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Environmental Conditions Affect Associations between Wheat Yield and Phenological Events

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ABSTRACT

The timing and duration of phenological events in wheat are important factors for adaptation and yield in a given environment. However, how important they are in the environmental conditions is a misunderstood issue. Associations between grain yield and phenological events in Iranian wheat cultivars were studied in Moghan region of Iran. Eighty-one wheat cultivars released from 1930 to 2006 were examined in 2010–2011 with normal sowing conditions and in 2013–2014 with late sowing conditions. Under both sowing dates, increasing anthesis thermal time up to special amount (1357 and 671 ℃ under normal and late sowing conditions, respectively) had positive effects on grain performance but these advantages disappeared with further increasing of anthesis thermal time. Grain filling duration positively correlated with grain yield under normal sowing conditions but the reverse trend was observed under late sowing conditions whereas increasing grain filling duration decreased main stem grain yield. There were positive links between spike filling rate and grain performance in both conditions tested, suggesting that spike filling rate could be a promising trait in wheat breeding program challenging with increasing grain yield.

Keywords: Anthesis, Grain Filling Duration, Grain Yield, Spike Filling Rate, *Triticum aestivum L.*

INTRODUCTION

Wheat is grown on 219 million hectares throughout the world producing approximately 716 million tons of grain. In Iran, the area under wheat cultivation during 2012/13 was 7 million hectares with a production of 14 million tonnes (FAO, 2013). Grain yield of wheat has increased noticeably from the beginning of the twentieth century. However, during the last decades, strategies of conventional breeding have been insufficient to keep improvement rate similar to the past, suggesting efficiency losses in breeding programs (García et al., 2011). Understanding agronomical, phenological, and physiological traits associated with grain yield can help wheat breeders to accelerate genetic improvement in grain yield potential.

The timing and duration of phenological events in wheat are important factors for adaptation and yield in a given environment (Motzo and Giunta, 2007). However, how important they are in the geographical positions is a misunderstood issue. In studies carried out in England, Foulkes et al. (2001) worked on six wheat cultivars under irrigated and un-irrigated conditions and reported that early flowering did help distribute water uptake more favorably towards the grain filling phase. Interestingly, Foulkes et al. (2007) using two wheat double-haploid populations (46 lines derived from crosses between Beaver × Soissons and 26 lines derived from crosses between Rialto × Spark) investigated the association of

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some phenological, physiological, and morphological traits with yield performance and stated that flowering date and grain yield had not significant associations in the first population but there was a positive relationship between these traits in the second population.

In respect to wheat life cycle length, Al-Karaki (2012) recommended selection for early maturity and long pre-heading period for the development of high yielding genotypes for the Mediterranean semi-arid area. In contrast, Akkaya et al. (2006) working on durum wheat in Turkey showed that days to maturity by the thermal time was significantly and positively correlated with grain yield over the three years of their experiments and vegetative period generally was not correlated with grain yield. These finding indicate that there are interactions between different traits associations and the environment in which these associations are studied.

There is a strong correlation between the length of the grain filling duration (GFD) and grain dry weight among wheat genotypes (Tewolde et al., 2006). Other studies showed that wheat genotypes with the highest grain dry weights had shorter duration and higher maximum rates of grain filling (Al–Karaki, 2012). Dias and Lidon, (2009) declared that in durum and bread wheat, grain filling rate (GFR) might be more important than GFD to increase the grain weight (as the GFD is more affected by the environment), particularly for regions having a grain filling duration restricted by high temperature.

Weather conditions have pronounced effects on relationships between phenological events and grain yield in wheat. Thus an association, observed between developmental phase and yield performance in one agro-ecological situation, is not necessarily similar in other situations (Joudi et al. 2014).

The objective of the present investigations was to study the associations between grain yield and phenological events in Iranian wheat cultivars grown in Moghan region of Iran under normal and late sowing conditions.

