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A simple model to predict phenology in malting barley based on cultivar thermo-photoperiodic response

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ABSTRACT

In the Pampean region of Argentina, farming systems are based on intensive land use, wheat/soybean double cropping being a key component of these agricultural systems. However, during the last years farmers have been replacing wheat for barley due to its earlier maturity date, reducing yield penalization in soybean as a consequence of delays in its sowing date, and improving the economic profits of the double cropping system. To maximize the benefits of barley/soybean double cropping system, the proper timing of key barley ontogenic stages should be easily identifiable by farmers. The objectives of the present study were to (i) characterize crop phenology through thermo-photoperiod models in response to different sowing dates, (ii) use the algorithms calculated in point (i) to generate a simple model for predicting phenology, using historical climatic series, and (iii) validate the model with independent data. Barley cultivars used in the present study did not show vernalization requirements. Variations in phenology, measured in thermal time, were mainly associated with variations in photoperiod sensitivity during the emergence-heading phase. Significant differences in photoperiodic sensitivity, from −65 °Cd h^{-1} (Scarlett) to −344 °Cd h^{-1} (Q. Ayelen), were observed among cultivars. However, cultivars did not show significant differences in critical photoperiod or intrinsic earliness. The slope of the relationship between heading time and date of emergence, calculated from the algorithms used to build the model, based on thermo-photoperiodic response, varied between locations and cultivars. When the model was tested with an independent data set, predictions for the sowing-flowering phase showed a root mean square error lower than 4% (similar to that observed using more complex models). The algorithms used in the model were masked into a friendly frame and outputs were shown in a simple and attractive manner for users. The model was uploaded to the web site of the University of Buenos Aires to be used by students, advisors, professionals and farmers barley.

1. Introduction

Ever since the no-tillage practice was introduced in the Pampean region of Argentina, farming systems have been based on an intensive use of land, wheat/soybean double cropping being a key component of these agricultural systems. Soybean – wheat double-cropping is also a common production system in other regions such as mid-southern and mid-western United States (Kyei-Boahen and Zhang, 2006; Egli, 2008), or central Europe (Basic et al., 2004). In the double-cropping system, soybean is planted immediately after wheat harvest (from late December to early January in the Pampean region) (Calviño et al., 2003). In the Southern Pampean region, each day of delay in soybean sowing after mid-December represents a soybean yield reduction of ca. 2% per day (Calviño et al., 2003). Under this scenario, barley is an alternative for replacing wheat as it normally matures earlier than wheat due to an earlier flowering (Miralles et al., 2000, 2001; Alvarez Prado et al., 2013). This barley-related benefit has been reflected in ca. 400% increase of the malting barley harvested area

Abbreviations: DOEm, day of year for seedling emergence; DOEmc, critical day of year for seedling emergence; DOFVN, day of year for first visible node; DOHd, day of year for heading; DOPM, day of year for physiological maturity; DOSow, day of year for sowing; Em, seedling emergence; FVN, first visible node; Hd, heading; Ie, intrinsic earliness (°Cd); N, nitrogen; P, phosphorus; PM, physiological maturity; *Ps*, photoperiod sensitivity (°Cd h^{-1}); RMSE, root mean square error; SD, sowing date treatments; Sow, sowing date; T_b, base temperature (°C); TT, thermal time units (°Cd).

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in the Pampa region during the last 10 years (MAGyP, 2011). In the same period, the introduction of new barley cultivars with similar or even higher yield potential than wheat, thus improving the economic profits of barley/soybean double cropping, contributed to expanding the malting barley harvested area. However, further opportunities to maximize benefits in this cropping system still exist if the timing of key barley ontogenic stages could be better and easily identified by farmers. Having a better knowledge of particular crop phases, such as the critical period when the number of grains is determined (Arisnabarreta and Miralles, 2008) or stages such as heading date, would help to make crop management decisions. One of the main restrictions when selecting sowing dates for winter cereals in the Rolling Pampas is the occurrence of frosts around heading. Thus, the evaluation of frost risk around heading should be considered when sowing date is brought forward to improve the benefit of early maturing. In order to turn barley into a better competitor than wheat, a "fine tune" crop management is required with a correct prediction of barley phenology.

Phenology of barley can be divided into the following phases: (i) sowing to emergence, (ii) emergence to heading, and (iii) heading to physiological maturity. Development (phenology) in barley is mainly determined by three factors: photoperiod, temperature and vernalization (Slafer and Rawson, 1994). Increases in temperature determined a reduction in the duration of the phases from sowing to physiological maturity. As temperature plays a major role in plant development from sowing to maturity, phenology is usually characterized in thermal time units (Bonhomme, 2000). In relation to its photoperiod response, barley is considered a long-day plant reaching heading more rapidly with increases in photoperiod until reaching the critical value (named optimum photoperiod); beyond optimum photoperiod, the emergence to heading phase is constant (when measured in thermal time and considering plants without vernalization requirements). Vernalization is the requirement by which extended exposure to low temperatures promotes the advance to reproductive stages (Brooking and Jamieson, 2002; Amasino, 2004). If the cultivar has strong sensitivity to vernalization, exposure to temperatures above ca. 16 °C will provoke a remarkable delay in heading date (Brooking and Jamieson, 2002). Under field conditions, changes in sowing date or location will determine changes in temperature and photoperiod to which barley crops are exposed. Thus, a delay in sowing date, associated to increases in mean photoperiod, will determine reductions in the duration of sowing-heading period due to increases in mean temperature, as well as in mean photoperiod (Hay and Ellis, 1998). However, if the cultivar has vernalization requirements, the delay in sowing date (i.e. higher temperatures) will determine a longer sowing to heading phase (Hay and Ellis, 1998). Therefore, for the same cultivar, observing longer durations of emergence to heading phase associated with delays in sowing date provides evidence of vernalization requirements (Whitechurch et al., 2007). The duration of the phase from heading to physiological maturity is only modified by temperature: an increase in mean temperature reduces the duration of the phase measured in days. However, for a particular genotype, if this phase is measured in thermal units the values should be constant (when the range of explored temperature is between the base and the optimum) independently of the occurrence of heading time.

Crop simulation models, such as those used for wheat (ARC-WHEAT1, Weir et al., 1984; CERES-Wheat, Ritchie and Otter, 1985; AFRCWHEAT2, Porter, 1993), and barley (CERES-Barley, Otter-Nacke et al., 1991; QBAR, Goyne et al., 1996) are powerful tools for predicting phenology (Goyne et al., 1996). Nevertheless, these models require several variables as inputs (i.e. crop management, soil description, climatic series and genetic coefficients) and some minimal training for users. These models are based on mathematical algorithms that describe variations in the rate of development over time, in response to environmental factors such as temperature and photoperiod (Otter-Nacke et al., 1991; Herndl et al., 2008). To develop this kind of models, it is necessary to count with a solid characterization of the cultivars response to temperature and photoperiod variations across specific locations as well as to determine the annual and inter-annual variations in crop phenology using historic climatic series. Alternatively, crop phenology could be easily simulated by simple and empirical models based on cultivar thermo-photoperiodic response in crops without vernalization requirements (McMaster and Wilhelm, 2003; Jamieson et al., 2007; He et al., 2012).

