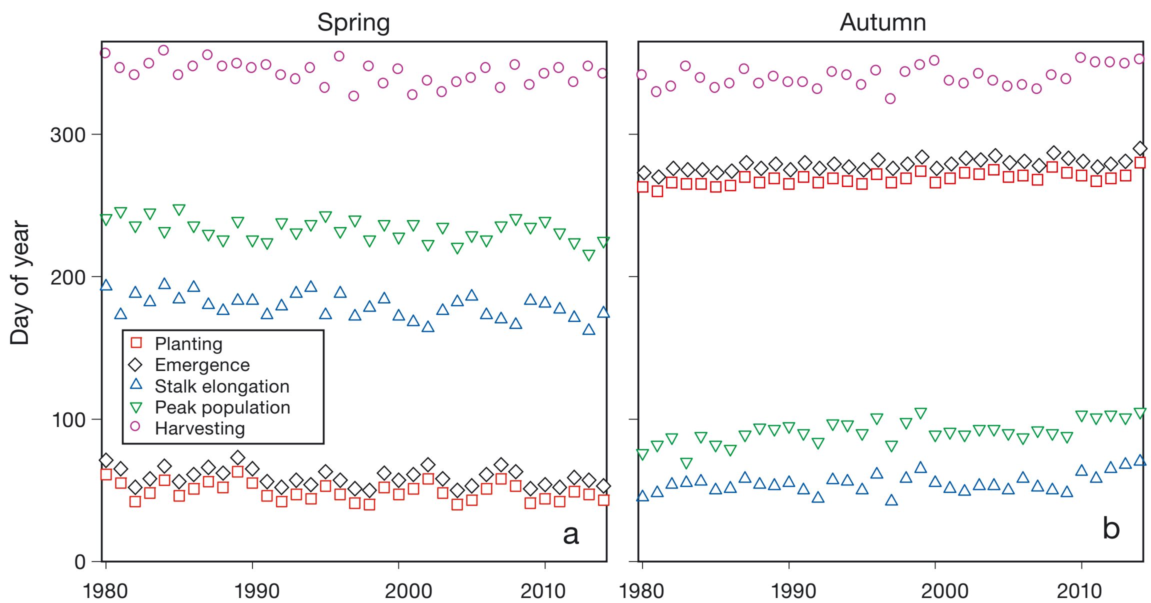

Fig. 5. Time series plots of observed dates of onset of phenological stages (planting, emergence, stock elongation, peak population and harvesting) for (a) spring and (b) autumn planted sugarcane in Punjab, Pakistan, from 1980 to 2014

decade^{-1} (statistically significant at 9 sites), with a mean of 4.38 d decade^{-1}, for autumn sugarcane. Peak population of spring and autumn sugarcane generally occurred from mid-July to mid-August and from the end of March to the end of April, respectively. Peak population of spring sugarcane advanced by 3.4 to 6.3 d decade^{-1} (statistically significant at 7 sites), with an average of 5.01 d decade^{-1}. The peak population of autumn sugarcane was delayed by 1.2 to 4.6 d decade^{-1} (statistically significant at 8 sites), with a mean of 3.13 d decade^{-1}. Harvesting of spring and autumn sugarcane generally occurred from the end of November to the end of December. Harvesting dates advanced by 5.1 to 7.6 d decade^{-1} (statistically significant at 8 sites) with a mean of 6.41 d decade^{-1} for spring sugarcane. Harvesting dates were delayed by 0.8 to 3.3 d decade^{-1} (statistically significant at 9 sites) with a mean of 2.17 d decade^{-1}, for autumn sugarcane.