MATERIALS AND METHODS

Seventy-five Iranian bread wheat, two foreign bread wheat, and four durum wheat cultivars released from 1930 to 2006 were considered in this work (Table 1). These were commonly grown in Iran during this period and covered 90% of wheat cultivated area (Joudi et al., 2014).

Experiments were performed at Parsabad, located in the Moghan region, in northwest Iran (39º360 N, 47º570 E and 45 m a.s.l.). Parsabad has a warm mediterranean climate, with cold winters, humid spring and summers with average annual precipitation of 271 mm.

Trials were conducted over crop growing seasons 2010–2011 and 2013–2014 under well-watered conditions at the agriculture research farm of Moghan College of Agriculture and Natural Resources, University of Mohaghegh Ardabili. In the first season, the cultivars were planted on 17–19 November, 2010 as a recommended date for wheat sowing. In the second season, the wheat cultivars were sown on 11 December, 2013 as a late sowing date, in which plants were exposed to higher temperature during grain filling period. Seeding rates were adjusted by cultivar according to 1,000 grain weight to achieve a target plant number of 300 m^{-2}. The experimental design was a simple lattice (9 × 9) with two replications. Plot size consisted of 4 rows with 2 m long and 0.2 m spacing. Fertilizer applied was 200 kg ha^{-1} of diammonium phosphate and 100 kg ha^{-1} of urea before planting, and 50 kg ha^{-1} of urea top-dressed at jointing stage (Zadoks GS 31, Zadoks et al., 1974). Herbicides and insecticide were sprayed to control weeds and insects. In the 2010–2011 and 2013–2014 seasons, plants were irrigated five and four times from sowing to maturity, respectively. Approximately, 55 mm of irrigation water was applied each time.

Table(1): Wheat cultivar names, origin and released year tested at Parsabad–Moghan research station

Cultivar name	Origin	Year of release in Iran	Cultivar name	Origin	Year of release in Iran
Arta	Iran	2006	Gholestan	CIMMYT	1986
Akbari	Iran	2006	Sabalan	Iran	1981
Bam	Iran	2006	Bistun	Iran	1980
Daria	CIMMYT	2006	Kaveh	Mexico	1980
Sepahan	Iran	2006	Azadi	Iran	1979
Sistan	ICARDA	2006	Alborz	CIMMYT	1978
Moghan 3	Iran	2006	Naz	CIMMYT	1978
Stark	CIMMYT	2005	Baiat	Iran	1976
Shovamald	CIMMYT	2003	Karaj 3	Iran	1976
Pishtaz	Iran	2002	Chenab	Pakistan	1975
Dez	CIMMYT	2002	Moghan 2	CIMMYT	1974
Shahriar	Iran	2002	Arvand	Iran	1973
Shiraz	Iran	2002	Khazar 1	Mexico	1973
Crossed Falat Hamun	Iran	2002	Karaj 1	Iran	1973
Hamun	Iran	2002	Karaj 2	Iran	1973
Azar2	Iran	1999	Moghan 1	Mexico	1973
Marvdasht	Iran	1999	Inia	CIMMYT	1968
Spring BC Roshan	Iran	1998	Navid	Iran	1968
Winter BC Roshan	Iran	1998	Shahi	Iran	1967
Chamran	CIMMYT	1997	Adl	Iran	1962
Simine	Iran	1997	Khalij	Iran	1960
Shirodi	CIMMYT	1997	Roshan	Iran	1958
Kavir	Iran	1997	Sorkhtokhm	Iran	1957
Durum Yavarus	CIMMYT	1996	Shole	Iraq	1957
Zakros	ICARDA	1996	Azar 1	Iran	1956
Atrak	CIMMYT	1995	Omid	Iran	1956
Estar	CIMMYT	1995	Tabasi	Iran	1951
Alvand	Iran	1995	Shahpasand	Iran	1942
Alamut	Iran	1995	Sardari	Iran	1930
Darab 2	CIMMYT	1995	Bulani	Iran	–
Zarrin	–	1995	Somaye 3	China	–
Mahdavi	Iran	1995	Frontana	Brazil	–
Niknazhad	ICARDA	1995	Fongh	China	–
Soissons	France	1994	Crossed Alborz	Iran	–
Gascogne	France	1994	Crossed Shahi	Iran	–
Gaspard	France	1994	Verinak	CIMMYT	–
Rasul	CIMMYT	1992	DN-11	CIMMYT	–
Marun	Iran	1991	WS-82-9	–	–
Hirmand	Iran	1991	Kauz	–	–
Falat	CIMMYT	1990	Montana	–	–
Ghods	Iran	1989			