The objectives of this study were to (i) characterize the crop phenology in response to changes in temperature and photoperiod in Argentine, Brazilian and Uruguayan barley cultivars, (ii) use the adjustments (algorithms) calculated in point (i) to generate a simple model for predicting phenology in different locations of the Pampean region, and (iii) validate the model with independent data. The criteria applied for building the model might be made extensive to other cultivars or crops and to different regions.

2. Materials and methods

2.1. General conditions and experimental design

A field experiment was carried out during the 2005/2006 growing season at the experimental field of the Department of Plant Production, University of Buenos Aires (34°35′S, 58°29′W). Treatments consisted of a combination of 7 sowing dates (SD) and 8 two-rowed commercial malting barley cultivars (*Hordeum vulgare* L.). The experiment was arranged in a randomized complete block design on sites with 3 blocks per treatment, where sowing dates represented the sites and cultivars were randomized within each sowing date and block. The cultivars included in the analysis were chosen because they represent those mainly used by the malting industry in Argentina (B1215, MP 1109, Quilmes Ayelén, Quilmes Painé and Scarlett), Uruguay (Danuta and Dayman) and Brazil (BRS 195) (Aguinaga, Pers. Com.; INTA, 2011). Plots (2.1 m long, 1.4 m wide, with rows 0.175 m apart) were sown on May 20, June 7 and 30, July 21, August 4, and September 1 and 26 (named as SD1 to SD7, respectively). Sowing density was ca. 335 seeds m^{-2} in all treatments for the range of sowing dates used in the experiment. Due to insufficient availability of seeds, cultivars BRS 195 and Dayman were not included on the first sowing date. The experiment was conducted without biotic limitations, since diseases and weeds were controlled. Plots were irrigated during the whole crop cycle to supplement natural rainfall with the aim of avoiding crop water stress. Soil samples were taken immediately before each sowing to determine nitrogen (N) and phosphorus (P) content within the first 0.6 and 0.2 m soil layers, respectively. Urea was applied in order to reach a soil nitrogen availability of 150 kg N ha^{-1}, in two different stages distributed between sowing and tillering DC 2.1 (Zadoks et al., 1974). No phosphorus fertilizer was added since P availability at sowing was high (25 mg kg^{-1}, Bray and Kurtz, 1945).

Maximum and minimum air temperature data were recorded hourly with a meteorological station (Vantage Pro2, Davis Instruments, CA, USA) located in the experimental field.

2.2. Measurements

Crop was monitored twice a week to determine phenology in all treatments. The phenological stages measured were: seedling emergence (Em, DC 1.0), first visible node (FVN, DC 3.1), heading (Hd, DC 6.0) and physiological maturity (PM, DC 9.0) (Zadoks et al., 1974). Em was recorded when 50% of the plants within each plot showed their first leaf above soil surface. FVN was recorded when 50% of 10 randomly selected tagged plants from central rows showed the first visible node 1 cm above the soil surface in the main stem. Hd was registered when 50% of the spikes within the plots were beginning to emerge over the flag leaf. From sowing (Sow) to heading, the phase duration between two stages was measured in days as well as in thermal time units (TT; °Cd, degree days; Eq. (1)), using 0 °C as base temperature (T_b) (Kirby, 1988).

$$TT(^{\circ}Cd) = \sum(T_m - T_b) \quad (1)$$

where: T_m is the daily mean temperature for the phase under study and T_b indicates the base temperature.

To determine PM, from heading to harvest maturity, three spikes per plot were randomly sampled two or three times a week (depending on the sowing date) and after oven drying for 72 hs, they were threshed and all grains weighed. Time of physiological maturity was considered when maximum grain weight was reached using a bi-linear model (Miralles and Slafer, 1996). The duration of the phase from Hd to PM was measured in thermal time units (°Cd) considering a T_b of 8.2 °C (Slafer and Savin, 1991).

2.3. Cultivar characterization

Cultivar characterization was done considering variations in the duration of each phase in thermal time due to changes in (i) the day of year when emergence occurs (DOEm), and (ii) the mean photoperiod of the corresponding phase.

2.3.1. Durations of the phases due to changes in the day of emergence (thermal model)

For each cultivar, the Sow-Em phase duration was characterized as constant when measured in thermal time (Eq. (2); Fig 1a)

$$TT\ Sow-Em(^{\circ}Cd) = a_{Sow-Em} \quad (\text{for all DOSow}) \quad (2)$$

where: $a_{Sow\text{-}Em}$ is the duration of the Sow-Em phase in TT (°Cd), which is a constant value obtained as an average considering all days of sowing (DOSow) for the range of used sowing dates.

Thermal time durations of the Em-FVN and FVN-Hd were plotted against the day of year of emergence (DOEm; measured as the day of year). Data were fitted with linear (Em-FVN, Eq. (3), Fig 1b; FVN-Hd, Eq. (4) models:

$$TT\ Em-FVN(^{\circ}Cd) = a_{Em-FVN} + b_{Em-FVN} * DOEm \quad (3)$$

where: $a_{Em\text{-}FVN}$ is the intercept (i.e. the maximum theoretical duration of the Em-FVN phase, °Cd), $b_{Em\text{-}FVN}$ indicates the rate of reduction of Em-FVN phase measured in degree days per day of delay in the date of emergence (°Cd day^{-1}) and DOEm is the day of emergence (day of year).

$$TT\ FVN-Hd(^{\circ}Cd) = a_{FVN-Hd} + b_{FVN-Hd} * DOEm \quad (4)$$

where: $a_{FVN\text{-}Hd}$ is the intercept (i.e. the maximum theoretical duration of the FVN-Hd phase, °Cd), $b_{FVN\text{-}Hd}$ indicates the rate of reduction of FVN-Hd phase measured in degree days per day of delay in the date of emergence (°Cd day^{-1}) and DOEm is day of emergence (day of year).

The adjustment of thermal time duration of the Em-Hd phase against the DOEm was fitted using a linear (Eq. (5), Fig. 1c) or bilinear (Eq. (6), Fig. 1d) model according to the cultivar. The use of linear or bi-linear equations to fit the data depended on the photoperiodic response of each cultivar. Those cultivars in which an optimum photoperiod was not identified (see below) were adjusted with a linear model (Eq. (5)), while in cultivars in which optimum photoperiod was reached, data were adjusted with a bilinear model (Eq. (6)):

$$TT\ Em-Hd(^{\circ}Cd) = a_{Em-Hd} + b_{Em-Hd} * DOEm \quad (5)$$

where: $a_{Em\text{-}Hd}$ is the intercept (i.e. the maximum theoretical duration of the Em-Hd phase, °Cd), $b_{Em\text{-}Hd}$ indicates the reduction rate of Em-Hd phase duration measured in degree days per day of delay in the date of emergence (°Cd day^{-1}) being DOEm the day of emergence (day of year).

$$TT\ Em-Hd(^{\circ}Cd) = a_{Em-Hd} + b_{Em-Hd} * DOEm \quad (\text{if DOEm} \leqslant \text{DOEmc}) \quad (6)$$

$$TT\ Em-Hd(^{\circ}Cd) = a_{Em-Hd} + b_{Em-Hd} * DOEmc \quad (\text{if DOEm} > \text{DOEmc})$$

where: $a_{Em\text{-}Hd}$ is the intercept (i.e. the maximum theoretical duration of the Em-Hd phase, °Cd), $b_{Em\text{-}Hd}$ is the rate of the reduction of Em-Hd phase measured in degree days per day of delay in the date of emergence (°Cd day^{-1}), DOEmc is the day of emergence on which the cultivar reached the minimum duration for that particular phase (critical day of emergence) and after that date an additional delay in the emergence does not reduce the duration of the phase.

