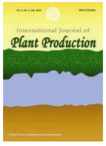

International Journal of Plant Production 7 (4), October 2013
ISSN: 1735-6814 (Print), 1735-8043 (Online)
www.ijpp.info

GUASNR

Relationship of base temperature to development of winter wheat

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Received 7 February 2013; Accepted after revision 6 July 2013; Published online 21 August 2013

Abstract

Development of wheat (*Triticum* spp.) is primary driven by temperature, but is also affected by other factors such as vernalization and photoperiod. Crop growth and development are often described in terms of calendar days. However, determining the development in terms of thermal time or physiological time is more accurate because it is an accumulation of the caloric energy needed for the occurrence of phenological stages. The objectives of this study were: (i) to determine the base temperature for key phenological stages of different winter wheat cultivars and (ii) to develop a phenological model using the base temperature for predicting the duration in terms of thermal time for different phenological stages. Eight wheat cultivars were selected according to their vernalization period to determine the base temperature for three critical developmental phases, i.e., planting to heading, heading to harvest and planting to harvest. For each cultivar, the base temperature for each critical period was estimated as well as the duration of the three key phenological stages in terms of thermal time for three locations in Georgia from 1999 to 2010. The base temperatures and the growing degrees varied widely depending both on the developmental stage and the cultivar. The estimated base temperatures for the eight wheat cultivars ranged from 3.1 to 8.1 ^{o}C, 10.6 to 18.4 ^{o}C and 1.6 to 8.4 ^{o}C, for planting to heading, heading to harvest maturity and planting to harvest maturity. Also, the duration in Growing Degree Days (GDD) was determined for each season and cultivar. When 0 ^{o}C was used as the base temperature, the GDD between cultivars varied from 1675-1844, 1017-1239 and 2827-2936 ^{o}C from planting to heading, heading to harvest maturity and planting to harvest maturity, respectively. The results from this study provided specific base temperatures for each developmental stage for each individual cultivar and, therefore, provided a more accurate estimation of GDD. The variation in base temperature and GDD accumulation is probably a selective advantage for winter wheat. Clearly more work is required to estimate the base temperatures and duration for others phenological stages and further evaluation is required for additional cultivars and a wider range of environments.

Keywords: Growing degree days; Development; Phenology.

Introduction

Temperature is one of the main driving forces for wheat growth and development and several phenological stages are manifested throughout its development. Phenology is commonly described as the changes that occur from emergence to harvest maturity and how these changes are affected by local environmental conditions. It is considered an important component in crop adaptation to local environmental conditions, and both season duration and the length of the phenological stages are important determinants of grain yield. The beginning and the ending of these stages are good indicators of potential crop growth (Anderson et al., 1978; Calviño et al., 2003; Schwartz, 1999). The effect of temperature on phenology and growth of crops has been studied under field condition through the determination of accumulated heat units. Each plant has a specific temperature requirement before certain phenological stages are attained (Sikder, 2009). Wheat is one of the most adapted species that grows in a wide range of environments, mainly because of its ability to resist low temperatures. Survival is accomplished primary through the process of cold acclimation or hardening. However, in winter wheat the cold acclimation process is genetically controlled (Briggleand Curtis, 1987; Fowler, 2008). Winter wheat phenology responds to many environmental variables and clearly temperature is the most dominant factor (Mc Master et al., 2012).

Precise estimation of crop phenology is a critical component of dynamic crop simulation model in order to be able to assess the sustainability of crop production in different environments or the impact of climatic change on wheat productivity and quality (He et al., 2012; Saiyed et al., 2009). Crop growth and development are often described in terms of calendar days and calendar time has been used for prediction of developmental stages (Slafer et al., 1991). However, several models have been proposed that describe the effect of temperature on phenological development as improvements on the use of calendar time for predicting development (Warrington and Kanemasu, 1983a; Warrington and Kanemasu, 1983b). One of the most extensively used method is the accumulation of daily mean temperature above a base temperature (T_b) (Monteith, 1984), known as degree days or thermal time (physiological time). This approach is more appropriate for describing development, since it is independent of environment or year (Ritchie and Ne Smith, 1991). A basic requirement for this approach is the determination of the critical temperature below which phenological development ceases, referred to as the base temperature (T_b) (Steinmaus et al., 2000). The accuracy of a thermal time model to predict the date of different developmental stages is partially dependent upon the accuracy of the determination of the base temperature (Morrison et al., 1989). Therefore, thermal time models for predicting phenological development require an accurate of the base temperature.

The concept of base temperature can be described either physiologically or statistically (Yang et al., 1995). The frequent differing T_b estimations between biological and mathematical models suggest that factors other than temperature that control plant growth are not properly taken into account in mathematical approaches (Arnold, 1959). Physiologically, it is assumed that below a certain temperature, crop growth and development cease, but this temperature can differ based on the particular physiological process. The T_b can be determined experimentally, based in part on complete cycle of growth and development of the crop. An accurate method for determining base temperature is to grow plants in controlled environments across a range of constant temperatures and to measure the rate of appearance of different organs of the plant following its developmental stage in each regime (Slafer and Rawson, 1995; Campbell et al., 1996; Qi et al., 1999). It is assumed that each developmental phase may have a different base temperature and the base temperature should be similar for a given crop developmental stage for any growing season. Statistically several methods can be used for estimating T_b. Some of the common are: the least standard deviation (SD) in GDD, the least SD in days, the least coefficient of variation (CV) in GDD and linear regression using the regression coefficient and the x-intercept methods (Arnold, 1959; Yang et al., 1995; Oliveira et al., 1998). Statistically, the base temperature is that which results in the lowest variation in GDD accumulation or Thermal Time (TT) which is a measure of heat that has accumulated overtime (Yang et al., 1995). The accumulated temperature is now recognized as the main factor influencing year-to-year variation in phenology. Increasing temperatures in general accelerate phenological development, which results in a shorter growth period (Asseng et al., 2011).