Dates of booting, anthesis, and physiological maturity were recorded. To achieve this, the plots were monitored every 2 days. Date of booting was recorded when about half of the main shoots showed emerged awns 1 cm beyond the flag leaf sheath (GS 45). Anthesis was recorded when about half of the main shoot spikes had visible anthers (GS 65). Dates of physiological maturity were recorded when peduncles on about half of the plants in plots were completely yellow. Grain filling duration (GFD) was recorded as the period from anthesis to physiological maturity. As temperatures varied between years, and with the objective of including temperature effects on the lengths of growth phases (Isidro et al., 2011), all developmental stages were expressed in the form of thermal time (TT), calculated as Σ [(Tmax+Tmin/2) –Tb], where, Tmax and Tmin are site daily maximum and minimum temperatures, and Tb is the base temperature (5°Cd).

Three main stems spike from the two middle rows of each plot were harvested at random at anthesis and physiologic maturity. The spikes immediately dried in a forced-air dryer at 70°C for 48 h to minimize respiration and weight losses. Spike filling rate (SFR) was calculated as (spike dry weight at maturity – spike dry weight at anthesis) / growing degree days (GDD) of anthesis – maturity.

In 2010–2011, grain yield was obtained from square meter. At maturity, 1 m^2 per plot sections were cut at ground level and then grain yield was obtained after threshing. In 2013–2014, since there were some sparse plots in the experiment, main stem grain yield was considered. To achieve this, ten main stems spike were taken at random at maturity, threshed and their average was obtained.

For individual experiments, analyses of variance (ANOVA) were carried out using statistical software SAS (SAS Users' Guide, 1994). Data from 1st and 2nd year were analyzed separately according to a lattice design and adjusted means were considered. Measured parameters were regressed against grain yield (gm^{-2}) in 1st year and main stem grain yield (g) in 2nd year and the best equations were fitted to the data. Relationships between traits were studied by correlation analysis. Regression and correlation analyses were performed using statistical software SPSS, version 17.0 (SPSS Base 17.0 for *Windows* User's Guide, 1998).

RESULTS

YEAR 1

Large variations were found among cultivars for grain yield; grain yield ranged from 293 to 746 gm^{-2} (Figure 1). Overall, new wheat cultivars produced more grain yield than old ones (data not shown).

The length of the sowing-booting period ranged from 1152 to 1351ºC (Table 2). Mean booting TT was 1240ºC. Relationship between booting TT and grain yield analyzed by correlation was not statistically significant (Table 4). Regression analysis showed a quadratic relationship between these parameters (Figure 1a).

The lowest and the highest values of TT from sowing to anthesis were 1287 and 1584ºC, respectively (Table 2). A clear correlation relationship was not found between anthesis TT and grain yield (Table 4). The response of anthesis TT to grain yield followed a quadratic function (Figure 1b). The grain yield was increased with the increasing of anthesis TT up to 1357ºC but declined with further increasing of anthesis TT. The earliest and the latest cultivar accumulated 2076 and 2265 ºC from sowing to maturity, respectively (Table 2). Cycle length from sowing to maturity was not significantly correlated with grain yield (Table 4). When maturity TT was regressed against grain yield, an inverted U shaped curve was fitted (Figure 1c).