3.3. Variability of phenological phases

The planting to stalk elongation phase of spring and autumn sugarcane was shorter by 1.2 to 2.0 d decade^{-1} (statistically significant at 9 sites) and by 1.7 to 3.2 d decade^{-1} (statistically significant at 8 sites), respectively, and on average by 1.60 and 2.21 d decade^{-1}, respectively (Fig. 6a,b). The stalk elongation to peak population phase of spring and autumn sugarcane was shorter by 0.2 to 1.1 d decade^{-1} (statistically significant at 9 sites) and 0.6 to 2.3 d decade^{-1} (statistically significant at 7 sites), respectively, and on average by 0.54 and 1.25 d decade^{-1}, respectively. The peak population to harvesting phase of spring and autumn sugarcane was shorter by 0.6 to 1.8 d decade^{-1} (statistically significant at 8 sites) and 0.4 to 1.5 d decade^{-1} (statistically significant at 9 sites), respectively, and on average by 1.40 and 0.96 d decade^{-1}, respectively. As a result of shorter planting to stalk population, stalk elongation to peak population and peak population to harvesting phases, the overall planting to harvesting phase was also shorter. The planting to harvesting phase of spring and autumn sugarcane was shorter by 2.70 to 4.60 d decade^{-1} (statistically significant at 9 sites) and 3.3 to 5.8 d decade^{-1} (statistically significant at 8 sites), respectively, and on an average by 3.54 and 4.42 d decade^{-1}, respectively.

3.4. Variability of total thermal time requirement

The total thermal time (total growing degree-days) requirements of sugar cane cultivars planted at the study sites increased. The total thermal time requirement for spring and autumn sugarcane from planting to peak population phase increased by a mean of 75 and 80°D decade^{-1}, respectively, and ranged from 60 to 92°D decade^{-1} (statistically significant at 5 sites) and 66 to 95°D decade^{-1} (statistically significant at 6 sites), respectively (Fig. 7). Likewise, the thermal time requirement of spring and autumn sugarcane from peak population to harvesting phase increased