Duration of the Hd-PM phase was characterized as a constant value when measured in thermal time units (Eq. (7), Fig 1e):

$$TT\ Hd-PM(^{\circ}Cd) = a_{Hd-PM} \quad (\text{for all DOHd}) \quad (7)$$

where: $a_{Hd\text{-}PM}$ is the duration of the Hd-PM phase in thermal time units (°Cd) which is a constant value obtained as an average of the duration of the Hd-PM phase for all the range of heading dates (DOHd).

2.3.2. Cultivar thermo-photoperiodic response

Thermal time durations of Em-FVN (Eq. (8)), FVN-Hd (Eqs. (9) and (11)) and Em-Hd (Eqs. (10) and (12)) phases were plotted against the average photoperiod of each phase. The data were fitted with linear (Eqs. (8) and (9) or (10)) or bi-linear (Eq. (11) or Eq. (12)) models depending on the phase and cultivar under study. Thus, in those phases and cultivars in which an optimum photoperiod was not reached, data were adjusted with a linear function, while in the cases when optimum photoperiod was obtained, data were fitted using a bilinear function. The linear models used were:

$$TT\ Em-FVN(^{\circ}Cd) = a_{Em-FVN} + Ps_{Em-FVN} * P_{Em-FVN} \quad (8)$$

where: $a_{Em\text{-}FVN}$ is the intercept (°Cd), $Ps_{Em\text{-}FVN}$ is the photoperiod sensitivity (°Cd h^{-1}; i.e. reduction in the phase duration per hour of photoperiod extension), and $P_{Em\text{-}FVN}$ is the mean photoperiod of Em-FVN phase (h).

$$TT\ FVN-Hd(^{\circ}Cd) = a_{FVN-Hd} + Ps_{FVN-Hd} * P_{FVN-Hd} \quad (9)$$

where: $a_{FVN\text{-}Hd}$ is the intercept (°Cd), $Ps_{FVN\text{-}Hd}$ is the photoperiod sensitivity (°Cd h^{-1}; i.e. reduction in the phase duration per hour of photoperiod extension), and $P_{FVN\text{-}Hd}$ is the mean photoperiod of FVN-Hd phase (h).

$$TT\ Em-Hd(^{\circ}Cd) = a_{Em-Hd} + Ps_{Em-Hd} * P_{Em-Hd} \quad (10)$$

where: $a_{Em\text{-}Hd}$ is the intercept (°Cd), $Ps_{Em\text{-}Hd}$ is the photoperiod sensitivity (°Cd h^{-1}; i.e. reduction in the phase duration per hour of photoperiod extension), and $P_{Em\text{-}Hd}$ is the mean photoperiod of the Em-Hd phase (h).

As indicated above, the duration of particular phases (FVN-Hd and Em-Hd) against photoperiod was fitted by a bi-linear model when the natural photoperiod explored by the cultivar was longer than optimum photoperiod, not modifying the duration of the phase:

$$TT\ FVN-Hd(^{\circ}Cd) = a_{FVN-Hd} + Ps_{FVN-Hd} * P_{FVN-Hd} \quad (\text{if } P_{FVN-Hd} \leqslant Po) \quad (11)$$

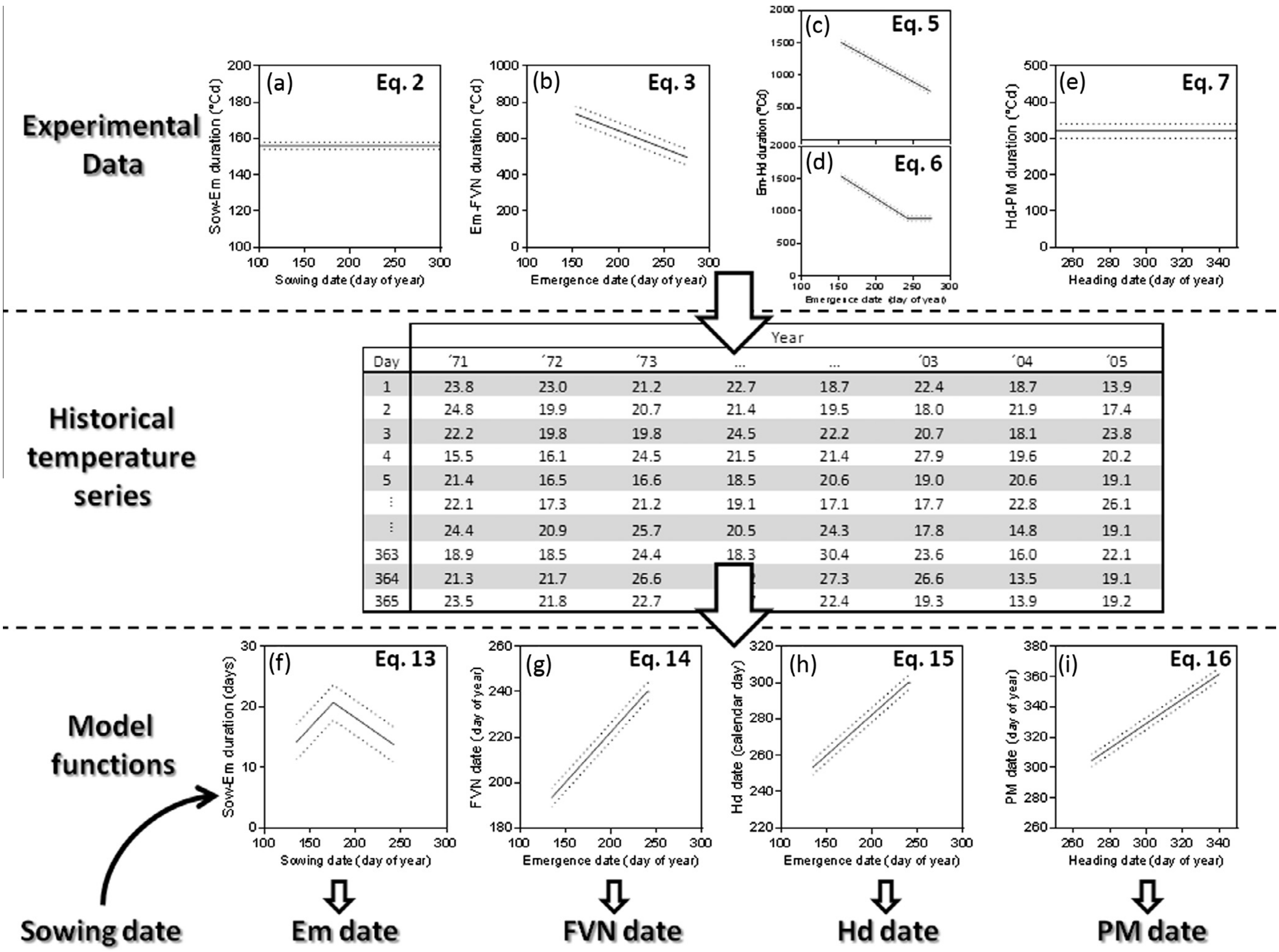

Fig. 1. Schematic diagram illustrating the methodology used to build a simple model for predicting phenology in this work. The upper panel shows the models used to analyze the experimental data, (a) relationship between duration of sowing-emergence phase (°Cd) and sowing date (day of year; Eq. (2)), (b) relationship between duration of emergence-first visible node (FVN) phase (°Cd) and emergence date (day of year; Eq. (3)), (c and d) relationship between duration of emergence-heading (Hd) phase (°Cd) and emergence date (day of year; Eqs. (5) and (6)), relationship between duration of heading-physiological maturity (PM) phase (°Cd) and heading date (day of year; Eq. (6)). The middle panel shows an example of historical temperature series. The bottom panel shows the model functions used to estimate the date of different stages under study, (f) relationship between sowing-emergence phase (days) and sowing date (day of year), (g) relationship between FVN date (day of year) and emergence date (day of year), (h) relationship between Hd date (day of year) and emergence date (day of year) and (i) relationship between PM date (day of year) and heading date (day of year). The white arrows showed outputs of the model.