Growing degree-days (GDD) are generally used to include the temperature effects and describe the timing of biological processes (Baker et al., 1984; Mc Master and Wilhelm, 1997).

GDD also vary with growing stage and allow for a rough estimation of the time at which a given growth stage is going to occur for a particular location (Fischer et al., 1976). Research has shown that the growing degree days and the accumulated TT for attainment of the phenological stages differ from cultivar to cultivar (Trudgill et al., 2005). Two basic assumptions considered in this study were: i) cultivars have different base temperatures for growth and development (Montieth, 1984) and ii) differential growth response to temperature exist among cultivars (Mann et al., 1985; Porter and Gawith, 1999).

For wheat the use of a base temperature of 0 ^{o}C independent of the phenological stage has been most common (Undersander and Christiansen, 1986; Stapper and Harris, 1989). However, when a base temperature was determined for a particular period (e.g. from floral initiation to anthesis) different values other than 0 ^{o}C have been reported (Angus, 1981; Midmore et al., 1982). Furthermore, the base temperature of wheat was observed to increase with plant age (Angus, 1981; Schafer and Savin, 1991). The objectives of this study were: (i) to determine the base temperature for key phenological stages of different winter wheat cultivars and (ii) to develop a phenological model using the base temperature for predicting the duration in terms of thermal time for different stages in the southeastern US.

Materials and Methods

The proposed phenological model for winter wheat *(Triticum aestivum* L.) consists of two components. The first one includes the estimation of the base temperature for each cultivar for three different phenological periods; and the second component is the estimation of the duration in growing degree days for predicting the heading and the harvest date. Inputs to the model include planting date and recorded heading and harvest dates (actual day of harvest) and the daily weather data, including maximum and minimum temperatures (^{o}C) for each location. There was not information available regarding vernalization for this study and, therefore, for this reason this component was not considered in this model. The photoperiod was also not taking into account due to little impact since the locations are positioned at the same latitude and longitude so there would only be a very small impact (Table 1).

Table 1. Description of the cultivars of winter wheat (*Triticum aestivum* L.) used in the study.

Cultivar	Vernalization period	Relative maturity
AGS2000	Medium	Medium
AGS2031	Medium/Long	Medium
AGS2020	Short	Early/Medium
PIONEER-26R12	Long	Late
PIONEER-26R61	Medium	Medium
Roberts	Long	Late
SS8641	Medium	Medium
UGS3592	Long	Medium/Late

The phenological data for eight winter wheat cultivars that are currently grown commercially in the southeastern U.S. were analyzed and the cultivars were selected according to their vernalization period (Table 1). The dates of planting, heading and harvest were obtained from three locations in the southeastern USA (Table 2). The heading date was recorded when the head (spike) of 50% of the wheat plants had appeared from the flag leaf. The period of record for these locations ranged from 1999 to 2010 (Table 3). The data were obtained from the Georgia Cooperative Extension Service (http://www.caes.uga.edu/extension) and the commodity specialist web site of the University of Georgia (http://www.caes.uga.edu/commodities/). The weather data were obtained from the automated weather stations of the Georgia Automated Environmental Monitoring Network (AEMN; www.Georgiaweather.net) for each location.

Table 2. Planting window, elevation, latitude and longitude of the study locations.

Location name	Planting window	Elevation (m)	Latitude	Longitude
Griffin	26 Oct-10 Nov	285	33° 26’ N	84° 28’ W
Plains	10 Nov-26 Nov	158	32° 05’ N	84° 37’ W
Tifton	10 Nov-26 Nov	118	31° 49’ N	83° 53’ W

Table 3. Years during which development was observed for each cultivar for the three locations.

Cultivar	Griffin	Plains	Tifton
AGS2000	1999-2008	1999-2007	1999-2007
AGS2031	2002-2009	2002-2009	2002-2009
AGS2020	2004-2009	2004-2009	2004-2009
PIO26R12	2002-2008	2002, 2004-2008	2002, 2004-2008
PIO26R61	1999-2008	1999-2010	1999-2010
Roberts	1999-2007	1999-2007	1999-2007
SS8641	2003-2010	2004-2009	2004-2009
UGS3592	2000-2008	2000-2008	2000-2008

Base temperature estimation

The base temperatures (T_b) for three key phenological stages of wheat were estimated from planting to heading (P_l-H_d), heading to harvest (H_d-H_v) and planting to harvest (P_l-H_v), for each cultivar and season by determining the heat sum and then minimizing the variance or the standard deviation of the heat sums calculated from a range of temperatures from 0 to 23 ^oC for the different stages considered in this study. 0 ^oC is normally assumed to be the base temperature for wheat. The temperature at which the variance or the standard deviation was smallest using a second degree regression model was assumed to be the optimum temperature for that stage (Salazar, 2006; Pulido et al., 2008; Anderson, 1978; Ruml et al., 2010). The program Solver, an add-in for Excel, was used for the estimation of T_b. Solver is an iterative nonlinear procedure that starts with the initial estimates of the parameter values and then either increases or decreases the parameter until it finds the minimum value of the sum of squares of the deviations (Salazar, 2006).