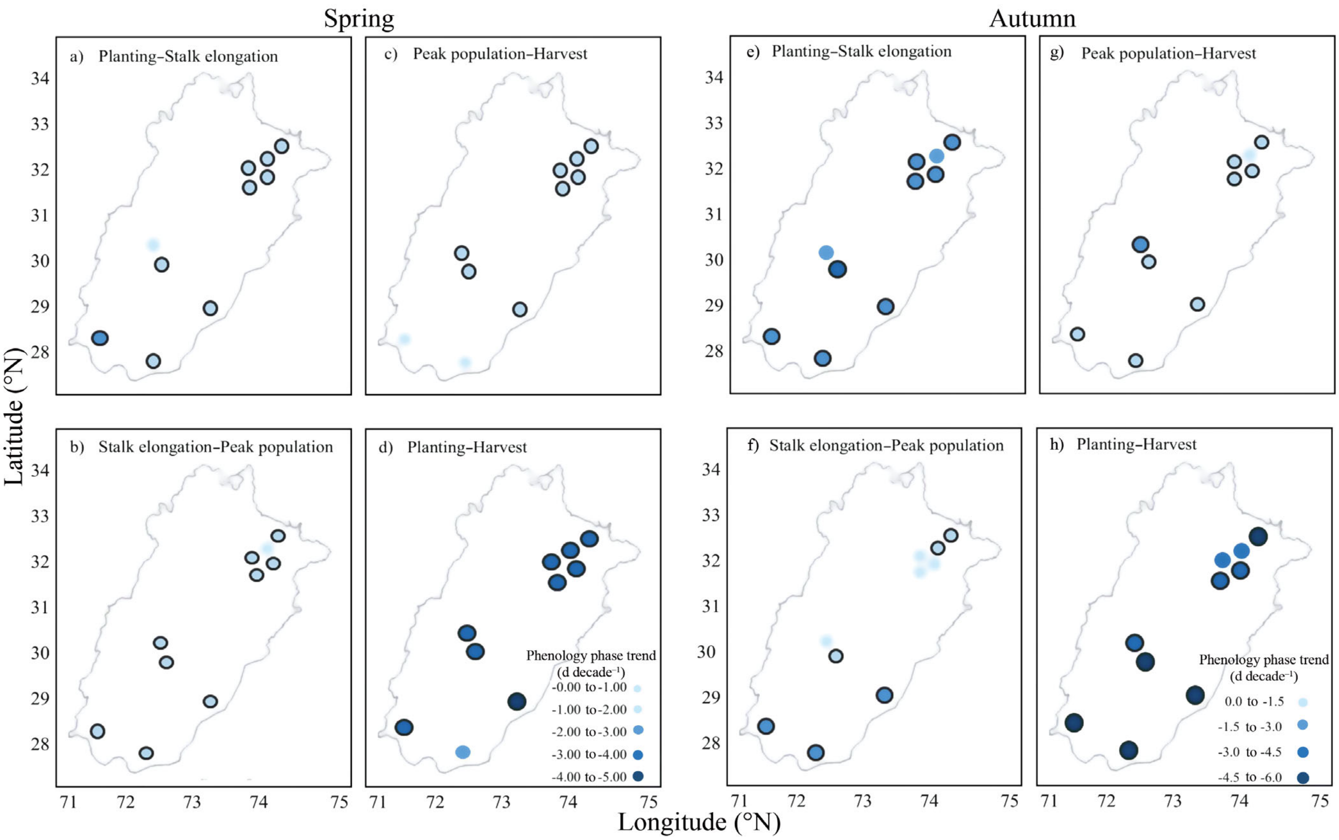

Fig. 6. Observed trends in the length of phenological phases for spring (left panels) and autumn (right panels) planted sugarcane from 1980 to 2014 in Punjab, Pakistan: (a,e) planting–stalk elongation, (b,f) stalk elongation–peak population, (c,g) peak population–harvest and (d,h) planting–harvest. Circles with black border indicate statistically significant trends at p = 0.05 probability level

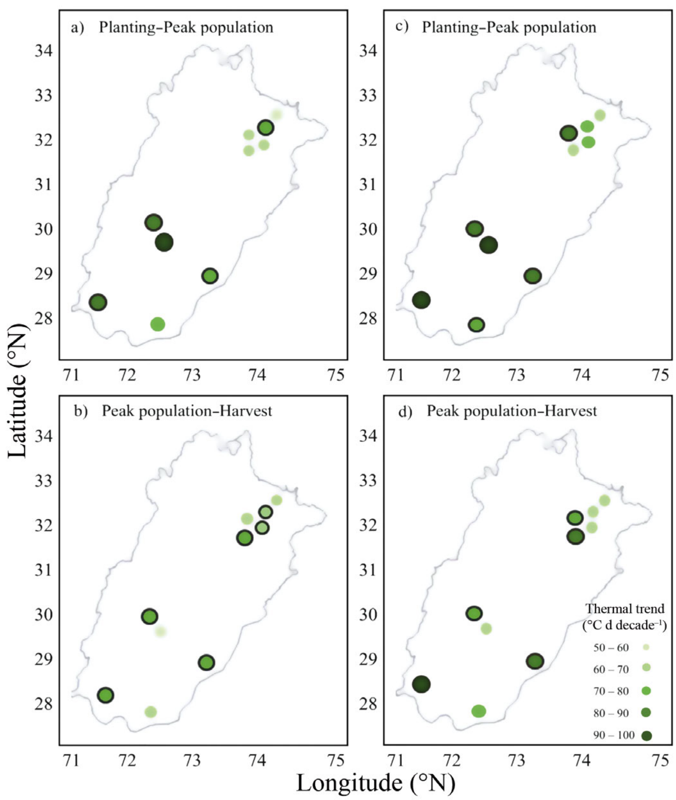

Fig. 7. Observed trends in thermal time required for spring (left panels) and autumn (right panels) planted sugarcane in Punjab, Pakistan, to advance from (a,c) planting to peak population and (b,d) peak population to harvest. Circles with black border indicate statistically significant trends at p = 0.05 probability level

by 56 to 80°D decade^{-1} (statistically significant at 6 sites) and 60 to 90°D decade^{-1} (statistically significant at 5 sites) and on average by 69 and 74°D decade^{-1}, respectively.

3.5. Responses of observed phenology to temperature

Temperature rises were negatively correlated with planting dates of spring sugarcane and positively correlated with planting dates of autumn sugar cane. Planting dates of spring sugar cane advanced 0.63 to 1.90 d °C^{-1} (statistically significant at 8 locations), with a mean of 1.29 d °C^{-1}, while planting dates of autumn sugar cane were delayed by 2.12 to 3.69 d

Table 3. Summary of observed and simulated phenology responses to temperature for spring and autumn planted sugarcane from 1980 to 2014 in Punjab, Pakistan. From left to right, the columns show the number of stations with negative correlations, positive correlations, significant negative correlations and significant positive correlations for the onset of 5 phenological stages (planting, emergence, stalk elongation, peak population and harvest) and the duration of 4 corresponding phenological phases. The final column shows the mean of regression coefficients in each case