$$\text{TT FVN} - \text{Hd}(^{\circ}\text{Cd}) = a_{\text{FVN-Hd}} + Ps_{\text{FVN-Hd}} * Po \quad (\text{if } P_{\text{FVN-Hd}} > Po)$$

where: $a_{FVN\text{-}Hd}$ is the intercept (°Cd), $Ps_{FVN\text{-}Hd}$ is the photoperiod sensitivity (°Cd h^{-1}; i.e. reduction in phase duration per hour of photoperiod extension, *Po* is optimum photoperiod (h), and $P_{FVN\text{-}Hd}$ is the mean photoperiod of FVN-Hd phase (h). In addition, the analysis using bi-linear models allowed the characterization of the intrinsic earliness (Ie) of the FVN-Hd phase, which indicates the minimum phase duration of each cultivar.

$$\text{TT Em} - \text{Hd}(^{\circ}\text{Cd}) = a_{\text{Em-Hd}} + Ps_{\text{Em-Hd}} * P_{\text{Em-Hd}} \quad (\text{if } P_{\text{Em-Hd}} \leqslant Po) \tag{12}$$

$$\text{TT Em} - \text{Hd}(^{\circ}\text{Cd}) = a_{\text{Em-Hd}} + Ps_{\text{Em-Hd}} * Po \quad (\text{if } P_{\text{Em-Hd}} > Po)$$

where:, $a_{Em\text{-}Hd}$ is the intercept (°Cd), $Ps_{Em\text{-}Hd}$ is the photoperiod sensitivity (°Cd h^{-1}; i.e. reduction in phase duration per hour of photoperiod extension, *Po* is optimum photoperiod (h), and $P_{Em\text{-}Hd}$ is the mean photoperiod of Em-Hd phase (h). In addition, the analysis using bi-linear models allowed the characterization of the intrinsic earliness (Ie) of Em-Hd phase which indicates the minimum phase duration of each cultivar.

Vernalization requirements were analyzed as a delay in the duration of the phases Em-FVN, FVN-Hd or Em-Hd on later sowing dates with respect to earlier ones (Whitechurch et al., 2007). If the difference of the duration of Em-FVN between an early and a late sowing date (e.g. SD1-SD7) was positive, it was assumed that the cultivar has no vernalization requirements (Whitechurch et al., 2007).

2.4. Model parameters for different crop phases

The duration of the phases Em-FVN, FVN-Hd and Em-Hd measured previously (Eq. (3)–(6)) in thermal time units was converted into days (day of year) considering the variations between years in daily mean temperature. To extrapolate the model to other locations (Barrow, 38°20′S, 60°17′W, and Bordenave, 37°47′S, 63°07′ W; see Fig. 1S- supplementary data-), historical temperature series for each location (at least 35 years) were used, considering the thermal model developed for each cultivar. In order to make results interpretation easier for farmers, occurrence of the different phenological stages was calculated in days for the range of sowing dates from May 1st to August 31st, following the next steps:

2.4.1. Sow-Em phase

Changes in duration of Sow-Em phase (days) under the different sowing dates was fitted using a bi-linear model (Eq. (13); Fig. 1f):

$$\mathrm{Sow-Em\,(days)} = a_{\mathrm{Sow-Em}} + b_{\mathrm{Sow-Em}} * \mathrm{DOSow} \quad (\text{if DOSow} <= \mathrm{DOSow_{max}}) \tag{13}$$

$$\mathrm{Sow-Em\,(days)} = a_{\mathrm{Sow-Em}} + b_{\mathrm{Sow-Em}} * \mathrm{DOSow_{max}} \quad (\text{if DOSow} > \mathrm{DOSow_{max}})$$

$$\mathrm{Sow-Em\,(days)} = a_{\mathrm{Sow-Em}} + d_{\mathrm{Sow-Em}} * (\mathrm{DOSow} - \mathrm{DOSow_{max}}) \quad (\text{if DOSow} > \mathrm{DOSow_{max}})$$

where: $a_{\text{Sow-Em}}$ indicates the intercept (days), $b_{\text{Sow-Em}}$ is the increase in the phase duration due to delays in sowing dates up to the inflection point (day day^{-1}), $\mathrm{DOSow_{max}}$ is the inflection point where the slope changes from a positive ($b_{\text{Sow-Em}}$) to a negative ($d_{\text{Sow-Em}}$) value (i.e. shortening of the Sow-Em phase due to delays in sowing date) and maximum duration occurs. The date of year of sowing (DOSow*)* is the input introduced by the users into the model to predict the Sow-Em duration (days).

2.4.2. Em-FVN and FVN-Hd phases

The day of occurrence of FVN (DOFVN) and Hd (DOHd) stages was plotted against the DOEm calculated through Eqs. (14) (Fig. 1g) and (15) (Fig. 1h), for each one of the years of the climatic series. Data were fitted with a linear function:

$$\mathrm{DOFVN} = a_{\mathrm{DOFVN}} + b_{\mathrm{DOFVN}} * \mathrm{DOEm} \tag{14}$$

where: DOFVN is the day of FVN (day of year), a_{DOFVN} is the intercept (day), b_{DOFVN} is the change in FVN date per day of delay in the emergence date (day day^{-1}), and DOEm is the day of emergence (day of year) derived from Eq. (13).

$$\mathrm{DOHd} = a_{\mathrm{DOHd}} + b_{\mathrm{DOHd}} * \mathrm{DOEm} \tag{15}$$

where: DOHd is the day of Hd (day of year), a_{DOHd} is the intercept (day), b_{DOHd} is the change in Hd date per day of delay in the emergence date (day day^{-1}), and DOEm is the day of emergence (day of year) derived from Eq. (13).

2.4.3. Hd-PM phase

The occurrence of PM date was estimated, for each year of the climatic series, as the day of year on which the thermal units to PM were reached. The day on which PM was reached was plotted against Hd date (as an independent variable) and the relationship was fitted with a linear regression (Eq. (16); Fig. 1i):

$$\mathrm{DOPM} = a_{\mathrm{DOPM}} + b_{\mathrm{DOPM}} * \mathrm{DOHd} \tag{16}$$

where: DOPM is the day of PM (day of year), a_{DOPM} is the intercept (day), b_{DOPM} is the change in Hd date per day of delay in the heading date (day day^{-1}), and DOHd is the day of heading (day of year) derived from Eq. (15).