Growing Degree Days estimation

Degree days is a measurement unit that combines temperature and time such that the development duration of an organism's life cycle, or any stage or portion of the life cycle, decreases as the temperature increases. It is expressed as the number of heat units required to complete development. Although temperatures and days may vary, the physiological time remains relatively constant. It is the simplest model to account for the temperature effect on vegetative and reproductive development and has some limitations for extreme high temperatures. Modified versions of the degree-day model exist that include an optimum temperature above which the rate of development does not increase and remains constant when the temperature increases above the optimum temperature or are based on four cardinal temperatures that define the temperature range under which development can occur. A degree day is accumulated when the average daily temperature is one degree above the T_b for a 24-hour period. In order to track crop development, a reference day or starting date is crucial. In this study the starting date was defined as the planting date for each individual cultivar for each season and each location.

The duration of each phase in growing degree days (GDD) was determined using the T_b that was estimated for each cultivar and for each of the three development phases. It was compared with T_b=0 ^oC which is the common temperature that has been used for estimating GDD for wheat (McMaster and Wilhelm, 1997). The thermal time was calculated as the summation of the difference between the average temperature and the base temperature for each stage Eq. (1).

$$TT = \sum_{i=1}^{n} (T_i - T_b) \tag{1}$$

Where, *TT* is the thermal time (^{o}Cd) accumulated during the *n* days until the stage appears, for the three stages (from planting to heading stage=1, heading to harvest stage=2 and planting to harvest stage=3), T_i is the daily average temperature for day *i* and T_b is the base temperature. The GDD for the *TT* accumulation were estimated using the following considerations:

$$T_i = (T_{\max} + T_{\min})/2 \tag{2}$$

$$T_i - T_b \quad when \quad T_i > T_b \tag{3}$$

$$T_i = 0 \quad when \quad T_i < T_b \tag{4}$$

where T_i is the daily average temperature for day *i*, T_b is the base temperature, T_{max} is the maximum temperature for day *i* and T_{min} is the minimum temperature for day *i*.

The model was developed applying the growing degree days concept, using a set of random data for each cultivar and for three locations, the summation of the temperature using T_b=0 were averaged for the duration from the planting date to the heading date and from the heading date to the harvest date for consecutive seasons. Then the average of TT obtained was used to evaluate the model for the remaining data. The same procedure was applied using the T_b estimated for each cultivar, stage and season.

Regression between observed and simulated values with both T_b=0 and T_b estimated were applied. For the cases where these regression models were significant ($P<0.05$), t-tests were conducted to determine whether the slope and intercepts were significantly different from 1.0 and 0.0, respectively. The determination coefficient (r^2), the Agreement Index (*d*) Eq. (5) and regression root mean square error (RMSE) Eq. (6) were calculated to determine overall model performance (Willmott, 1982). A descriptive statistical analysis was also performed using SAS Version 9.2 (SAS Institute, 2009).

$$d = 1 - \left[\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} (\left|P_i'\right| + \left|O_i'\right|)^2} \right], \quad 0 \le d \le 1 \tag{5}$$

where (n) is the number of observations, (P_i) the predicted value for the i^{th} date and (O_i) observed value for the i^{th} date, $P_i' = P_i - \overline{O}$ and $O_i' = O_i - \overline{O}$, the overall mean of observed values is $\overline{O}$:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{n}} \tag{6}$$

where (n) is the number of observations, (P_i) the predicted value for the i^{th} date and (O_i) observed value for the i^{th} date.

Results and Discussion

Differences in the heading dates for the wheat cultivars were detected for the three locations (Figure 1). In general, heading occurred earlier in Tifton compared to Plains and Griffin for all the years that were studied. The temperature among locations indicated that the average mean temperature was higher in Tifton, followed by Plains and then Griffin. Therefore, there was a temperature effect on heading appearance that explained why in Tifton heading occurred earlier when compared to the other locations (Table 4). A significant increase in temperature occurred at the beginning of spring (around March) until the end of the growing season (end of April) (Figure 2). March and April were the months where the highest temperatures were reported for all three locations and which were the months where the earliest heading occurred (Table 4).

The average temperature across years for the complete season (planting to harvest) was 10.5 ^oC (SD=3.8 ^oC), 11.9 ^oC (SD=3.7 ^oC) and 13.3 ^oC (SD=3.5 ^oC) for Griffin, Plains and Tifton, respectively. In general the coldest years were 2001, 2003, 2009 and 2010, while the warmest years were 2000, 2002 and 2006 for all three locations. The coldest month for the wheat growing season was January, ranging from 3.4 ^oC to 10.2 ^oC, 6.1 ^oC to 11.9 ^oC and 7.2 ^oC to 12.8 ^oC for Griffin, Plains and Tifton (Table 4).