Phenology	Negative	Positive	Significant negative	Significant positive	Reg. mean (d °C^{-1})
Spring sugarcane stages and phases (observed)					
Planting	10	0	8	0	−1.29
Emergence	10	0	7	0	−1.18
Stalk elongation	10	0	9	0	−2.01
Peak population	10	0	7	0	−2.25
Harvesting	10	0	8	0	−2.88
Planting–stalk elongation	10	0	9	0	−0.72
Stalk elongation–peak population	10	0	9	0	−0.57
Peak population–harvest	10	0	8	0	−0.63
Planting–harvest	10	0	9	0	−1.59
Spring sugarcane phases (simulated)					
Planting–stalk elongation	10	0	8	0	−1.18
Stalk elongation–peak population	10	0	9	0	−0.82
Peak population–harvest	10	0	8	0	−1.00
Planting–harvest	10	0	9	0	−1.98
Autumn sugarcane stages and phases (observed)					
Planting	10	0	0	9	2.97
Emergence	10	0	0	9	2.80
Stalk elongation	10	0	0	8	1.96
Peak population	10	0	0	8	1.41
Harvesting	10	0	0	9	0.98
Planting–stalk elongation	10	0	8	0	−1.05
Stalk elongation–peak population	10	0	7	0	−0.56
Peak population–harvest	10	0	9	0	−0.43
Planting–harvest	10	0	8	0	−2.01
Autumn sugarcane phases (simulated)					
Planting–stalk elongation	10	0	9	0	−1.49
Stalk elongation–peak population	10	0	8	0	−0.81
Peak population–harvest	10	0	8	0	−0.79
Planting–harvest	10	0	10	0	−2.27

°C^{-1} (statistically significant at 9 locations), with a mean of 2.97 d °C^{-1} (Table 3, Fig. 8). Emergence dates of spring and autumn sugarcane were negatively and positively correlated with increasing temperature, respectively. Mean emergence dates advanced 1.18 d °C^{-1} in spring sugarcane and were delayed by 2.80 d °C^{-1} in autumn sugar cane, with changes ranging from advances of 0.50 to 1.78 d °C^{-1} (statistically significant at 7 locations) and delays of 1.81 to 3.59 d °C^{-1} (statistically significant at 9 locations), for spring and autumn sugar cane, respectively. Stalk elongation of spring sugarcane advanced 1.32 to 2.47 d °C^{-1} (statistically significant at 9 locations), with a mean of 2.01 d °C^{-1}. Stalk elongation of autumn sugarcane was delayed by 1.2 to 2.88 d °C^{-1} (statistically significant at 8 locations), with a mean of 1.97 d °C^{-1}. Peak populations of spring and autumn sugarcane were negatively and positively correlated with increasing temperature, respectively. Peak population of spring sugar cane advanced 1.51 to 2.79 d °C^{-1} (statistically significant at 7 locations), with a mean of 2.25 d °C^{-1}. Peak population of autumn sugar cane was delayed by 0.53 to 2.10 d °C^{-1} (statistically significant at 8 locations), with a mean of 1.41 d °C^{-1}. Harvesting of spring sugarcane advanced 2.32 to 3.38 d °C^{-1} (statistically significant at 8 locations), with a mean of 2.88 d °C^{-1}. Harvesting of autumn sugarcane was delayed by 0.52 to 1.50 d °C^{-1} (statistically significant at 9 locations), with a mean of 0.98 d °C^{-1}.

The lengths of all growth and developmental phases (phenological phases) of spring and autumn sugarcane were negatively correlated with rising temperature trends. The planting to stalk elongation phase of spring and autumn sugarcane was reduced by 0.54 to 0.90 d °C^{-1} (statistically significant at 9 locations) and by 0.77 to 1.44 d °C^{-1} (statistically significant at 8 locations) and on average by 0.72 and 1.05 d °C^{-1}, respectively. Mean stalk elongation to peak population phase of spring and autumn sugarcane decreased by 0.57 and 0.64 d °C^{-1}, respectively, with values ranging from 0.34 to 0.92 d °C^{-1} (statistically significant at 9 locations) and 0.36 to 1.04 d °C^{-1} (statistically significant at 7 locations), respectively. The peak population to harvesting phase of spring and autumn sugarcane decreased by 0.25 to 0.81 d °C^{-1} (statistically significant at 8 locations) and 0.23 to 0.68 d °C^{-1} (statistically significant at 9 locations) and by a mean of 0.63 and 0.43 d °C^{-1}, respectively. The planting to harvesting phase of spring and autumn sugarcane decreased by 1.22 to 2.07 d °C^{-1} (statistically significant at 9 locations) and 1.49 to 2.61 d °C^{-1} (statistically significant at 8 locations) and on average by 1.59 and 2.01 d °C^{-1}, respectively.