2.5. Inputs and outputs of the model

The thermo-photoperiodic characterization of the cultivars (Section 2.3, Eqs. (1)–(8), (10)–(12)) and the use of Eqs. (13)–(16) determine the inputs of the model, which are: cultivar, location and day of sowing (day of year), while the outputs of the model are: day of occurrence of Em, FVN, Hd and PM, as well as, the durations measured in days and thermal time units of the Em-Hd, Em-FVN, FVN-Hd and Hd-PM phases. As the equations of the model were generated considering historic climatic series, the mean and the standard error of the each variable is shown as output.

2.6. Model validation

The model was validated with independent data obtained from other experiments and field plots. For this purpose, data were collected in 3 locations (Barrow, Bordenave, and Buenos Aires, which are situated in the main barley production area of Argentina) from experiments conducted within the National Barley Variety Testing of Argentina (INTA, 2011) and from different private malting companies of Argentina (data were provided by Antonio Aguinaga from Ambev company). Six out of eight cultivars used in the present study were included in the validation analyses (B1215, Danuta, MP1109, Q. Ayelén, Q. Painé and Scarlett) during 13 different growing seasons (1996–2008). The availability of independent data to validate the model was different for each phase under study. Em-FVN (n = 54) and Hd-PM (n = 34) phases had lower amount of data with respect to Em-Hd phase (n = 242), as in the National Barley Variety Testing, registration of the occurrence of FVN and PM stages in commercial fields is not frequent.

The model performance was evaluated fitting linear regressions between the estimated and the observed duration of the Sow-Em, Sow-Hd and Hd-PM phases, and calculating the root mean square error (RMSE) (Willmott, 1982).

3. Results

3.1. Cultivar characterization: thermal time duration of ontogenic stages

Thermal time for Sow-Em phase was not affected by sowing dates or cultivars ($P > 0.05$) (Fig 2), showing 156 °Cd on average with a narrow range of variation (from 150 to 161 °Cd) among treatments. On the other hand, the duration of Em-Hd phase showed a consistent reduction when sowing date was delayed, although cultivars shortened the duration of the phase with a different magnitude, evidencing a significant cultivar x sowing date interaction ($P < 0.05$) (Fig. 2). During Em-Hd phase, four out (B1215, Danuta, MP 1109 and Q. Painé) of eight cultivars showed a bi-linear response when the DOEm was delayed. The response of those four cultivars was characterized by a decrease in the duration of Em-Hd phase with delays in sowing date until a critical sowing date (ranging from 225 (B 1215) to 252 (MP 1109) day of year, Table 1) after which Em-Hd phase remained constant.

Sub-phases Em-FVN and FVN-Hd reduced linearly ($P < 0.05$) when sowing dates were delayed in all cultivars. Em-FVN phase duration ranged from 435 to 809 °Cd depending on the cultivar and sowing date (Fig. 2). The rate of reduction of Em-FVN phase was between −1.4 (Danuta) and −2.1 (MP 1109) °Cd day^{-1} per each day of delay in the DOEm, without significant differences ($P > 0.05$) among cultivars. However, the intercepts of Em-FVN phase showed remarkable differences between cultivars, ranging between 927 °Cd (Danuta) and 1113 °Cd (BRS 195) (Table 1).

The shortening rate of FVN-Hd phase, due to delays in DOEm, was greater than that observed in the immediately previous phase (Em-FVN), ranging between −0.1 (Scarlett) and −4.8 (MP 1109 and Q. Ayelen) °Cd day^{-1} per day of delay in the crop DOEm (Table 1). FVN-Hd phase intercept was also significantly different among cultivars ($P < 0.05$), ranging from 395 (Scarlett) to 1787 °Cd (MP 1109) (Table 1). Thus, crop sensitivity for the duration of the phases up to Hd, measured as shortenings in their duration due to delays in the crop DOEm, increased from the vegetative (Em-FVN) to the reproductive (FVN-Hd) phases: on average each day of delay in the DOEm shortened 1.8 °Cd Em-FVN phase and 2.9 °Cd FVN-Hd phase (Table 1).

When sowing date was modified, grain filling phase (i.e. Hd-PM) showed lower variation in its duration than the previous

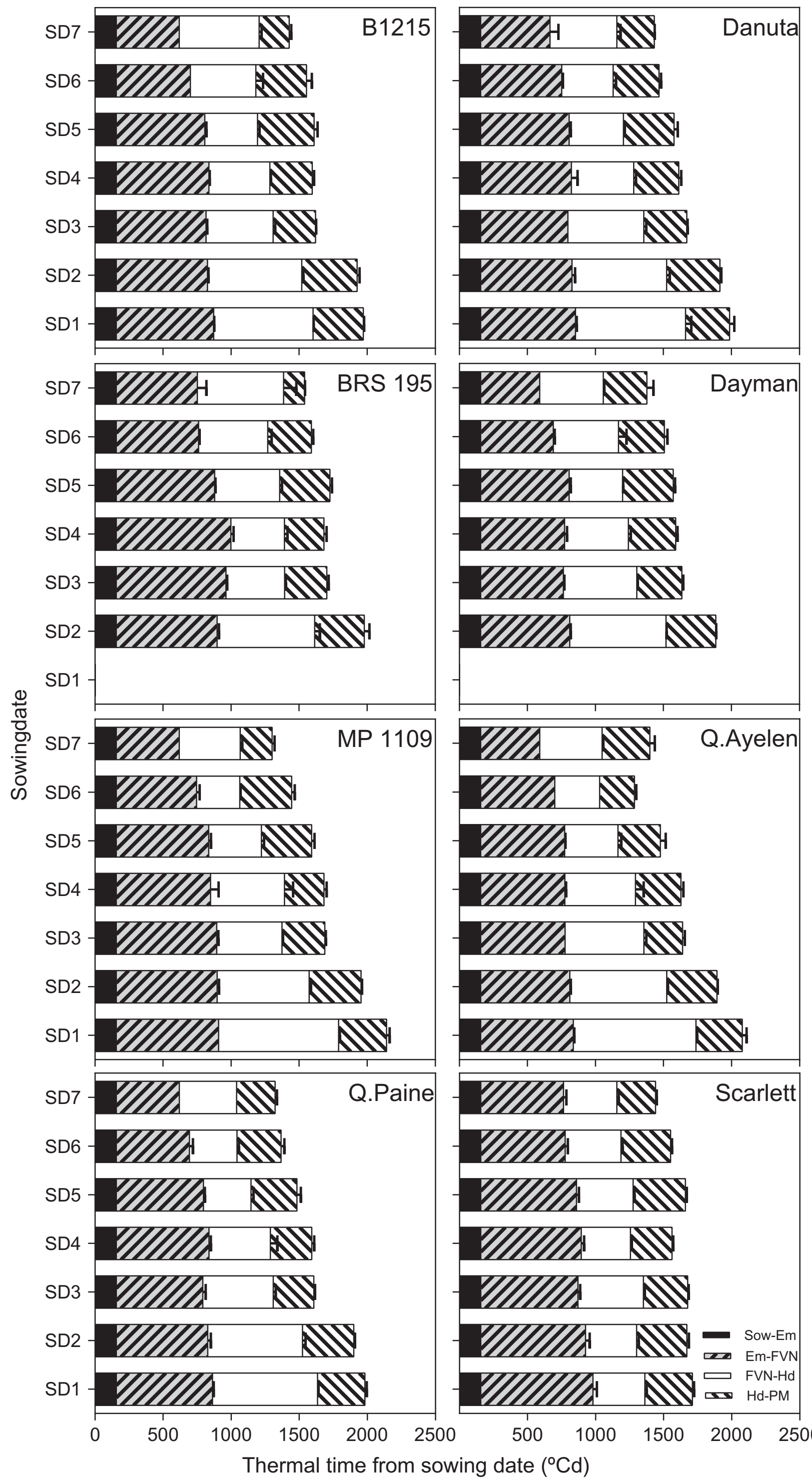

Fig. 2. Duration in thermal time (°Cd) of the phases sowing (Sow)-emergence (Em) (solid bars), Em-first visible node (FVN) (upwards diagonal bars), FVN-heading (Hd) (open bars) and Hd-physiological maturity (PM) (downwards diagonal bars), under seven sowing dates (SD1, the earliest, and SD7, the latest) for eight barley cultivars. Horizontal bars represent one standard error for each particular phase.

phases (Fig. 2). On average, grain filling duration was *c.* 330 °Cd (ranging from 160 to 410 °Cd) (Fig. 2).