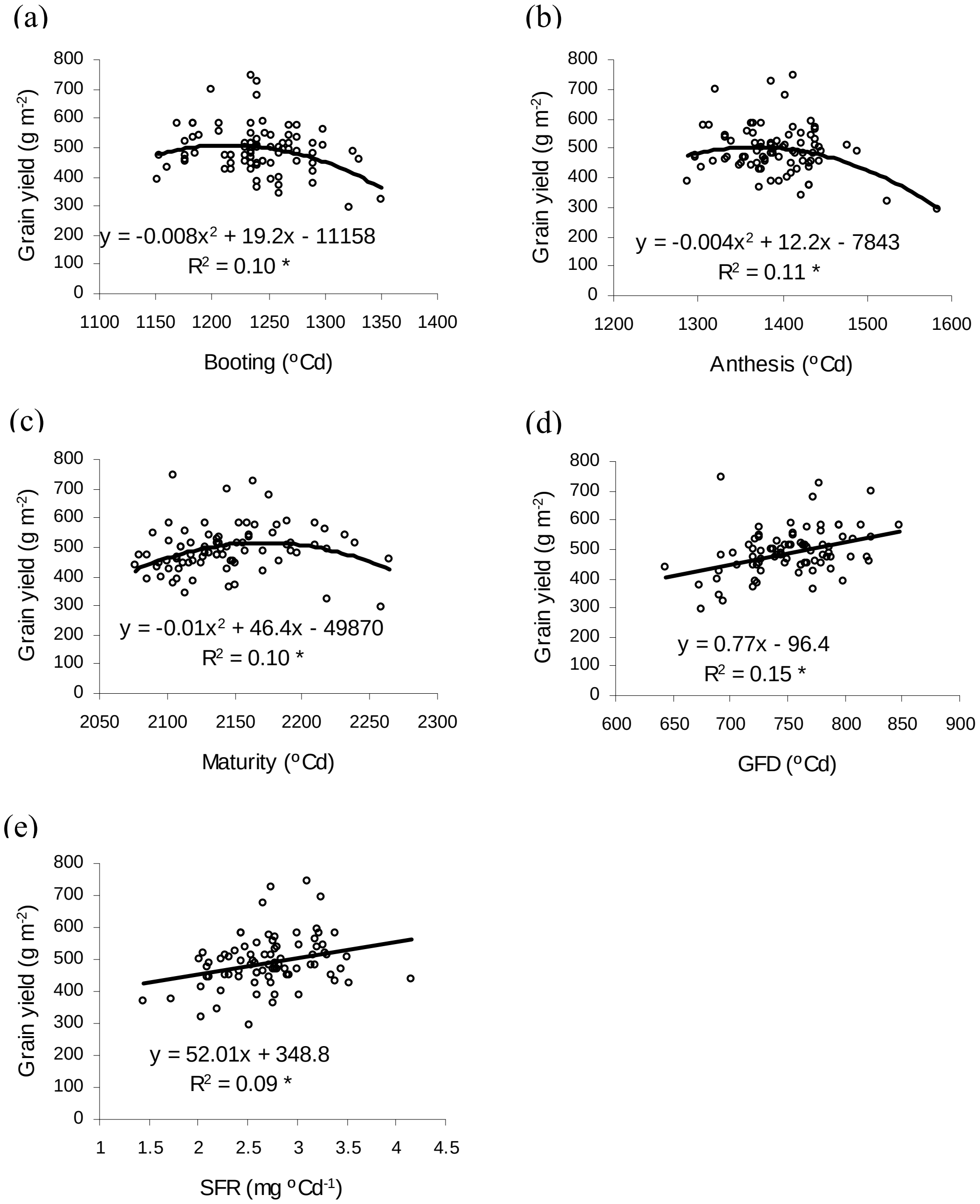

Figure (1): Relationships between grain yield and (a) booting, (b) anthesis, (c) maturity, (d) grain filling duration (GFD), and (e) spike filling rate (SFR) in Iranian wheat cultivars grown at Parsabad–Moghan in 2010–2011 under normal sowing conditions. Each point represents the mean value of one cultivar.