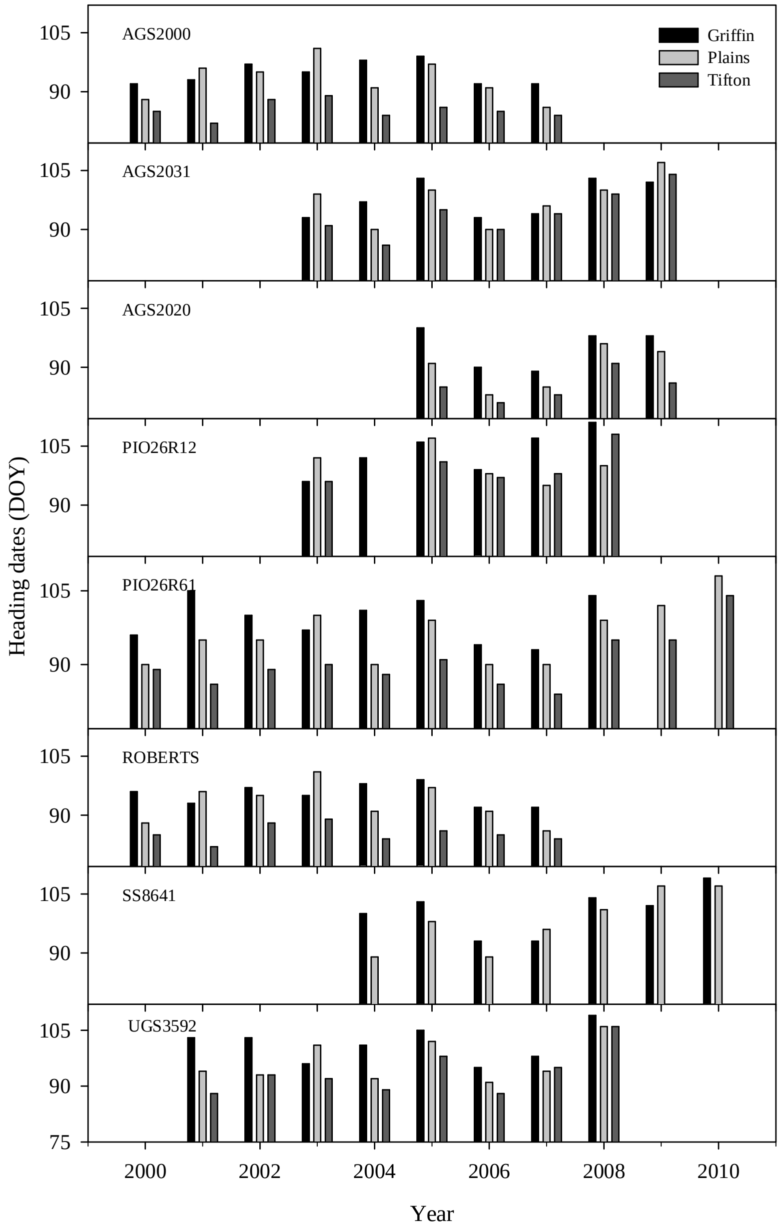

Figure 1. Winter wheat heading dates (as day of year DOY) for the three locations. Each panel shows heading date for each cultivar for the 2000 to 2010 seasons.

Table 4. Monthly and seasonal average temperature from 1999-2010 for the three locations.

Temperature (^oC)							
Year	Nov	Dec	Jan	Feb	Mar	Apr	Average
Griffin							
2000	12.9	8.0	6.5	10.3	14.2	14.7	11.1
2001	10.5	2.3	5.3	10.5	10.2	17.2	9.3
2002	14.5	9.6	8.2	7.5	12.9	18.6	11.9
2003	10.1	6.2	4.4	8.1	13.2	16.4	9.8
2004	14.0	5.6	5.9	6.3	14.6	16.6	10.5
2005	12.9	6.8	8.3	9.6	11.1	15.5	10.7
2006	12.8	5.9	10.2	7.5	12.6	18.9	11.3
2007	11.2	9.7	7.7	7.0	15.2	15.1	11.0
2008	11.4	10.3	5.8	9.6	12.3	16.3	10.9
2009	9.8	9.3	6.7	8.7	12.4	16.0	10.5
2010	11.6	5.8	3.4	4.0	10.1	18.2	8.9
Average	12.0	7.2	6.6	8.1	12.6	16.7	10.5
Plains							
2000	13.4	8.9	7.9	11.3	15.0	15.9	12.1
2001	12.1	4.4	6.3	12.1	11.3	17.9	10.7
2002	15.8	10.8	9.0	8.2	13.9	19.9	12.9
2003	11.5	7.8	6.1	10.1	15.1	17.8	11.4
2004	15.1	7.0	7.8	8.0	15.4	17.6	11.8
2005	14.6	8.3	9.8	11.3	12.5	16.4	12.1
2006	14.3	7.7	11.9	9.3	14.1	20.0	12.9
2007	12.5	11.2	9.7	8.9	16.2	16.7	12.5
2008	12.6	11.5	6.9	10.6	13.5	17.2	12.1
2009	11.0	11.0	8.3	9.4	13.2	16.6	11.6
2010	12.9	8.4	5.7	6.1	11.5	18.9	10.6
Average	13.3	8.8	8.1	9.6	13.8	17.7	11.9
Tifton							
2000	15.2	10.8	9.8	13.0	16.8	17.5	13.8
2001	13.8	6.9	8.2	14.2	13.5	19.1	12.6
2002	17.0	13.0	10.9	10.3	15.9	21.1	14.7
2003	12.9	9.3	7.2	11.3	16.2	18.8	12.6
2004	16.2	8.6	9.4	9.5	16.5	18.3	13.1
2005	15.5	9.6	11.1	12.0	13.6	16.9	13.1
2006	15.8	9.0	12.8	10.6	15.2	20.5	14.0
2007	13.5	13.1	11.0	10.2	16.7	17.7	13.7
2008	13.9	13.5	8.7	12.3	14.5	18.4	13.5
2009	12.6	12.9	10.0	10.6	14.9	18.3	13.2
2010	14.2	10.1	7.1	7.4	12.4	19.4	11.8
Average	14.6	10.6	9.7	11.0	15.1	18.7	13.3