3.2. Photoperiodic sensitivity and vernalization requirements

For the range of photoperiods below optimum, cultivars reduced Em-Hd phase duration with increases in the mean photoperiod explored during the phase. Once optimum photoperiod was reached, no variations in the duration of Em-Hd phase were evident. Photoperiod sensitivity showed significant differences among cultivars ranging from −65 (Scarlett) to −344 (Q. Ayelen) °Cd h^{-1}. However, no significant differences were observed among cultivars for optimum photoperiod or intrinsic earliness (Table 2). Optimum photoperiod ranged from 12.8 to 13.6 h and intrinsic earliness varied from 885 to 1135 °Cd.

When Em-FVN and FVN-Hd phases were analyzed, responses to photoperiod were different depending on the phase. The relationship between the duration (in thermal time) of Em-FVN phase

Table 1
Parameters of the regression between the duration of different phenological phases (°Cd) and emergence date (day of year): intercept (a, °Cd ± se, °Cd), slope of the regression (b, °Cd day^{-1} ± se), and the date of emergence after which the duration of the phase was constant (critical day of emergence, DOEmc ± se, day of year) for eight barley cultivars. The phenological phases characterized are: Em-FVN (Eq. (4)), FVN-Hd (Eq. (4)) and Em-Hd (Eqs. (5) and (6)). Parameters derived from Eqs. (3)–(6). In all cases the adjustment was $r^2 \geqslant 0.90$ ($p < 0.0001$).

Cultivar	Em-FVN		FVN-Hd		Em-Hd		
	a_{Em-FVN}	b_{Em-FVN}	a_{FVN-Hd}	b_{FVN-Hd}	a_{Em-Hd}	b_{Em-Hd}	DOEmc
B 1215	997 ± 77	−1.8 ± 0.4	1116 ± 98	−2.2 ± 0.5	2270 ± 135	−5.5 ± 0.8	225 ± 7.9
BRS 195	1113 ± 173	−1.8 ± 0.8	817 ± 84	−1.1 ± 0.7	1972 ± 133	−3.4 ± 0.6	
Danuta	927 ± 57	−1.4 ± 0.3	1499 ± 102	−3.7 ± 0.5	2365 ± 81	−5.9 ± 0.4	233 ± 5.1
Dayman	1008 ± 116	−1.9 ± 0.5	1227 ± 74	−2.7 ± 0.4	1962 ± 137	−3.9 ± 0.6	
MP 1109	1112 ± 80	−2.1 ± 0.4	1787 ± 87	−4.8 ± 0.5	2554 ± 191	−6.5 ± 1.1	252 ± 12.7
Q. Ayelén	954 ± 64	−1.7 ± 0.3	1770 ± 65	−4.8 ± 0.4	2145 ± 145	−4.9 ± 0.7	
Q. Painé	988 ± 77	−1.7 ± 0.4	1564 ± 94	−4.1 ± 0.5	2349 ± 116	−5.9 ± 0.6	247 ± 7.9
Scarlett	1072 ± 53	−1.7 ± 0.3	395 ± 65	−0.1±0.8	1478±98	−1.6±0.5	

and mean photoperiod of that phase was linear in all cases, suggesting that cultivars did not reach optimum photoperiod under the photoperiodic range explored. In that phase, significant differences in photoperiod sensitivity were observed among cultivars, being Dayman (−47 °Cd h^{-1}) and MP 1109 (−85 °Cd h^{-1}) the cultivars that registered the lowest and the highest photoperiod sensitivity, respectively (Table 2).

In contrast to Em-FVN phase, the relationship between FVN-Hd phase duration and mean photoperiod was best fitted with a bi-linear model (Table 2). The exceptions were BRS 195 and Scarlett cultivars, which were relatively insensitive to photoperiod during FVN-Hd phase (i.e. −3 and −20 °Cd h^{-1} in Scarlett and BRS 195 cultivars, respectively), while the other cultivars showed remarkable photoperiod sensitivity in that phase (−362 °Cd h^{-1}, on average) (Table 2). Optimum photoperiods in FVN-Hd phase were similar to those observed for Em-Hd phase, without significant differences among cultivars, while intrinsic earliness values were about half of those observed for the Em-Hd phase (Table 2). None of the cultivars extended the duration of Em-FVN, FVN-Hd or Em-Hd phases, measured in thermal time, when crops were sown on extremely late sowing dates (i.e. out of the normal agronomic range of sowing dates and under high temperatures and long photoperiods). As a consequence of this, none of the cultivars used in our study registered vernalization requirements. Therefore, variations in thermal time of Em-Hd, Em-FVN and FVN-Hd phases were attributed to changes in photoperiod during each particular phase (and particularly to differences in the photoperiod sensitivity).

Table 2
Parameters of the linear and bi-linear regressions for the adjustments between the duration of the Em-Hd (Eqs. (10) and (12)), Em-FVN (Eq. (8)) and FVN-Hd (Eqs. (9) and (11)) phases (°Cd), and mean photoperiod (h) of each particular phase in different barley cultivars: photoperiod sensitivity (Ps; °Cd h^{-1} ± se), optimum photoperiod (Po; h ± se), intrinsic earliness (Ie; °Cd ± se) and the correlation coefficient (r^2) for each regression analysis.

Cultivar	Ps	Po	Ie	r^2
Em-Hd				
B1215	−278 ± 03	12.8 ± 0.12	1034 ± 30	0.87
BRS 195	−175 ± 15	13.2 ± 0.38	1135 ± 50	0.69
Danuta	−290 ± 18	13.1 ± 0.05	988 ± 11	0.93
Dayman	−236 ± 14	13.2 ± 0.16	958 ± 24	0.79
MP 1109	−317 ± 32	13.6 ± 0.11	904 ± 16	0.82
Q. Ayelén	−344 ± 24	13.3 ± 0.11	884 ± 04	0.89
Q. Painé	−304 ± 23	13.3 ± 0.12	885 ± 06	0.91
Scarlett	−65 ± 13			0.85
Em-FVN				
B1215	−70 ± 02			0.81
BRS 195	−70 ± 20			0.68
Danuta	−47 ± 12			0.85
Dayman	−64 ± 01			0.65
MP 1109	−85 ± 07			0.89
Q. Ayelén	−66 ± 02			0.83
Q. Painé	−68 ± 09			0.78
Scarlett	−73 ± 39			0.92
FVN-Hd				
B1215	−355 ± 30	12.9 ± 0.1	476 ± 19	0.54
BRS 195	−20 ± 59			0.02
Danuta	−377 ± 70	13.2 ± 0.1	423 ± 14	0.94
Dayman	−374 ± 76	13.1 ± 0.1	445 ± 16	0.90
MP 1109	−398 ± 51	13.4 ± 0.1	399 ± 05	0.65
Q. Ayelén	−332 ± 24	13.5 ± 0.1	394 ± 09	0.84
Q. Painé	−356 ± 39	13.3 ± 0.1	385 ± 05	0.86
Scarlett	−3 ± 25			0.01