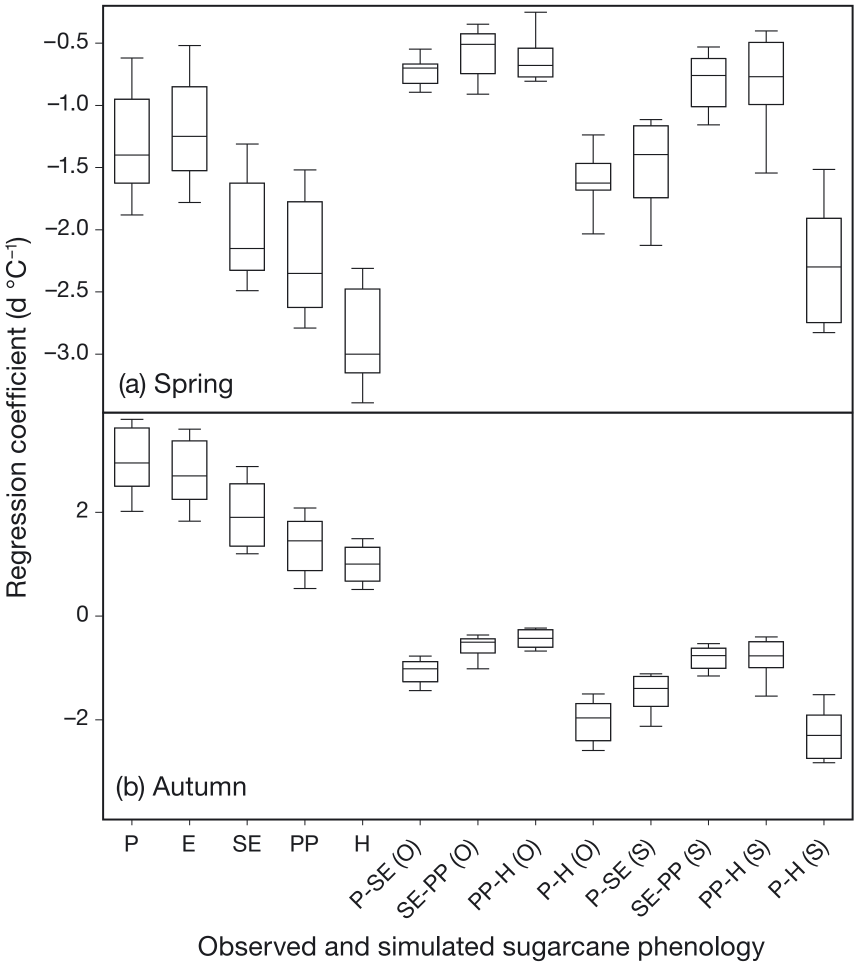

Fig. 8. Observed phenology (stages and phases) and simulated phenology (phases) versus temperature trends of (a) spring and (b) autumn planted sugarcane, based on data from 10 locations in Punjab, Pakistan, from 1980 to 2014. P: planting; E: emergence; SE: stalk elongation; PP: peak population; H: harvesting; P–SE: planting–stalk elongation; PP–H: peak population-harvest; P–H: planting-harvest; (O): observed; (S) simulated. Horizontal line: median; box: 25th and 75th percentiles; whiskers: minimum and maximum values