Grain filling duration, on average, accounted for 35% of the duration from sowing to maturity (Table 2). GFD ranged from 644 to 847 ºC. Overall, the cultivars reached anthesis earlier showed a longer duration of GFD (Data not shown). A significant positive correlation (*r* = 0.38; *P* < 0.001) was found between GFD and grain yield (Table 4). Most of the cultivars that had longer duration of GFD were higher yielding cultivars. Regression analysis showed a linear association between GFD and grain yield so that grain yield increased significantly with increasing of GFD (Figure 1d).

Wheat cultivars, on average, could accumulate 2.72 mg dry matter per ºC in their spike (Table 2). There was a close positive association between SFR and grain yield (Table 4, Figure 1e).

Table (2): Basic statistics [minimum and maximum value, mean, standard deviation (SD) and coefficient of variation (CV)] for studied traits in 81 wheat cultivars grown in the Parsabad–Moghan region with normal sowing conditions during 2010–2011 growing season.

	Grain yield (g m^{-2})	Booting (ºC)	Anthesis (ºC)	Maturity (ºC)	Grain filling duration (ºC)	Spike filling rate (mg $ºC^{-1}$)
Minimum	293	1152	1287	2076	644	1.44
Maximum	746	1351	1584	2265	847	4.16
Mean	490	1240	1392	2145	752	2.71
SD	810	41	50	42	40	0.46
CV	17	3	4	2	5	0.05

YEAR 2

Cultivars differed markedly in main stem grain yield; this trait varied from 1.02 to 2.51 g (Table 3). The amount of main stem grain yield, generally, was higher in the modern than the old cultivars (data not shown).

Under late sowing conditions, wheat cultivars reached booting with lower TT when compared to year 1. On average, TT from sowing to booting was 575 ºC, 54% lower than year 1 (Tables 2 and 3). There was a significant negative correlation between booting TT and main stem grain yield (Table 4). The regression analysis showed that relationship between booting TT and main stem grain yield was quadratic (Figure 2a).

Cultivars, on average, reached anthesis with 694 ºC, 50% less than observed in year 1 (Table 3). The differences between the highest (818ºC) and the lowest (584ºC) values of anthesis TT was 234ºC. When the relationship between anthesis TT and main stem grain yield was studied by correlation analysis, it was found that there is a negative correlation between these traits. The relationship between anthesis TT and main stem grain yield was best described by a quadratic function obtained by regression analysis (Figure 2b). Main stem grain yield increased as a function of anthesis TT when TT was below a threshold of 671ºC. Above this threshold, main stem grain yield decreased as a function of anthesis TT.

The earliest and the latest cultivars accumulated 1174 and 1366 ºC from sowing to maturity, respectively (Table 3). Maturity mean TT was 1250ºC, 42% less than observed in year 1 (Tables 2 and 3). There was a significant negative association between main stem grain yield and maturity TT, indicating that main stem grain yield decreases by increasing the value of maturity TT (Table 4, Figure 2c).