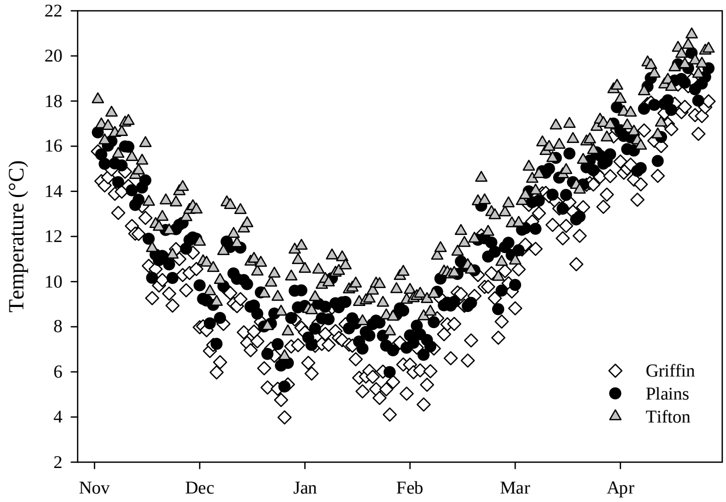

Figure 2. Daily average temperature from 1999 through 2010 for the three locations during the growing season for winter wheat.

The heading dates were different among cultivars. In general, the earliest heading date was observed for the cultivar AGS2020 for all three locations, while heading was delayed for the cultivar PIO26R12 followed by the cultivars UGS3592 and Roberts. Thus, if the temperature pattern during the winter wheat growing season is similar over many growing seasons, the same cultivar should show similar phenology and have similar heading dates independent of the growing season (Hu Qi et al., 2005). In contrast, changes in the heading or flowering date would indicate changes in temperatures, particularly during spring.

Base temperature estimation

Models for phenological development prediction require an estimation of base temperature (Roché et al., 1997). The least variance method was used, which is a relatively easy method for estimating the base temperatures (Yang et al., 1995). The results showed that the T_b varied depending on the development stage of the crop and cultivars. The standard deviation (SD) of the heat sum accumulation for the estimation of T_b i.e. for heading to harvest, is shown in Figure 3. We noticed in our study and the study of Yang et al. (1995) that SD and the variance method produced the same results with respect to the estimation of T_b. The lowest T_b value from planting to heading was found for AGS2020 (T_b=3.1 °C), in contrast to the cultivar UGS3592 that had the highest value (T_b=8.1 °C) (Table 5). The lowest base temperature estimated from planting to heading was related to the short vernalization characteristic of AGS2020 and the highest temperature estimated from planting to heading was associated with the long vernalization characteristics of UGS3592. It is well known that vernalization is cultivar-specific (Mc Master et al., 2008; White et al., 2008) and that its major effects are the reduction of the duration from the end of the low temperature treatment to flowering and to shorten the duration of phenological phases (Levy and Peterson, 1972; Robertson et al., 1996).

