



Can Growing Degree Days and Photoperiod Predict Spring Wheat Phenology?

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Wheat (*Triticum aestivum*) production in the rainfed area of Pothwar Pakistan is extremely vulnerable to high temperature. The expected increase in temperature due to global warming should result in shorter crop life cycles, and thus lower biomass and grain yield. Two major factors control wheat phenological development: temperature and photoperiod. To evaluate wheat development in response to these factors, we conducted experiments that created diverse temperature and daylength conditions by adjusting the crop sowing time. The study was conducted during 2013–14 and 2014–15 using five spring wheat genotypes, four sowing times, at three sites under rainfed management in Pothwar, Pakistan. Wheat crops experienced more cold days with early sowing, but later sowing dates resulted in higher temperatures, especially from anthesis to maturity. These treatments produced large differences in phenology, biomass production, and yield. To investigate whether growing degree days (GDD) and photoperiod algorithms could predict wheat phenology under these changing conditions, GDD was calculated based on the method proposed by Wang and Engel while photoperiod followed the approach introduced in the APSIM crop growth model. GDD was calculated separately and in combination with photoperiod from germination to anthesis. For the grain filling period, only GDD was calculated. The observed and predicted number of days to anthesis and maturity were in good agreement, showing that the combination of GDD and photoperiod algorithms provided good estimations of spring wheat phenology under variable temperature and daylength conditions.

Keywords: wheat, temperature, photoperiod, growing degree days, sowing dates

INTRODUCTION

Based on projections of the Intergovernmental Panel on Climate Change (IPCC, 2014) it is expected that the average surface temperature of the world will increase by 1.5–4.5°C by 2100 if the recent greenhouse gas emission rates continue. Hansen et al. (2012) estimated an increase in average universal temperature of 0.18°C per decade. IPCC (2014) reported 2000s as the warmest decade and 2014 as the warmest year. Agricultural productivity is under threat due to climate change all over the globe as predicted by current and future scenarios (van Ogtrop et al., 2014; Ahmad et al., 2017; Dettori et al., 2017). Increased temperature significantly influences crop productivity and can lead

to dramatic yield loss. Climate change in the form of increased temperature has reduced cereal yield up to 17% (Lobell et al., 2011). Pakistan is also facing impacts of climate change in different socio-economic sectors (Akram and Hamid, 2015; Ahmad et al., 2017). The warming trend, predicted to be 2–4°C at the end of century, will drastically affect agriculture (Rasul et al., 2012). Dwivedi et al. (2017) reported yield loss associated with high temperatures in Eastern Indo-Gangetic Plains (EIGP). In their experiments the average temperature during anthesis of late and very late sowing conditions were 2.7°C and 5.2°C higher than that of the optimum sowing which resulted in the reduction in grain filling duration by 8.6–12.6 days, and average yield loss of 18 and 34% for late sown and very late sown conditions, respectively.

Global warming is producing a shift in crop phenology over the globe (Root et al., 2003; Parmesan, 2006; Ahmad et al., 2017). A warmer climate accelerates crop phenology and affects crop yield (Madan et al., 2012; Zhang et al., 2013; Ahmed et al., 2016). Craufurd and Wheeler (2009) reported earlier flowering and crop maturity under high temperature conditions. Higher temperature resulted in a shorter growing season, accelerated leaf aging/senescence and reductions in biomass and yield (Tao et al., 2013; Figueiredo et al., 2015). High temperature had a negative effect on biomass, spike length, grain yield and harvest index (Plaut et al., 2004).

Wheat production in the rainfed area of Pothwar Pakistan is highly vulnerable to higher temperature (Ahmed and Hassan, 2015). The wheat-growing season in this area starts with the onset of winter and ends in April-May. Due to low soil moisture, wheat sowing is delayed which results in high temperature at anthesis and during grain filling. This high temperature can reduce final yield, and the probability of high temperature is being exacerbated by global warming (Dias and Lidon, 2009, 2010; Modarresi et al., 2010). Joshi et al. (2007) reported heat stress as a major abiotic stress due to delayed sowing affecting wheat cultivation in South Asia. The optimum temperature range for wheat during anthesis and grain filling is between 12 and 22°C. Wheat exposure to above 30°C at pre- and post-anthesis stages reduces the grain filling rate and thereby decreases grain yield and quality (Barnabas et al., 2008). High temperature (>30°C) during anthesis is deleterious (Langer and Olugbemi, 1970; Tashiro and Wardlaw, 1990), while short exposure to very high temperature (>35°C) during anthesis and grain filling can result in substantial reduction of grain yield in wheat (Randall and Moss, 1990; Stone and Nicolas, 1994). Hussain and Mudasser (2007) conducted an experiment in the rainfed area of Pakistan to investigate the effect of high temperature on growing season length. They reported that a 1.5°C increase in temperature shortened the crop life cycle and lowered grain yield by 7%. However, a temperature increase of 3°C reduced wheat yield by 24%.

A prerequisite for modeling crop growth is good forecasting of plant development, with air temperature recognized as the principle regulator of plant development (Bewick et al., 1988). Growing degree day (GDD) values are utilized for predicting crop development (Yang et al., 1995; McMaster and Wilhelm, 1997), which usually integrate temperature values on a daily basis. With increasing global temperature, faster accumulation of

GDDs will take place. In addition to temperature, photoperiod is also a major environmental factor determining time to flower initiation and first flower appearance in plants (Daba et al., 2016), and flowering in wheat is sensitive to photoperiod. Thus, plant development is a function of temperature and daylength (Slafer and Rawson, 1994; Cao and Moss, 1997), and both should be included in predictive algorithms.