3.3. Model parameters

As stated before, variations in the duration of each particular phase measured in thermal time should be ascribed to variations in photoperiod. Therefore, for a particular combination of cultivar, sowing date and location, the duration of each phenological phase in thermal time will be the same. Thus, with the exception of Sow-Em and Hd-PM phases (which only respond to temperature), changes in sowing dates will modify the duration -measured in thermal time- of the rest of the phases. However, the duration of the phases measured in days will be different depending on the temperatures experienced by the crop within each environment (year, location, etc.). As duration (°Cday) of Sow-Em phase did not change ($P > 0.05$) among sowing dates or cultivars, its duration was assumed to be fixed (156 °Cd) in the model. Thus, in the model DOEm was estimated when the thermal time duration from Sow to Em was reached within the climatic series for each location for each year (Eq. (13)), obtaining the average value of DOEm and its standard deviation. Changes in the locations generated different delays in DOEm in response to variations in sowing date (Eq. (13), Fig. 1f). Buenos Aires showed the lowest sensitivity, followed by Barrow and Bordenave (i.e. 0.10, 0.16 and 0.20 day day^{-1}, respectively). The duration of this phase increased up to day of year 174 (24th June), and then decreased at a rate of −0.07, −0.10 and −0.14 day day^{-1} in Buenos Aires, Barrow and Bordenave, respectively. Significant differences among locations were observed in the intercept, showing Buenos Aires the highest values, followed by Barrow and Bordenave (ca. 4, 8 and 12 days, respectively) (Fig. 3).

DOFVN and DOHd were estimated considering, for each stage, the day on which the thermal time requirements from emergence were reached for each year of the historical climate series. (Eqs. (14) and (15); Fig. 4). Thus, it becomes possible to obtain the average heading date (day of year) for the different years included in the historical series and the deviation of the predicted date (Fig. 4).

The slopes of the relationship between heading time and DOEm varied between locations and cultivars (ranging between 0.13 and 0.46 day day^{-1} in Barrow, 0.09 and 0.41 day day^{-1} in Bordenave and from 0.33 to 0.66 day day^{-1} in Buenos Aires). Cultivars

MP1109 and Scarlett had the lowest and the highest sensitivity, respectively (Table 3). That approximation makes it possible to quantify frost risk after heading for the different cultivars. Thus, the frost risk was lower in MP1109 than in Scarlett, especially with early sowing dates (Fig. 4).

The relationship between PM and Hd date varied slightly across locations and ranged between 0.62 (Bordenave) and 0.87 (Barrow) day day^{-1} (Table 3). Cultivars did not show significant differences in the changes in PM for each day of delay in the Hd date (Table 3).

3.4. Model validation

Model performance was validated with independent data sets, including most of the cultivars and three locations (Barrow, Bordenave and Buenos Aires), for different sowing dates and years. In the independent data set, duration of the different phases showed an important range of variability: Em-FVN phase ranged from 50 to 99 days, Em-Hd phase from 63 to 163 days and Hd-PM phase ranged from 23 to 39 days.

Em-Hd phase duration was estimated by the model with a $r^2 = 0.83$ and a RMSE of 10 days (9.8%; Table 4). The performance of the model depended on the rainfall during the crop cycle. When data were grouped by rainfall for the historical data series, the model showed a RMSE value of 4 days with normal rainfall during the crop cycle (i.e. similar to the mean rainfall of the region) and/or irrigation was supplemented (Fig. 5). In contrast, when the model was used to predict heading time in dry years, the RMSE increased to 14 days due to an overestimation of the model relative to observed values (Fig. 5). The slopes of the linear regression between predicted and observed data were not significantly different from one ($P > 0.05$) in dry and normal years. The intercept in dry years were significantly different from zero, while in years without water stress the intercepts were not significantly different from zero (Table 4; Fig. 5). However, in years without water stress, the prediction of the model (measured as the differences in the error mean squares) increased as rainfall was higher (Fig. 6) during Sow-FVN phase.

The model predicted the duration of Em-FVN phase with a RMSE of 6 days (8.5%, $n = 54$) and all data were included between the range of ±4 days compared to the 1 to 1 ratio (Fig. 7). Finally, the model predicted the duration of the grain filling phase (i.e. Hd-PM) with a RMSE of 4 days, being most of the evaluated data ($n = 34$) within the range of ±4 days compared to the 1 to 1 ratio line (Fig. 8).

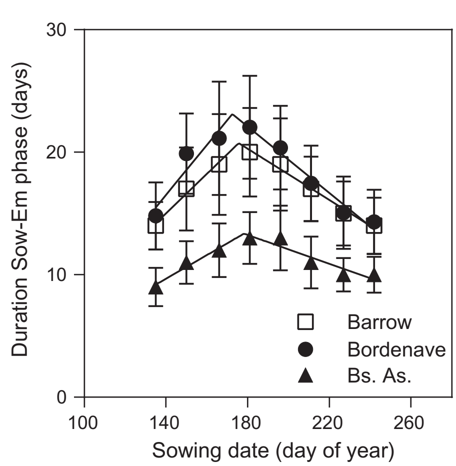

Fig. 3. Relationship between duration of sowing (Sow) – emergence (Em) phase (days) and sowing date (Sow; day of year) for eight barley cultivars grown in Barrow (empty squares), Bordenave (full circles) and Buenos Aires (full triangles). Vertical lines represent one standard deviation.

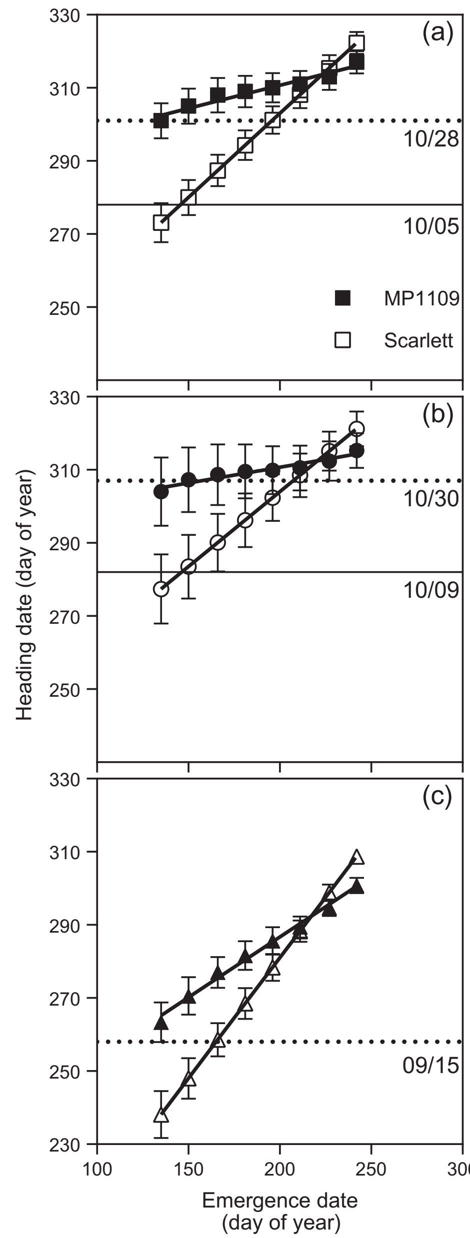

Fig. 4. Relationship between heading date and emergence date (day of year) for the cultivars MP1109 (diamonds) and Scarlett (circles) grown in (a) Barrow, (b) Bordenave and (c) Buenos Aires. Vertical lines represent one standard deviation and the solid and horizontal dotted lines represent the mean date of last frost and the last frost plus one standard deviation for each location, respectively. In Buenos Aires (c) the mean date of last frost is not shown because it is out of axis range.