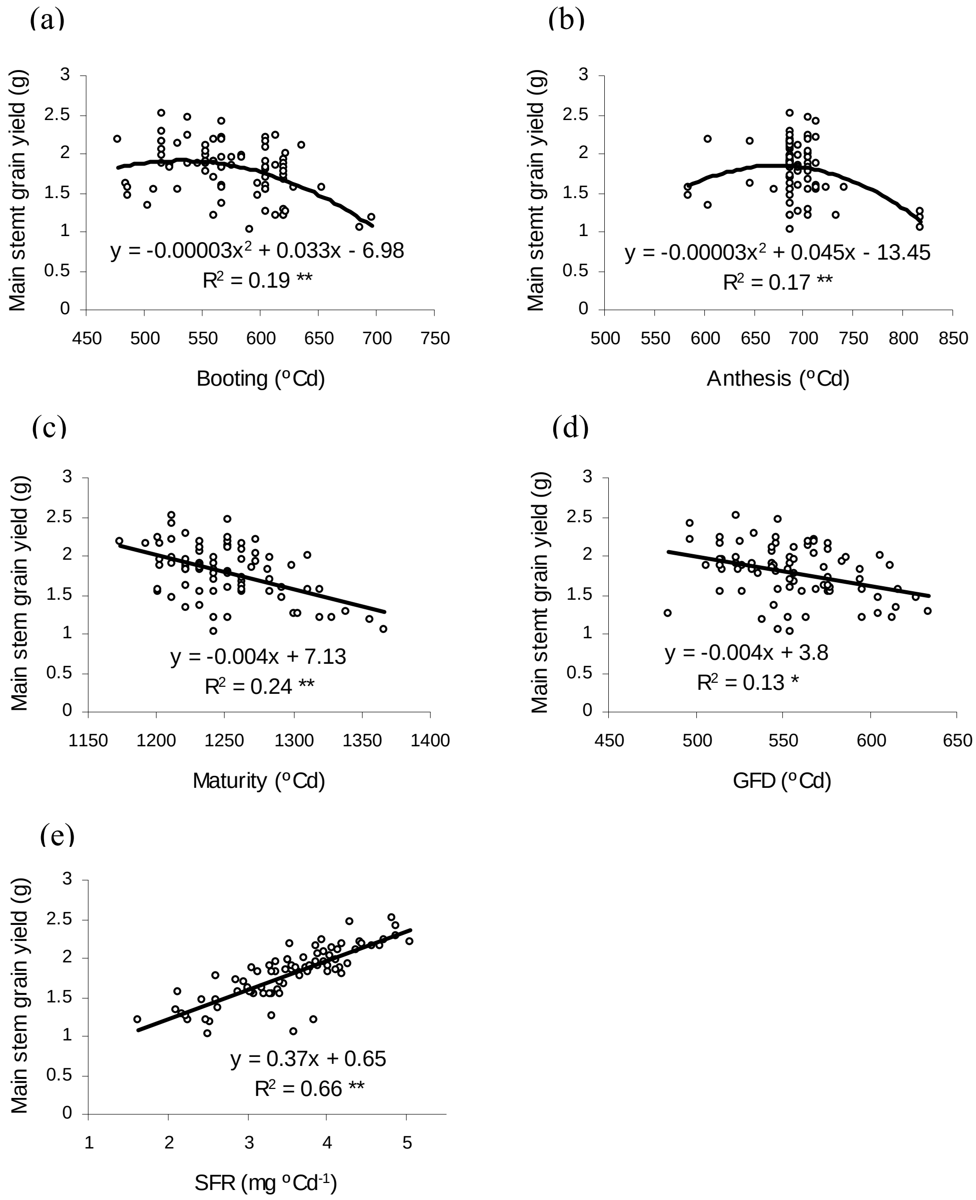

Figure (2): Relationships between main stem grain yield and (a) booting, (b) anthesis, (c) maturity, (d) grain filling duration (GFD), and (e) spike filling rate (SFR) in Iranian wheat cultivars grown at Parsabad–Moghan in 2013–2014 under late sowing conditions. Each point represents the mean value of one cultivar.

The GFP, on average, accounted for 44% of the duration from sowing to maturity (Table 3). Mean TT for GFP was 556ºC, 196ºC lower than the year 1 (Tables 2–3). Interestingly, a strong negative association was found between TT of GFP and main stem grain yield, suggesting that longer GFP would lead to reduced main stem grain yield (Table 4, Figure 2d).

The mean SFR was 3.03 mg, 10% more than observed in year 1 (Tables 2–3). Unlike to GFD, there was a strong positive association between SFR and main stem grain yield (Table 4, Figure 2e).

Table (3): Basic statistics [minimum and maximum value, mean, standard deviation (SD) and coefficient of variation (CV)] for studied traits in 81 wheat cultivars grown in the Parsabad–Moghan region with late sowing conditions during 2013–2014 growing season.