To investigate temperature and photoperiod effects on wheat development, we artificially created different temperature and daylength conditions for wheat by varying the sowing times. Early-sown wheat encountered more cold days but late-sown wheat experienced higher temperatures, especially during anthesis to maturity. To support the projection of changes in phenology in responses to future global warming, we used the experimental results to evaluate the ability of GDD and photoperiod algorithms to predict wheat crop phenology.

MATERIALS AND METHODS

Site Description

The current study was conducted at varying climatic locations of Pothwar, Pakistan, including three sites: Islamabad (33° 40' N, 73° 10' E, 508m a.s.l.) with low temperature/high rainfall, URF-Koont (32° 93' N, 72° 86'E, 506m a.s.l.) with medium temperature/rainfall, and Talagang (32° 55' N, 72° 25' E, 458m a.s.l.) with high temperature/low rainfall (**Figure 1**). The soils at Islamabad, URF-Koont and Talagang were loam, sandy clay loam and sandy loam, respectively. The physiochemical properties of the study sites (**Table 1**) were recorded by taking a representative soil sample before sowing to a depth of 90 cm using a king tube.

Climate Description

The daily maximum and minimum temperature, rainfall and day length data were obtained from the meteorological observatories located near the study sites during both years. Missing data were calculated using DSSAT Perturb (2014). The average temperature during 2014–15 was higher (1.32°C) at all the study sites than 2013–14 (**Table 2**) and this variation in average temperature had a direct influence on wheat growth, development and phenology. The temperature 7 days before and after anthesis (Anthesis Temperature) was recorded and presented in **Table 2**. Total seasonal rainfall was higher at Islamabad than the other two study sites.

Experimental Design

To investigate GDD and photoperiod as predictors of wheat phenology, the current study was conducted during 2013–14 and 2014–15 using five spring wheat genotypes and four sowing times under rainfed conditions in Pothwar (350–580 m a.s.l.), Pakistan. A randomized complete block experimental design was used with five wheat genotypes, four sowing dates, and three sites providing diverse environmental conditions (Islamabad, URF-Koont and Talagang). The genotypes used were Dharabi (Parentage: HXL7573/2*BAU//PASTOR, Pedigree:

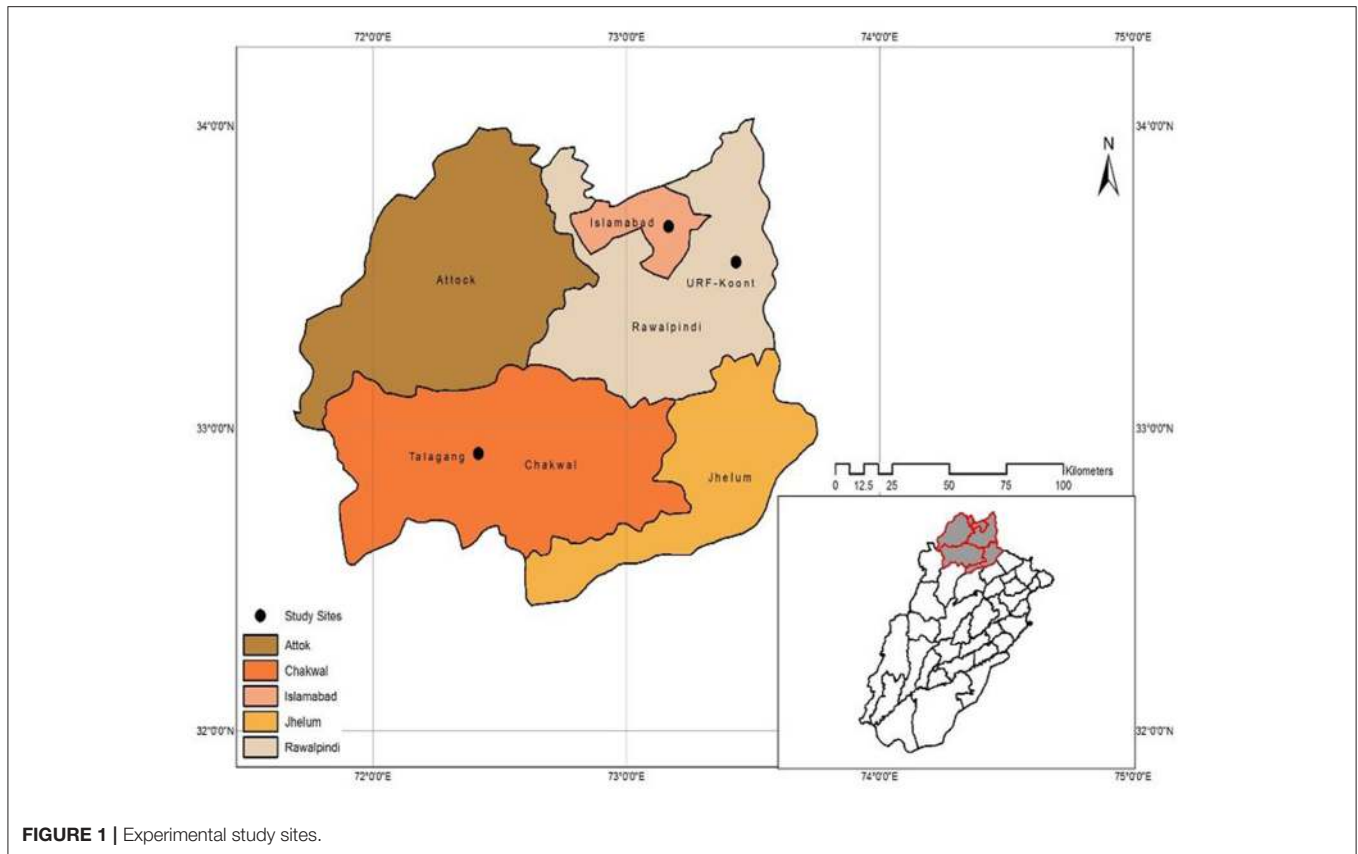


FIGURE 1 | Experimental study sites.

TABLE 1 | Soil physiochemical properties for three study sites.

Parameters	Units/depth	Islamabad			URF-Koont			Talagang		
		0–30	30–60	60–90	0–30	30–60	60–90	0–30	30–60	60–90
Organic carbon	%	0.89	0.62	0.43	0.69	0.46	0.32	0.62	0.74	0.56
Silt	%	33	33	32	22	20	20	27	28	28
Sand	%	35	35	34	56	56	55	59	56	53
Clay	%	32	32	34	22	24	25	14	16	19
Texture		Loam	Loam	Loam	Sandy clay loam	Sandy clay loam	Sandy clay loam	Sandy loam	Sandy loam	Sandy loam
Bulk density	gcm ⁻³	1.33	1.49	1.62	1.37	1.6	1.73	1.43	1.64	1.75
SLL	mmmm ⁻¹	0.12	0.13	0.13	0.07	0.08	0.08	0.07	0.08	0.08
SDUL	mmmm ⁻¹	0.29	0.26	0.23	0.22	0.19	0.18	0.16	0.16	0.17
Saturated SW	mmmm ⁻¹	0.44	0.37	0.32	0.43	0.33	0.28	0.39	0.32	0.27

SLL, Soil lower limit; SDUL, Soil drain upper limit and Saturated; SW, Saturated soil water.

CMSS97Y03676S-040Y-050M-040SY-030M-21SY-010M-0Y-0SY), Chakwal-50 (Origin: Advance line from CIMMYT, Pedigree: ATTILA/3/HUI/CARC//CHEN/CHTO/4/ATTILA, Selection history: CMBW90M4860-0T0PY-16M-10M-010Y-1M-015Y-0Y), NARC-2009 (Pedigree: INQALAB91/2/TUKURU, Selection history: CGSS99B00015F-099Y-099M-099Y-099M-29Y-0B-0ID), Pak-13 (Parentage and Pedigree information not available at <http://wheatatlas.org/country/varieties/PAK/0>) and AUR-809 (Parentage and Pedigree information not available at <http://wheatatlas.org/country/varieties/PAK/0>). The genetic

phenotypic architecture of wheat genotypes is presented in **Table 3**.

Sowing dates were planned in such a manner that the growing wheat plants would likely experience cooler, optimum and warmer conditions. Sowing times were 21–30 Oct (SD₁, early sowing), 11–20 Nov (SD₂, normal sowing), 1–10 Dec (SD₃, late sowing) and 21–30 Dec (SD₄, very late sowing) during 2013–14 and 2014–15. The normal sowing time was taken as the reference for GDD calculation at each location, and days to flowering and maturity were predicted for each sowing time.

TABLE 2 | Rainfall (mm), day length (hours), average seasonal and anthesis temperature (7 days before and after anthesis) (°C) at the three study sites for four sowing dates (SD) and 2 years.

Locations	Sowing dates	Rainfall		Photoperiod		Mean Temperature		Anthesis Temperature	
		2013–14	2014–15	2013–14	2014–15	2013–14	2014–15	2013–14	2014–15
Islamabad	SD ₁	661	428	102	92	14.3	14.8	12.4	11.5
	SD ₂	636	390	102	95	14.1	14.3	13.8	13.7
	SD ₃	636	390	96	89	14.2	14.8	15.8	13.9
	SD ₄	627	382	92	80	15.3	15.9	17.5	19.8
URF-Koont	SD ₁	289	233	41	35	16	18.1	14.1	14.4
	SD ₂	298	226	44	38	15.6	18	15.1	16.4
	SD ₃	299	222	49	37	15.6	17.8	16.2	19.4
	SD ₄	192	245	50	39	16	19	16.3	21.7
Talagang	SD ₁	126	110	38	38	18.8	18.8	15.8	14.7
	SD ₂	128	110	42	37	18.6	19.5	16.5	17.8
	SD ₃	150	126	45	37	18.7	20.1	18.3	24.5
	SD ₄	150	102	46	40	19.1	21.2	17.6	28.0

TABLE 3 | Phenological characteristics of five wheat genotypes used in this study.