3.6. Responses of simulated phenology to temperature

The lengths of model-simulated phenological phases of spring and autumn sugarcane were negatively correlated with rising temperature (Table 3, Fig. 8). The planting to stalk elongation phase of spring and autumn sugarcane was shortened, by a mean 1.18 and 1.49 d °C^{-1}, respectively, and values ranged from 0.92 to 1.88 d °C^{-1} (statistically significant at 8 sites) and 1.11 to 2.15 d °C^{-1} (statistically significant at 9 sites), respectively. The stalk elongation to peak population phase of spring and autumn sugarcane was reduced by 0.49 to 1.28 d °C^{-1} (statistically significant at 9 sites) and 0.53 to 1.16 d °C^{-1} (statistically significant at 8 sites) and on average by 0.82 and 0.81 d °C^{-1}, respectively. Peak population to harvesting of spring and autumn sugarcane was also shortened, by a mean 1.0 and 0.79 d °C^{-1}, with values ranging from 0.57 to 1.85 d °C^{-1} and 0.40 to 1.60 d °C^{-1} (in both cases statistically significant at 8 sites), respectively. The planting to harvesting phase of spring and autumn sugarcane was shortened, by a mean 1.98 and 2.27 d °C^{-1}, respectively, and values ranged from 1.52 to 2.77 d °C^{-1} (statistically significant at 9 sites) and 1.75 to 2.83 d °C^{-1} (statistically significant at 10 sites), respectively

Table 4. Comparison of the responses to climate warming of spring and autumn sugarcane for the period 1980–2014 in Punjab, Pakistan, based on analysis of regression coefficients for length of phenological phase versus mean temperature using observed and simulated data. Data in 'Regression coefficient' columns are means of regression coefficients. *Significant at $p \le 0.01$ probability level

Phenological phase	Regression coefficient: observed data (d °C^{-1})		Regression coefficient: simulated data[a] (d °C^{-1})		Difference: observed vs. simulated regression correlations (d °C^{-1})		*t*-test (p-value)	
	Spring	Autumn	Spring	Autumn	Spring	Autumn	Spring	Autumn
Planting–stalk elongation	−0.72	−1.05	−1.18	−1.49	0.46	0.44	0.0012*	0.0025*
Stalk elongation–peak population	−0.57	−0.56	−0.82	−0.81	0.25	0.25	0.0014*	0.0022*
Peak population–harvest	−0.63	−0.43	−1.00	−0.79	0.37	0.36	0.0017*	0.0026*
Planting–harvest	−1.59	−2.01	−1.98	−2.27	0.39	0.26	0.0015*	0.012*

[a]Duration of sowing to maturity

3.7. Observed and simulated phenology of spring and autumn sugarcane

The temperature sensitivity phenology for the observed data of spring and autumn sugarcane was lower than simulated phenological data (Table 4). The differences between regression coefficients from observed and simulated data were statistically significant for spring and autumn sugarcane, with values of 0.46, 0.25, 0.37 and 0.39 d °C^{-1} for planting to stalk elongation, stalk elongation to peak population, peak population to harvesting and planting to harvesting, respectively for spring sugarcane, and 0.44, 0.25, 0.36 and 0.26 d °C^{-1} for planting to stalk elongation, stalk elongation to peak population, peak population to harvesting and planting to harvesting, respectively, for autumn sugarcane. The difference in simulated and observed changes in phenology of cultivars of spring and autumn sugarcane indicated that different new cultivars were introduced during the period 1980 to 2014, which had greater growing degree-days requirements.

4. DISCUSSION

Rising temperature was the most important factor causing the observed changes in growth and development of spring and autumn sugarcane in central and lower Punjab over the past 3 decades. Farmers adapted by changing the planting dates and growing new cultivars which had higher total thermal time requirements, which partially influenced the phenology of spring and autumn sugarcane (Biggs et al. 2013). This agrees with the results of other studies showing that planting dates of crops are changed by the local farming community in response to changes in environmental conditions (Estrella et al. 2007, Knox et al. 2010, M. Wang et al. 2011, He et al. 2015). In this case, a 1°C temperature rise led to the advancement of planting dates by a mean 1.29 d for spring sugarcane and a delay in planting dates by a mean 2.97 d for autumn sugarcane.