The estimated T_b from planting to heading ranged from 3.1 °C to 8.1 °C for the eight cultivars studied, while the estimated T_b from heading to harvest ranged from 10.6 °C to 18.4 °C and from planting to harvest ranged from 1.6 °C to 8.4 °C (Table 5). This showed that T_b is not constant throughout the vegetative and reproductive stages and that, therefore, the use of one value is not appropriate (Slafer and Savin, 1991). In wheat, it has been common to use a base temperature of 0 °C irrespective of the phenological stage (Baueret al., 1984; Frank and Bauer, 1984; Ritchie and Otter, 1984; Klepper et al., 1988; Stapper and Harris, 1989). Several studies have reported different base temperatures for the different phenological stages of spring and Mediterranean wheat. Among six spring wheat cultivars the base temperatures ranged from 1.2 to 1.6 °C (Seefeldt et al., 2002). Angus et al. (1981) observed that base temperatures varied from 2.6 °C to 8.9 °C for spring wheat. Different base temperatures ranging from 4 °C to 9.5 °C were reported for Mediterranean wheat at different phenological stages (Slafer and Savin, 1991). Porter et al. (1987) also reported base temperature values for wheat of T_b=0.1 °C; 2 °C; 3.5 °C and 5.7 °C for different developmental stages. After heading until harvest, the base temperature estimated in this study increased for all the cultivars, from 10.6 °C to 18.4 °C. This increase can be explained by the fact that T_b is highest during those phases of development that have the most active metabolic activity such as grain filling (Wilhelm et al., 1999; Slafer and Savin, 1991). It could also mean that T_b indicates an adaptation to low temperatures during early developmental prior to flowering and to higher temperatures during the reproductive phases and especially grain filling (Angus et al., 1981). Numerous studies in wheat have indicated an inverse relationship between temperatures over 15 °C and duration of grain filling (Spiertz, 1974; Chowdhury and Wardlaw, 1978; Wiegand and Cuellar, 1981; Sayedand Ghandorah, 1984; Vos, 1981). Hunt et al. (1990), describe that high post anthesis temperatures is one of the factors that determines the final grain mass and the rate of grain filling (Spiertz, 1974; Wardlaw et al., 1980). Consequently, final grain mass in wheat decreases with post anthesis temperatures over 15 ^{o}C (Sofield et al., 1971; Wardlaw et al., 1980; Wiegand and Cuellar, 1981; Sayed and Ghandorah, 1984). However, Hunt determined experimentally that, if the temperature increase from 15/15 ^{o}C to 20/15 ^{o}C, final kernel weights increased in some cultivars, decreased in others and were unaffected in yet others.

Heading and flowering dates are affected by genetics and environmental conditions (Zhang et al., 2008). A strong interaction between genetics and the temperature occurs when the crop is exposed to low temperatures during vegetative and reproductive development and which is affected by sowing date, seeding rate, fertilizer applications, irrigation and fluctuations in short-term weather and long-term climate conditions (Hu Qi et al., 2005). Base temperature estimation based on cultivar genotypes is promising for future studies that include its response in combination with vernalization, photoperiod and thermal development rates. The results from this study showed that the base temperature is not constant throughout the different stages for winter wheat and that the use of a single value of 0 ^{o}C it is not recommended, which is in agreement with Schafer and Savin (1991).

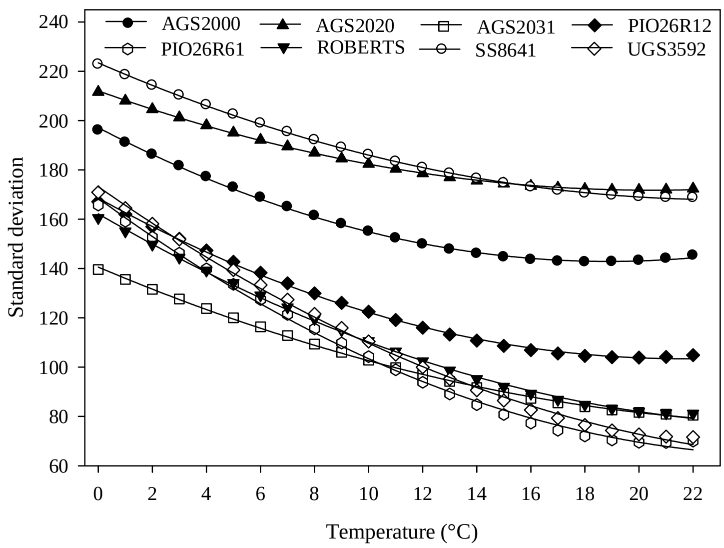

Figure 3. Standard deviation of the heat sums for the different temperatures used for the estimation of the base temperature for each cultivar.

Table 5. Estimated base temperature for the period from planting to heading (P-H), heading to harvest ($H\text{-}H_v$) and planting to harvest ($P\text{-}H_v$).

Cultivar	Temperature (°C)		
	P-H	$H\text{-}H_v$	$P\text{-}H_v$
AGS2000	4.0	17.4	8.2
AGS2031	4.2	17.4	5.3
AGS2020	3.1	10.6	1.6
PIO26R12	5.3	18.4	6.3
PIO26R61	5.2	17.4	8.4
Roberts	7.5	17.4	8.4
SS8641	5.4	17.4	7.3
USG3592	8.1	18.4	8.4
Average	5.4	16.8	6.7

Growing Degree Days estimation

Similar to other studies, the cultivars differed in the number of days and thermal time required to reach heading and harvest. Two different base temperatures were used for GDD accumulations, i.e. T_b=0 and T_b estimated for the each cultivar and growth stage (Table 6). Based on T_b=0, winter wheat cultivars required an average of 1605 to reach heading from the planting day and an average of 1110 from heading to accomplish harvest. However, when an estimated base temperature was applied for each cultivar, the average of GDD to complete heading from planting day was 886 and to complete harvest from heading was 222 from heading to harvest. In general the time required to attain heading from planting in calendar days varied from 142 to 154 with an average of 147 days for all cultivars (Table 6).

When 0 °C was used as the base temperature, the lowest GDD requirement was for AGS2000 and AGS2020, with an average accumulation for all seasons and years that were considered of 1534 °C and 1553 °C, respectively. However, AGS2020 is well known as an early maturing cultivar and AGS2000 is a medium maturing cultivar, both cultivars accumulated similar GDDs. This is in contrast to PIO26R12, which is a late maturing cultivar and requires more time to reach maturity with a GDD requirement of 1711 °C (Lee et al., 2007).