Genotypes	Days to Anthesis	Day to maturity	Days to grain filling	Photoperiod sensitivity
NARC-2009	100.4	140.0	39.7	Yes
AUR-809	101.4	141.0	39.7	Yes
Pak-13	101.1	140.9	40.1	Yes
Dhurabi	100.9	140.3	39.3	Yes
Chakwal-50	100.5	140.0	39.2	Yes

Crop Phenology

Days to anthesis and days to maturity were recorded using Zadok's scale for all study sites, sowing dates, and years (Zadoks et al., 1974).

Growing Degree Days and Photoperiod Calculations

Growing degree days were calculated using the Wang and Engel (1998) method, separately and in combination with photoperiod.

The Wang and Engel (1998) equations used for GDD calculation are

$$\alpha = \ln 2 / \ln \left(\frac{T_{max} - T_{min}}{T_{opt} - T_{min}} \right) \quad (i)$$

$$\text{Numerator} = 2 (T_{av} - T_{min})^\alpha (T_{opt} - T_{min})^\alpha - (T_{av} - T_{min})^{2\alpha} \quad (ii)$$

$$\text{Denominator} = (T_{opt} - T_{min})^{2\alpha} \quad (iii)$$

Then

$$WEDD = \left(\frac{\text{Numerator}}{\text{Denominator}} \right) (T_{opt} - T_{min}) \quad (1)$$

Where WEDD is degree days calculated by the Wang and Engel (1998) method. If $T_{av} < T_{min}$ or $T_{av} > T_{max}$ then

WEDD = 0. The cardinal temperatures for GDD calculations pre anthesis were $T_{min} = 0$, $T_{opt} = 27.7$, and $T_{max} = 40$. For the post anthesis period, the cardinal temperatures were $T_{min} = 0$, $T_{opt} = 32.75$, and $T_{max} = 44$.

Photoperiod was calculated using the approach introduced in the APSIM wheat model (Zheng et al., 2014), where photoperiod affects the phenology between emergence and floral initiation.

$$\text{Photoperiod} = 1 - 0.002 (\text{Photoperiod coefficient}) \times (20 - \text{day length})^2 \quad (2)$$

where *day length* is in hours and the *Photoperiod coefficient* ranges from 0 to 4.

Photo Growing Degree Days (PGDD), the combination of GDD and photoperiod effects on wheat development between emergence and floral initiation, were calculated by multiplying WEDD by photoperiod as follows:

$$PGDD = (WEDD) (\text{Photoperiod}). \quad (3)$$

Statistical Analysis

Analysis of variance (ANOVA) was performed to test the significant differences among means of various parameters for five genotypes across four sowing dates (SDs) and three locations for the 2013–2015 wheat growing seasons using R software.

RESULTS

Observed Parameters (Days to Anthesis and Days to Maturity)

Observed days to anthesis and days to maturity averaged for all genotypes showed significant differences among location and sowing dates in both years (Table 4). The largest number of days to anthesis (110.4) was observed for SD₂ during 2013–14 at Islamabad while the lowest number of days to anthesis (86) was recorded for SD₄ during 2014–15 at Talagang. On the other hand,

TABLE 4 | Observed wheat phenological development at the three study sites, including four sowing dates (SD) and 2 years.

Location	Sowing date	Days to anthesis		Days to maturity	
		2013–14	2014–15	2013–14	2014–15
Islamabad	SD ₁	106.2CD	107C	165.4A	151.8E
	SD ₂	110.4A	104.4E	161.6B	152.2DE
	SD ₃	102.6F	96.4JK	149.4F	140.4K
	SD ₄	96.8J	93.2L	138.2L	128.2O
URF-Koont	SD ₁	99.4I	95.8K	159C	145.2H
	SD ₂	108.4B	102FG	153.2D	141.8J
	SD ₃	101.6GH	92.4LM	147.4G	126.4P
	SD ₄	91.8M	84.8Q	135.8M	118.2S
Talagang	SD ₁	102.2FG	103.8E	143.4I	142.6I
	SD ₂	106D	99.6I	142.2J	132.6N
	SD ₃	100.8H	90.8N	135.4M	122R
	SD ₄	89.8O	86.6P	124.4Q	114.2T

Means with similar letter(s) have no significant difference while different letters A, B, C, D, E showed that means are significantly different from each other at 0.05 probability levels.

the largest number of days to maturity was observed for SD₁ (165 d) while lowest number of days to maturity was recorded for SD₄ (114 d). Among locations, the cooler location, Islamabad, had more days to anthesis and maturity than the moderate (Koont) and warmer (Talagang) locations.

Days to Maturity in Relation to Seasonal Temperature and Temperature during Flowering

Wheat phenology was significantly changed in response to average seasonal temperature in all sowing dates, sites, and years. At Islamabad, average seasonal temperature ranged from 12 to 17.5°C and for URF-Koont and Talagang it was in the range of 14–22°C and 16.5–24.6°C, respectively. More days to maturity were observed at Islamabad than URF-Koont and Talagang (Figure 2). At later sowing dates, average seasonal temperature was higher than the early sowing so the wheat matured in fewer days during both years. Similarly, average temperature during the 7 days before and after anthesis (average anthesis temperature) greatly influenced the number of days to maturity at three study sites during both years. Average anthesis temperature was higher at Talagang than URF-Koont and Islamabad. Average anthesis temperature was in the range of 10.74–19.97°C, 13.67–21.83°C, and 12.63–28.09°C at Islamabad, URF-Koont and Talagang, respectively (Figure 2B). At Islamabad days to maturity dropped to 127 from 169, while days to maturity dropped to 116 from 161 and 113 from 145 at URF-Koont and Talagang, respectively.