	Main stem grain yield (g)	Booting (ºC)	Anthesis (ºC)	Maturity (ºC)	Grain filling duration (ºC)	Spike filling rate (mg ºC^{-1})
Minimum	1.02	478	584	1174	484	1.13
Maximum	2.51	696	818	1366	634	4.56
Mean	1.79	575	694	1250	556	3.03
SD	0.34	46	36	39	32	0.72
CV	0.03	5.10	3.97	4.29	3.56	0.08

Table (4): Correlation coefficients among grain yield and measured traits in 81 wheat cultivars grown at Parsabad–Moghan in 2010–2011 with normal sowing conditions and in 2013–2014 with late sowing conditions.

		Booting (º C)	Anthesis (º C)	Maturity (º C)	Grain filling duration (ºC)	Spike filling rate (mg ºC^{-1})
Normal sowing condition	Grain Yield (g m^{-2})	- 0.21^{ns}	- 0.21^{ns}	- 0.10^{ns}	0.38**	0.29**
Late sowing condition	Main stem grain yield (g)	- 0.36**	- 0.20^{ns}	- 0.49**	- 0.36**	0.81**

Table (5): Number of days with daily maximum air temperature exceeding 25 or 30 ºC during grain filling duration in Parsabad-Moghan.

Season	Days number from the earliest anthesis date to the latest maturity date	Days with maximum air temperature	
		> 25 ºC (days)	>30 ºC (days)
Normal sowing conditions	47	35	9
Late sowing conditions	45	43	27

DISCUSSION

Optimizing grain yield of wheat is a main issue for many scientists and agronomist worldwide. In this respect, wheat breeders working on plant performance should pay special attention to climate changes. Future climate scenarios predict further reductions in winter rainfall and an increase in temperate and atmospheric CO_2 (cited in Ludwig and Asseng, 2010). Therefore, in order to increase the efficiency of wheat breeding programs it is necessary to link theses activities with predicted future climate changes.

Temperature is an important factor affecting the rate of plant growth and development especially at low latitudes where photoperiod-insensitive cultivars predominant. Under high temperature, the wheat plant completes its life cycle much faster than under normal temperature conditions (Kamrun et al., 2010).

Phenological traits are of critical importance as they may not only confer adaptability to particular environments but also influence yield improvement through increasing yield potential (Borras et al., 2009). However, the consistent relationship between phenological events and performance of wheat are not found and these associations vary with environment.

Our results indicated that there were large variation in time and duration of phenological events among Iranian wheat cultivars (Tables 2 and 3). Variation in duration of developmental phase could be used for different purposes. For example, a longer anthesis-maturity phase is selected to attain more grain yield under favorable environments, whereas this strategy may not be suitable for rainfed conditions in which water shortage and high temperatures hamper desired grain filling.

The timing of anthesis is one of the most important traits related to the adaptation of wheat cultivars under prevalent filed conditions in particular areas. Wheat cultivars must phase to anthesis when they have accumulated satisfied total dry matter before flowering and also have the right grain filling period. In this study, regression analysis showed that under normal sowing condition, increasing anthesis TT up to 1357ºC could increase grain yield, but further increasing anthesis TT reduced grain yield (Figure 1b). It seems that up to the certain amount of anthesis TT, the net benefits of pre-anthesis total dry matter accumulation on grain yield are more than the advantages of grain filling period. Later on, however, the plants need enough grain filling periods to fill the formed grains by current photosynthesis and remobilization of stored carbohydrates. Interestingly, under late sowing conditions, lengthening anthesis time up to 671ºC had positive effects on main stem grain yield. Afterwards, increasing anthesis TT had negative effects on main stem grain yield (Figure 2b). The advantages of definite lengthening of anthesis TT under late sowing conditions might come directly by increasing grain number per spike or indirectly by accumulating dry matter and then remobilizing it to the grain. Further increasing of anthesis TT exposes anthesis and GFP stages to higher temperature and decreases main stem grain yield.