From heading to harvest, AGS2020 required more time to mature and accumulated 1239, followed by AGS2000 and PIO26R61. ROBERTS is considered as a medium long maturity cultivar and required slightly more GDD to fully develop.

Table 6. Average of GDD accumulated using T_b=0 and estimated base temperatures for each stage in winter wheat. *DAP* days after planting, *DAH* days after heading, *SD* standard deviation.

Cultivar	Planting to Heading					Heading to Harvest					Planting to Harvest				
	GDD	SD	DAP	GDD	SD	GDD	SD	DAH	GDD	SD	GDD	SD	DAP	GDD	SD
	T_b=0 °C			*T_b estimated		T_b=0 °C			*T_b estimated		T_b=0 °C			*T_b estimated	
AGS2000	1534	155	143	997	139	1152	162	58	186	46	2686	199	201	1182	147
AGS2031	1614	172	148	1028	151	1095	124	55	181	45	2709	215	202	1209	169
AGS2020	1553	102	142	1131	92	1239	157	63	576	92	2792	189	205	1708	143
PIO26R12	1711	176	154	953	145	1017	144	50	136	42	2729	228	203	1089	163
PIO26R61	1582	149	146	884	127	1111	161	55	189	47	2693	202	201	1073	137
Roberts	1588	179	146	628	132	1098	148	55	180	44	2686	199	201	808	142
SS8641	1620	164	149	879	137	1090	137	54	187	43	2710	210	203	1066	145
UGS3592	1635	197	150	588	133	1075	161	53	144	42	2710	210	203	732	144
Average	1605	162	147	886	132	1110	149	55	222	50	2715	206	202	1109	149

* T_b estimated for each cultivar and each stage.

Heat unit requirements to produce a mature crop are approximately 1550 GDD for spring and 2200 GDD for winter wheat (Fowler, 2002). In our study for winter wheat the average GDD requirements from planting to heading was 2705. There are large variations in temperature from day to day and growing season to growing season. The use of thermal time rather than calendar time takes this variability into consideration and provides an explanation for differences in crop maturity when observations from different years are compared (Fowler, 2002). The results indicated that the number of days required for attaining heading from planting ranged from 149 to 197 days, heading to harvest ranged from 50 to 63 days and the complete cycle ranged from 201 to 205 days (Table 6). The heading or flowering date of winter wheat is mainly a function of spring temperatures (Xue et al., 2004; Hu et al., 2005). Earlier heading or flowering dates indicate warmer spring season temperatures in the region. Thus, a phenological adaptation occurs when breeding techniques are applied reducing the duration of the entire biological cycle, for instance for durum wheat. This is manifested by the shortening of the developmental phases, affecting the period between sowing and anthesis. More time and heat required to reach harvest also could suggests that a crop in certain ways was limited during key stages of development. Therefore, it becomes important to be able to control the duration of these phases to adapt cultivars for specific environments and to comprehend their function in breeding applications (Isidro et al., 2011).

The second approach was to incorporate the previously estimated T_b as a lower threshold value in the model. GDD from planting to heading and heading to harvest were estimated as the mean value of GDD obtained for all the locations and all the seasons by cultivar. A reduction in the standard deviation was observed when the T_b estimated was included for the calculation of GDD compared when T_b=0 was used (Table 6). The model was evaluated comparing the predicted and the observed date for heading (Figure 4) and the predicted and the observed date for harvest (Figure 5). The parameters of the regression analysis showed that the model was able to satisfactorily predict the dates when the estimated T_b for the different stages was used (Figure 4 and Figure 5). A good statistical agreement was found; the intercept was not significantly different from zero ($P<0.05$) and the slope was statistically equal to 1. These are estimates expected for very good goodness of fit between predicted and observed values. Additionally, the regression also showed high coefficients of determination (R^2). The mean root square error (RMSE) and the d index also reflect a good fit for each cultivar and stage (Figure 4 and Figure 5). The opposite occurred when T_b=0 was used. Accumulation of the Growing Degree Days from specified base temperature for each cultivar and the accumulation for different cultivars using specific base temperature and Growing Degree Days accumulation using T_b=0 is also presented (Figure 6).

The variation in base temperature and GDD accumulation was probably a selective advantage for winter wheat. It also provides the basis for adjusting the sowing date, to achieve the yield potential with different growth characteristics. This approach of GDD accumulation has also been confirmed by others who have worked with wheat (Mc Master and Smika, 1988; Li et al., 2012) and other crops (Slafer and Savin, 1991; Snyder et al., 1999; Ruml et al., 2010).