Biological Yield in Relation to Seasonal Temperature and Temperature during Flowering

Biological yield, i.e., above-ground biomass, differed considerably with average seasonal temperature at all sowing dates among all locations during both growing seasons. At Talagang average

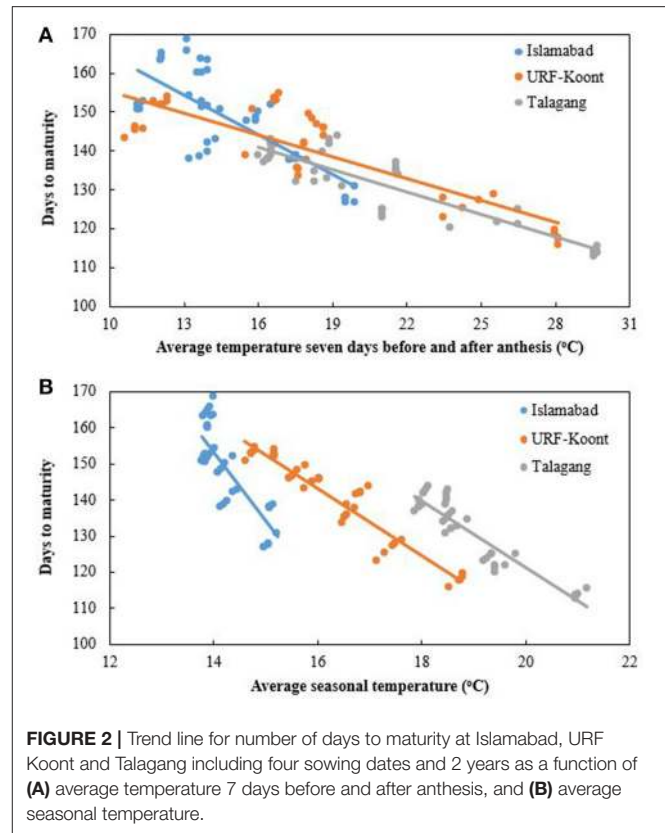
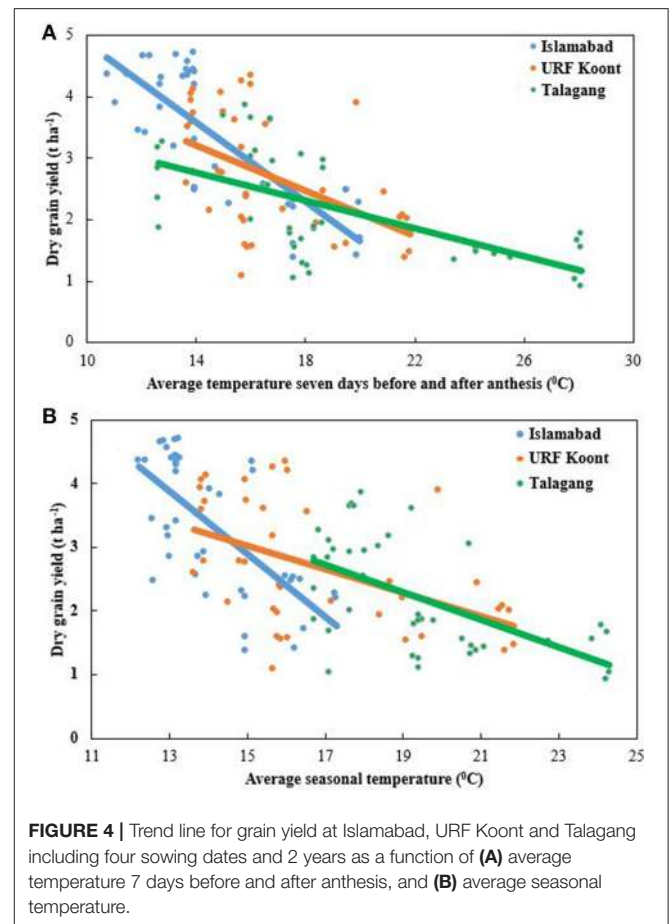
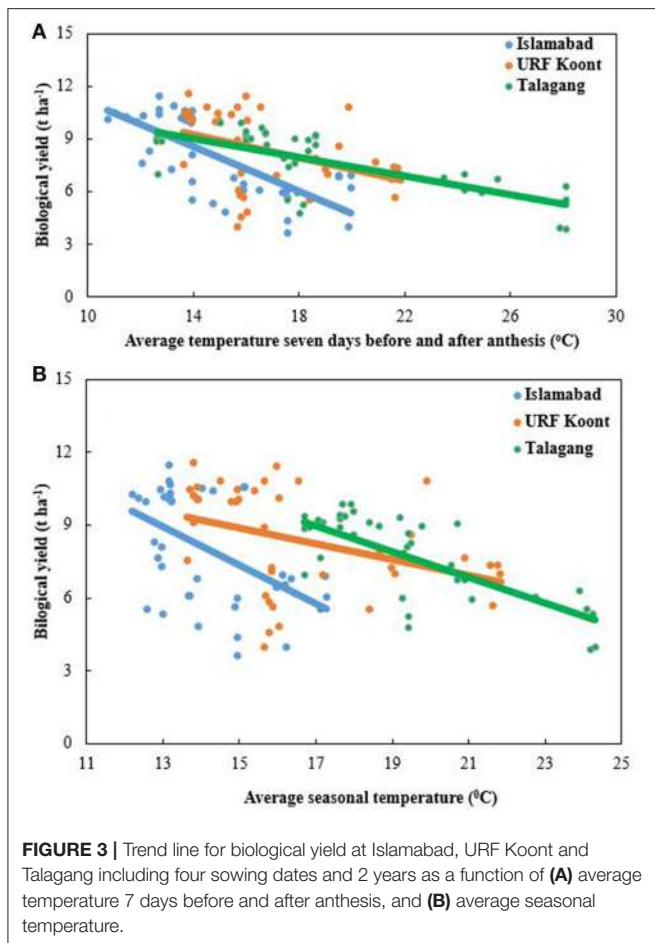