The warming trend in Punjab accelerated the growth and development of both spring and autumn sugarcane, which reduced the length of all phenological phases studied (planting to stalk elongation, stalk elongation to peak population, peak population to harvesting and planting to harvesting). Climate warming in the previous decades has advanced phenology in various natural systems (Sparks et al. 2000, Abu-Asab et al. 2001, Fitter & Fitter 2002, Chen & Liu 2014, Li et al. 2014, Carvalho et al. 2015, He et al. 2015). Similarly, phenology has also advanced in other crops (Williams & Abberton 2004, Hu et al. 2005, Sparks et al. 2005, Wang et al. 2008, Xiao et al. 2013). Several studies have reported that the length of planting to harvesting phase (total crop duration) has decreased in in other crops, based on observed field data (Tao et al. 2012, Zhang et al. 2013) and simulated results of various crop growth models (Tubiello et al. 2002, Yang et al. 2004, Sadras & Monzon 2006, Streck et al. 2008, Grassini et al. 2009, Lashkari et al. 2012, Everingham et al. 2015, He et al. 2015).

New cultivars are constantly being produced by means of different breeding methods and introduced to local farming community. These new cultivars are better adapted to current environmental growing circumstances including changing climatic conditions (Liu et al. 2013, Moradi et al. 2013, He et al. 2015, Melgar & Quemé 2015, Xiao et al. 2015). The most recent cultivars have new phenological characteristics (Deressa et al. 2005). In this research, we separated out the impact of the most recently introduced sugarcane cultivars by using the CSM-CANEGRO-Sugarcane model to predict the phenology of spring and autumn sugarcane for the same cultivar at each site over the course of the study period. Simulated phenology was more sensitive to temperature than were observed data. Almost one-third (spring sugar cane: 31.5%; autumn sugarcane: 29.3%; Table 4) of the direct negative effect of rising temperature on phenology was mitigated by growing new cultivars with higher thermal time requirements. Thus the negative effect of warming was partially mitigated by growing sugarcane with longer phenological phases. This adaptation strategy has also been reported for maize in the USA (Sacks & Kucharik 2011), winter wheat in the North Plain of China (Liu et al. 2010, He et al. 2015) and maize in China (Tao et al. 2014). If the growth duration of cultivars is short then grain yield is reduced because the total growing degree-day requirements of the cultivars are not fulfilled and thus less time is available for total dry matter accumulation during the vegetative period (Araya et al. 2015, Zhao & Li 2015). Therefore, local farming communities will benefit from adaptation of new, longer duration, cultivars of spring and autumn sugarcane.

Crop phenology plays a key role in growth and development and ultimately in determining yields (Gouvêa et al. 2009, Ainsworth & Ort 2010). Accumulation of dry matter is reduced if flowering is earlier, which results in a reduction in yield (Lobell et al. 2013, Meng et al. 2014).

Warming trends will have more serious consequences for agriculture in the future (IPCC 2014).

Climate models predict that the mean temperature could increase 2 to 4°C in Punjab by the end of this century. Furthermore, extreme events like heat waves, droughts and floods are expected to be more common in coming decades (Rasul et al. 2012). Phenology will accelerate even more rapidly in coming years due to the increasing thermal trend (Gouache et al. 2012, Z. Liu et al. 2012, Marin et al. 2013, Zhang & Huang 2013). Therefore, breeding and growing new cultivars with higher thermal time requirement and temperature tolerance will make an important contribution towards offsetting the negative impacts of the thermal trend.

5. CONCLUSIONS

A warming trend caused a change in observed phenological stages of spring and autumn sugarcane in Punjab, Pakistan from 1980 to 2014. Phenological stages of spring sugarcane, i.e. planting, emergence, stalk elongation, peak population and harvest dates advanced by a mean 2.87, 2.63, 4.47, 5.01 and 6.41 d decade^{-1}, respectively, while those of autumn sugarcane were delayed by 6.59, 6.21, 4.38, 3.13 and 2.17 d decade^{-1}, respectively. As a result, the lengths of phenological phases, i.e. planting to stalk elongation, stalk elongation to peak population and peak population to harvesting and planting to harvesting, were reduced by a mean 1.60, 0.54, 1.40 and 3.54 d decade^{-1}, respectively for spring sugarcane and 2.21, 1.25, 0.96 and 4.42 d decade^{-1}, respectively for autumn sugarcane, which negatively impacted sugarcane yield. The negative influence of the warming trend was partially mitigated by adoption of new cultivars with higher growing degree-day requirements. Approximately one-third of the negative impact of warmer temperatures on phenology of spring and autumn sugarcane was compensated for by planting new cultivars with higher total growing degree-day requirements.

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