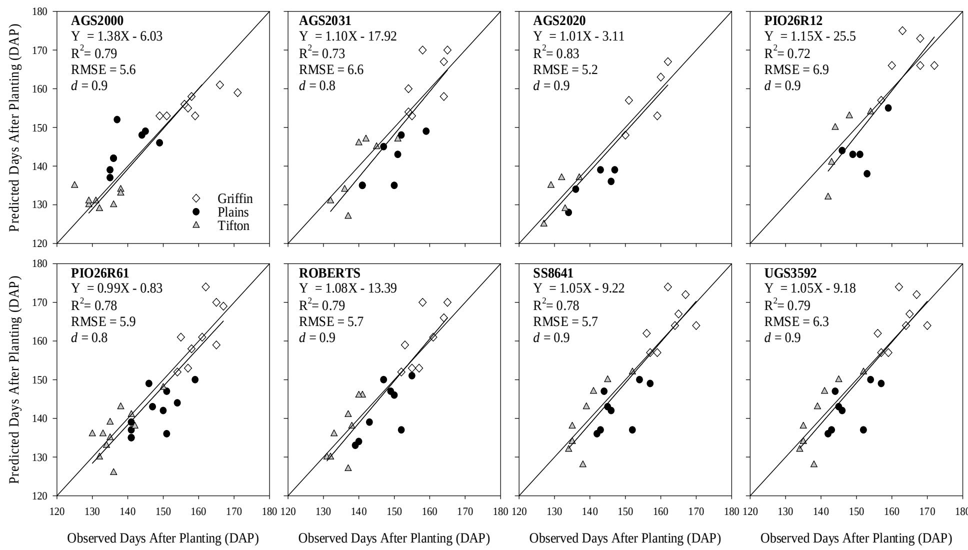

Figure 4. Predicted and observed heading dates (DAP) for winter wheat using the stage-specific base temperature.

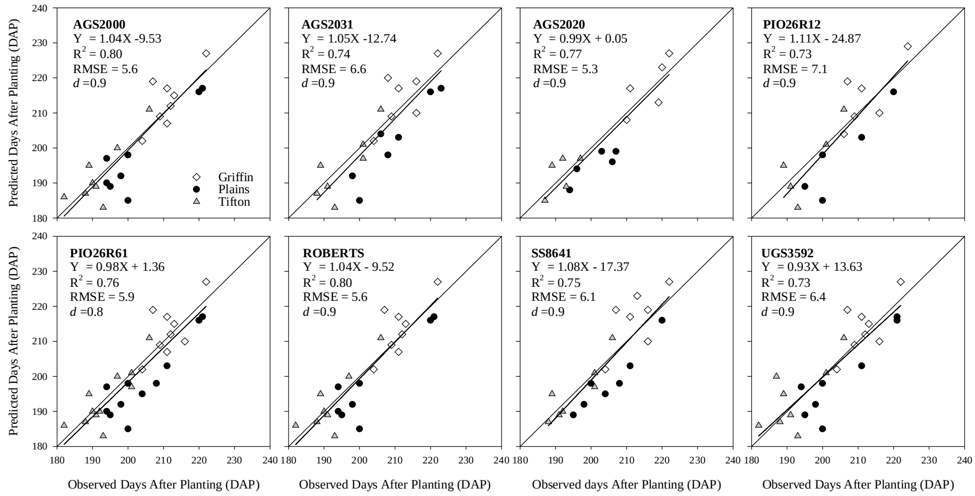

Figure 5. Predicted and observed days from heading to harvest for winter wheat based on GDD for each cultivar evaluated.

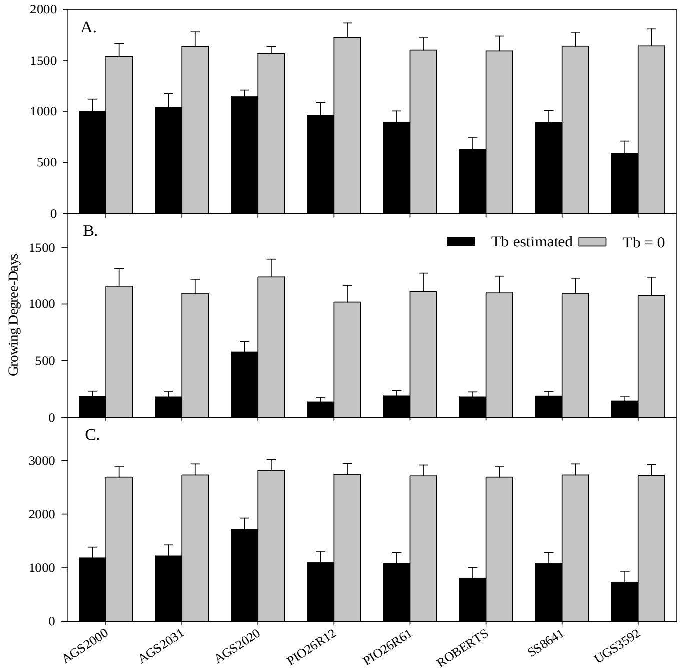

Figure 6. Accumulation of GDD from a specified base temperature for each cultivar and the GDD accumulation using a base temperature of 0°Cfrom Planting to heading (A), Heading to harvest (B) and Planting to harvest (C).

Conclusion

The heat accumulated over time provides a more accurate physiological estimate than counting calendar days. Knowing the base temperature for each individual developmental stage for a cultivar can be useful for the development of commonly used wheat simulation models. The predicted heading and harvest days based on the accumulated GDD above a phase specific T_b can be useful for crop management, such as fertilization, irrigation, spray applications, scheduling of harvest and other management practices that are associated with different crop phenological stages. These results imply that the harvest date can be successfully predicted using GDD based on estimated base temperature for each individual development stage. Cultivars differed significantly and more work is required to estimate the base temperatures and duration for others phenological stages and further evaluation is required under a wider range of cultivars and environment.

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