FIGURE 2 | Trend line for number of days to maturity at Islamabad, URF-Koont and Talagang including four sowing dates and 2 years as a function of (A) average temperature 7 days before and after anthesis, and (B) average seasonal temperature.

seasonal temperature ranged from 16.5 to 24.6°C and for URF-Koont and Islamabad it was in the range of 14–22°C and 12–17.5°C, respectively. Higher biological yield was observed at Islamabad than URF-Koont and Talagang (Figure 3). At later sowing dates, average seasonal temperature was higher than the early sowing so the crop matured in fewer days resulting in less production of biomass during both years. The range of average anthesis temperature is presented in Figure 3. A reduction in biological yield was noted with an increase in anthesis temperature. At Islamabad, biological yield was reduced from 11.43 t ha⁻¹ to 3.41 t ha⁻¹, while biological yield decreased from 9.90 t ha⁻¹ to 3.22 t ha⁻¹ and from 9.81 t ha⁻¹ to 3.28 t ha⁻¹ at URF-Koont and Talagang, respectively.

Grain Yield with Respect to Seasonal Temperature and Temperature during Flowering

A reduction in grain yield was recorded with an increase in the average seasonal temperature. At Islamabad, grain yield dropped to 1.10 t ha⁻¹ from 4.08 t ha⁻¹, while grain yield decreased to 0.86 t ha⁻¹ from 3.68 t ha⁻¹ and 0.82 t ha⁻¹ from 3.07 t ha⁻¹ at URF-Koont and Talagang, respectively. Higher grain yield was recorded at Islamabad than at the warmer study sites, URF-Koont and Talagang (Figure 4). At later sowing dates, average seasonal temperature was higher than the early sowing so the wheat matured in fewer days, causing a reduction in grain yield during both years. Average anthesis temperature was higher at



Talagang than URF-Koont and Islamabad (Figure 4). Higher anthesis temperature reduced grain yield at all locations.

Harvest Index with Respect to Seasonal Temperature and Temperature during Flowering

A reduction in harvest index (HI) was noted with an increase in average seasonal temperature. At Islamabad HI dropped from 0.38 to 0.18, while it dropped from 0.38 to 0.20 and 0.35 to 0.17 at URF-Koont and Talagang, respectively. A higher HI was recorded at Islamabad compared to the warmer study sites (Figure 5A). Higher temperature resulted in a reduction of grain numbers and size (data not presented), thus reducing HI. Average anthesis temperature was higher at Talagang than URF-Koont and Islamabad (Figure 5B). Average anthesis temperature likely influenced grain number, size, yield and HI at the three study sites during both years, but the experimental protocol did not permit isolation of the effects of seasonal and anthesis temperature.