Rate and duration of grain filling determine final grain dry weight which is a major component of grain yield in wheat (Duguid and Brûlé-Babel, 1994). Our results showed that in Moghan region with normal sowing conditions, increased grain filling duration will result in increased grain yield. However, such an association is not true for late sowing conditions (Table 4, Figure 1d and 2d). The possible explanation for the negative association between GFD and main stem grain yield in year 2 could be attributed to the prevalence of air temperature during grain filling. Table 5 shows that the number of days with maximum air temperature exceeding 25 or 30 ºC during GFP are higher in year 2.

Therefore, wheat cultivars in year 2 were exposed more to higher temperature stress during grain filling than those in year 1.

Since there is no further significant increase in chaff weight (i. e. rachis and glumes without grain) after anthesis (Ehdaie et al., 2008), the differences of spike dry weight at anthesis and maturity could be an indication of partitioned dry matter to the grain during anthesis–maturity. Interestingly, there were close positive relationships between grain yield and SFR or GFR in both years (Table 2). These results are in line with results of Dias and Lidon (2009) who believe that GFR in wheat is determined by genotypes, whereas environmental factors such as temperature affect the duration of grain filling period.

CONCLUSION

Our studies in Moghan region of Iran clearly showed that association between yield performance and phenological events varied with environment. For example, a significantly positive correlation was found between grain yield and grain filling duration (GFD) under normal sowing conditions. In contrast, main stem grain yield was correlated negatively with GFD under late sowing conditions. Regression analysis revealed that the associations between yield performance and developmental phases do not follow simple relationships in a given region. It suggests that if altering phenology is to be achieved, it is necessary to determine an optimum amount of growing degree days (GDD) which would lead to higher grain yield for each phenol-phase. This special amount of GDD (which is cultivar and phenol-phase specific) varies under different environmental conditions. The current work showed that under normal sowing conditions, increased GFD and grain filling rate (GFR) would result in improved grain yield. However, under late sowing conditions, where grain filling takes place under higher air temperature, the increased GFR will accompanied with higher yield performance.

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الظروف البيئية التي تؤثر على الارتباط بين محصول القمح والأحداث الفيزيولوجية

مهدي جودي[1]✉

ملخص

إن توقيت ومدة الأحداث الفيزيولوجية في القمح من العوامل الهامة للتكيف ومردود الإنتاج في بيئة معينة. ومع ذلك، مدى أهمية وجودهم في الظروف البيئية هي مسألة يساء فهمها. تم دراسة الارتباط بين محصول الحبوب والأحداث الفيزيولوجية في أصناف القمح الإيرانية في منطقة موجافي إيران. تم فحص (81) صنفا من أصناف القمح التي تم إصدارها ما بين الأعوام 1930–2006 في الفترة 2010–2011، مع ظروف زراعة البذار الطبيعية في 2013–2014 و ظروف البذر في وقت متأخر. في كلا مواعيد زراعة البذار، وزيادة الوقت الحراري لفترة أزهار المتوك الذكرية ما يصل إلى (1357 و 671 درجة مئوية تحت ظروف الزراعة الطبيعية والمتأخرة، على التوالي)، كان لها آثار إيجابية على أداء الحبوب ولكن اختفت هذه المزايا مع مواصلة زيادة مدة الزمن الحراري وقد لوحظ أن مدة فترة ملء الحبوب ارتبطت ارتباطا إيجابيا مع محصول الحبوب في ظل ظروف البذر الطبيعية. ولكن الاتجاه كان عكسيا في ظل ظروف البذر في وقت متأخر بينما كانت زيادة فترة ملء الحبوب قد عملت على تخفيض محصول الحبوب الرئيس. هناك روابط إيجابية بين ارتفاع معدل ملء سنابل القمح وأداء الحبوب في كلا الظروف التي تم فحصها، مما يشير إلى أن معدل ملء سنابل القمح يمكن أن يكون سمة واعدة في برنامج تربية القمح و يكون منافسا مع زيادة محصول الحبوب.

الكلمات الدالة: أزهار المتك الذكري، مدة ملء الحبوب ، محصول الحبوب، ارتفاع معدل ملء السبلة، القمح الطري *Triticum aestivum* L.

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