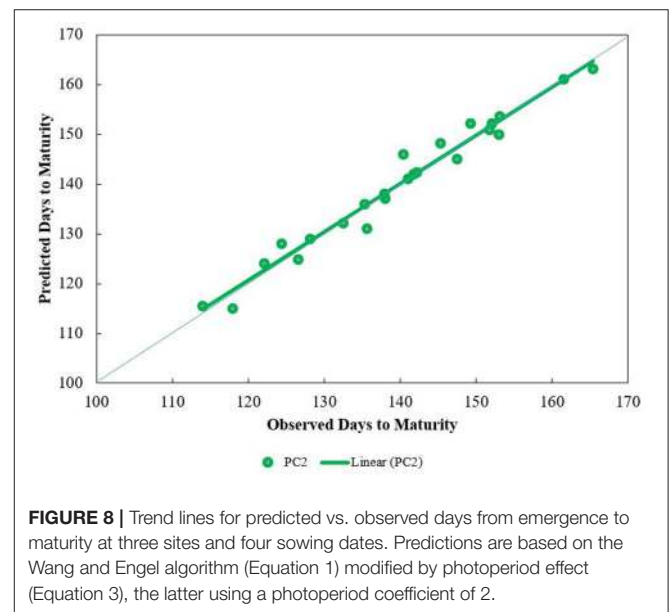
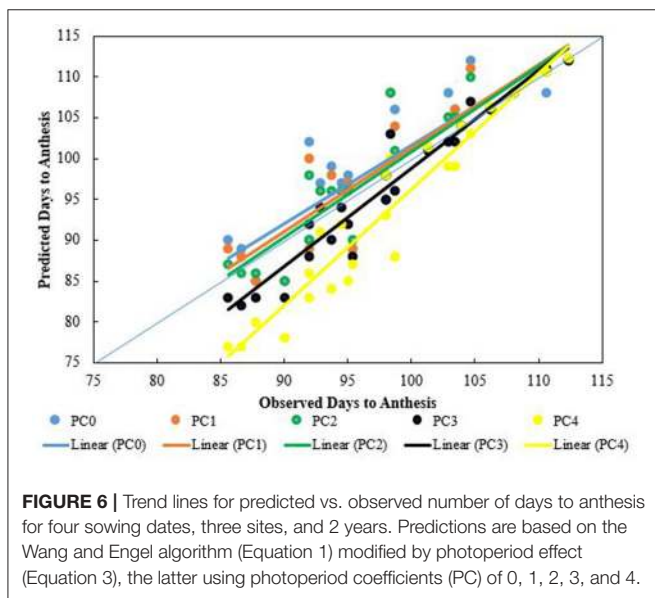
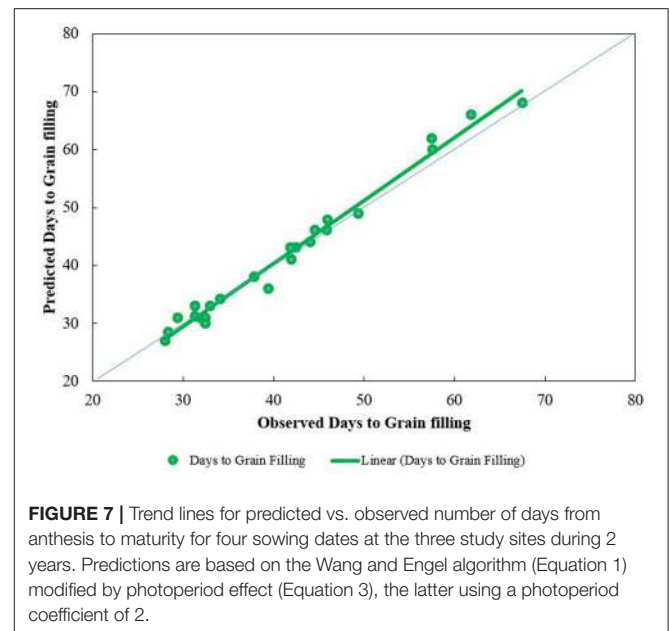
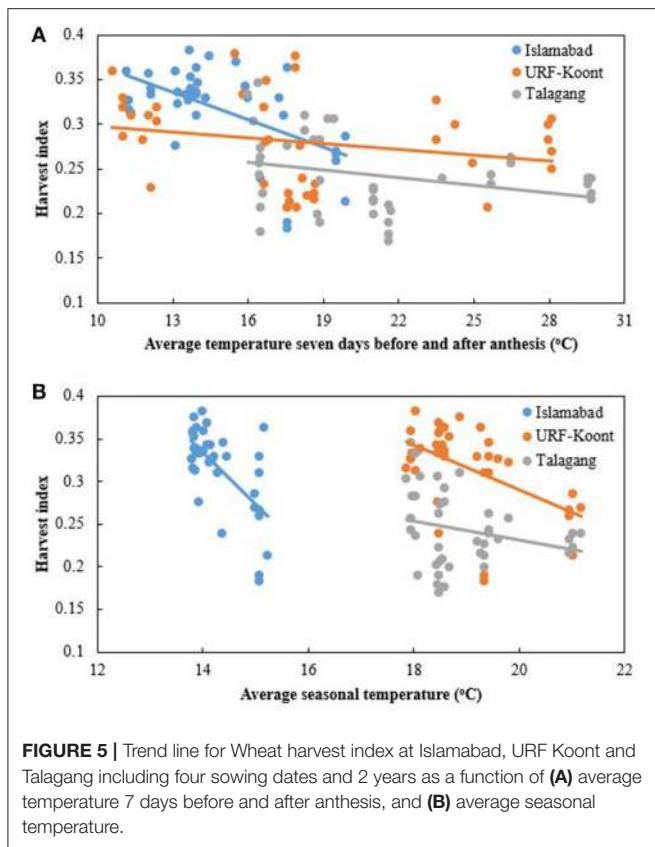
Predicted Days to Anthesis, Anthesis to Maturity and Maturity

The Wang and Engel (1998) method was used to predict days to anthesis using temperature and phenological observations

from SD_2 for calibration at each site. Because the difference in phenological stages between genotypes was small, the genotype, Pak-13, was used as representative of wheat phenological responses to temperature. The Wang and Engel (1998) method of GDD calculation with no photoperiod effect overestimated days to anthesis (Figure 6, blue data). When the Wang and Engel (1998) method was combined with photoperiod and setting its coefficient value = 1, the predicted days to anthesis were reduced but they were still higher than the observed days to anthesis. A photoperiod coefficient value of 2 produced predicted days to anthesis that were very close to the observed days to anthesis. With further increases in photoperiod coefficient (3 and 4) the predicted days to anthesis were under estimated (Figure 6, black and yellow data).

The predicted number of days from anthesis to maturity matched well the observations (Figure 7). The longest observed and predicted number of days from anthesis to maturity were 67 and 68 days, respectively, while the shortest were 28 and 27 days.

The predicted days from emergence to maturity were calculated by adding the number of days to anthesis (using a photoperiod coefficient of 2) plus days from anthesis to maturity. Predicted days to maturity were very close to observed days to maturity (Figure 8).



DISCUSSION

In this study, we saw a reduced number of days to maturity due to higher temperature, which has been reported by other authors, e.g., Sadras and Monzon (2006), who concluded that wheat phenology has a strong correlation with temperature.

Temperature effects at three different study sites resulted in reduced number of days to maturity. The differences in phenology were due to variation in climatic parameters that prevailed during the crop life cycle at these sites (Table 2), in addition to the effect of higher seasonal temperature resulting from delayed sowing. Our results were in agreement with the findings of Asseng et al. (2011), Deryng et al. (2014), Hawkins et al. (2013), and Lobell et al. (2011). Wolkovich et al. (2012) reported that a change in the phenology of a crop is the most important indicator of climate change. Furthermore, Wang et al. (2015) suggested adjusting the sowing date to minimize the impact of heat stress, as well as using late-maturing cultivars to

maintain crop phenology patterns that utilize resources more effectively. Using crop models to design ideotypes could be a good approach to predict the best genotypes for a target environment under climate change (Gouache et al., 2015). Since phenology is a key component in ideotype design, matching crop growth stages to optimal growing conditions is necessary to utilize resources effectively and to avoid climatic stresses such as the terminal heat stress observed in our studies (Foulkes et al., 2011; Sylvester-Bradley et al., 2012). Gomez-Macpherson and Richards (1995) concluded that phenology is an important aspect of adaptation and maximization of yield as phenology controls the duration of critical growth stages of the crop which has associations with abiotic stresses and further partitioning of assimilates. Accurate prediction of phenology is a very important step to calibrate different crop models (Ceglar and Kajfež-Bogataj, 2012; Archontoulis et al., 2014; Ahmed et al., 2016). Models can capture cultivar variations which affect leaf area development, biomass production and grain yield only if they can capture crop phenology accurately. Phenological parameters such as days to maturity are directly linked to crop productivity. Under normal conditions the more days to maturity, the higher is the yield. The higher seasonal temperature obtained in this study by sowing wheat late reduced days to maturity during both years. The Wang and Engel (1998) GDD method with photoperiod adjustments predicted days to maturity accurately, suggesting that spring wheat phenology is sensitive to both temperature and photoperiod. Zhang et al. (2015) argued that wheat genotypes were highly sensitive to photoperiod.

Crop biomass is closely associated with life cycle duration, and temperature is a dominant environmental factor influencing crop development (Liu et al., 2016). Camargo et al. (2016) reported that the relative timing of flowering and grain filling has a direct influence on wheat productivity. In our studies, a decrease in biomass due to higher temperature is consistent with earlier findings that higher heat accelerates crop phenology and crop senescence, which results in earlier crop maturity, lower biomass and lower crop yield (Zhao et al., 2007; Prasad et al., 2008; Hatfield and Prueger, 2015; Prasad and Jagadish, 2015). With higher temperature leading to earlier maturity and lower biomass production, it is critical to consider changing both sowing date and genotype under future warming. In all earlier studies a reduction in growing season length was associated with higher temperature, so current varieties may not be suitable in the future due to shortened growing seasons (Xiao et al., 2010; Asseng et al., 2015; Wang et al., 2015).

An increase in daily atmospheric temperature will accumulate more degree days and hasten maturity. Observed days to maturity varied significantly with atmospheric temperature. An increase in seasonal atmospheric temperature of 2–4°C (e.g., Wheeler et al., 2000) can shorten the crop life cycle, which ultimately reduces yield (Batts et al., 1997; Ahmed and Hassan, 2015). Semenov (2009) used a modeling approach and future climate projections and found that phenology is reduced to 14–16 days due to higher temperature. In our study, higher temperature

had a negative correlation with biological and grain yield under all treatments.

For wheat, the Wang and Engel GDD method with photoperiod adjustment (for the period from emergence to anthesis) was effective in predicting days to anthesis and days from anthesis to maturity as a function of changing sowing dates and associated seasonal temperatures. This provides indication that this approach can be useful for predicting crop phenology under global warming scenarios.

CONCLUSIONS

Spring wheat phenology is driven by both temperature and photoperiod. Increasing temperatures have a significant effect on wheat crop phenology, biomass production, grain yield, and harvest index. High temperatures occurring in a period 7 days before and after anthesis affected grain numbers (data not presented) and yield but it could not be isolated from the effect of seasonal high temperatures. The Wang and Engel method for the calculation of GDD, coupled with an algorithm to adjust GDD as a function of day length extracted from the APSIM crop growth model, provided good estimates of number of days to anthesis across all sites, sowing dates and years. The Wang and Engel GDD method also provided excellent estimates of the number of days between anthesis and maturity. The good predictive capability of the algorithms tested suggests that they are adequate for estimation of global warming effects on wheat phenology.

AUTHOR CONTRIBUTIONS

MAA conducted field experiments, collected, and analyzed the data, CS and MA designed the idea. MAA, MA, CS, SH, and RH wrote and finalized the manuscript; MA, CS, and SH conceived, directed the project, and approve of the final version of the manuscript. FH did editing of the article.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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