4. Discussion

4.1. Cultivar thermo-photoperiodic sensitivity

As expected, the duration of Sow-Em phase did not change when it was measured in thermal time, although important variations were evident when that phase was measured in days in agreement with previous works in wheat (Weir et al., 1984; Kirby, 1993; Jamieson et al., 1998a). Thermal time duration of the different sub-phases from Em to Hd were significantly reduced as sowing dates were delayed. Cultivars in which the duration of Em to Hd phase in the first sowing dates were much shorter than in the last sowing dates could be characterized as sensitive to vernalization (Whitechurch et al., 2007); however, no cultivar showed

Table 3
Parameters of the linear regression between the occurrence (day of year) of FVN (Eq. (14)) and Hd (Eq. (15)) with date of emergence (day of year), and PM occurrence with date of heading (day of year; Eq. (16)) for eight barley cultivars in three locations (Barrow, Bordenave, Buenos Aires): intercept (*a*, day of year ± se), slope (*b*, day day^{-1} ± se) and the correlation coefficient (r^2) for each regression analysis is shown.

Location	Cultivar	First visible node			Heading			Physiological maturity		
		$a_{Em\text{-}FVN}$	$b_{Em\text{-}FVN}$	r^2	$a_{Em\text{-}Hd}$	$b_{Em\text{-}Hd}$	r^2	$a_{Hd\text{-}PM}$	$b_{Hd\text{-}PM}$	r^2
Barrow	B 1215	145 ± 4.6	0.60 ± 0.02	0.99	260 ± 4.1	0.23 ± 0.02	0.95	62 ± 1.4	0.87 ± 0.00	0.99
	BRS 195	163 ± 4.6	0.56 ± 0.02	0.99	247 ± 2.1	0.33 ± 0.01	0.99	52 ± 2.0	0.89 ± 0.01	0.99
	Danuta	140 ± 4.5	0.63 ± 0.02	0.99	271 ± 3.3	0.18 ± 0.02	0.95	56 ± 2.4	0.88 ± 0.01	0.99
	Dayman	146 ± 4.4	0.59 ± 0.02	0.99	246 ± 2.0	0.30 ± 0.01	0.99	56 ± 1.3	0.88 ± 0.00	0.99
	MP1109	159 ± 4.1	0.56 ± 0.02	0.99	286 ± 2.4	0.13 ± 0.01	0.95	56 ± 3.0	0.88 ± 0.01	0.99
	Q. Ayelén	140 ± 4.7	0.62 ± 0.02	0.99	259 ± 2.1	0.23 ± 0.01	0.99	60 ± 1.6	0.87 ± 0.01	0.99
	Q. Painé	145 ± 4.5	0.60 ± 0.02	0.99	272 ± 2.2	0.17 ± 0.01	0.97	68 ± 1.6	0.86 ± 0.01	0.99
	Scarlett	158 ± 4.6	0.57 ± 0.02	0.99	211 ± 2.3	0.46 ± 0.02	0.99	56 ± 1.8	0.88 ± 0.01	0.99
Bordenave	B 1215	161 ± 3.9	0.53 ± 0.02	0.99	270 ± 4.6	0.18 ± 0.02	0.91	154 ± 5.0	0.62 ± 0.02	0.99
	BRS 195	178 ± 3.7	0.49 ± 0.02	0.99	258 ± 1.9	0.27 ± 0.01	0.99	141 ± 5.6	0.65 ± 0.02	0.99
	Danuta	155 ± 4.2	0.56 ± 0.02	0.99	279 ± 3.5	0.14 ± 0.02	0.91	149 ± 5.2	0.63 ± 0.02	0.99
	Dayman	162 ± 3.9	0.52 ± 0.02	0.99	256 ± 2.1	0.25 ± 0.01	0.99	147 ± 5.4	0.63 ± 0.02	0.99
	MP1109	174 ± 3.6	0.48 ± 0.02	0.99	294 ± 1.9	0.09 ± 0.01	0.92	145 ± 5.3	0.64 ± 0.02	0.99
	Q. Ayelén	156 ± 4.0	0.54 ± 0.02	0.99	268 ± 2.1	0.19 ± 0.01	0.98	153 ± 5.1	0.62 ± 0.02	0.99
	Q. Painé	161 ± 4.0	0.53 ± 0.02	0.99	281 ± 2.1	0.12 ± 0.01	0.96	167 ± 4.1	0.59 ± 0.01	0.99
	Scarlett	173 ± 3.7	0.50 ± 0.02	0.99	222 ± 1.9	0.41 ± 0.02	0.99	145 ± 5.0	0.64 ± 0.02	0.99
Buenos Aires	B 1215	95 ± 4.6	0.76 ± 0.02	0.99	196 ± 4.0	0.43 ± 0.02	0.99	85 ± 2.1	0.81 ± 0.01	0.99
	BRS 195	109 ± 4.1	0.73 ± 0.02	0.99	186 ± 3.7	0.51 ± 0.02	0.99	77 ± 2.2	0.83 ± 0.01	0.99
	Danuta	90 ± 5.0	0.79 ± 0.03	0.99	205 ± 3.4	0.39 ± 0.02	0.99	82 ± 2.2	0.82 ± 0.01	0.99
	Dayman	96 ± 4.7	0.75 ± 0.02	0.99	181 ± 3.6	0.50 ± 0.02	0.99	82 ± 2.1	0.82 ± 0.01	0.99
	MP 1109	107 ± 4.0	0.72 ± 0.02	0.99	221 ± 2.4	0.33 ± 0.01	0.99	80 ± 2.5	0.83 ± 0.01	0.99
	Q. Ayelén	90 ± 5.0	0.78 ± 0.03	0.99	194 ± 3.1	0.44 ± 0.02	0.99	84 ± 2.1	0.82 ± 0.01	0.99
	Q. Painé	95 ± 4.7	0.77 ± 0.02	0.99	206 ± 3.0	0.38 ± 0.02	0.99	95 ± 2.4	0.79 ± 0.01	0.99
	Scarlett	105 ± 4.8	0.74 ± 0.02	0.99	149 ± 2.4	0.66 ± 0.02	0.99	79 ± 2.4	0.83 ± 0.01	0.99

Table 4
Parameters for the linear regression between the predicted and the observed duration for the sowing – heading phase (Sow-Hd): intercept (*a*, day), slope (*b*, day day^{-1}) and the correlation coefficient (r^2) for each regression analysis, number of data taken in the analyses (n), root mean square error (RMSE, in days and percentage). Data included Barrow, Bordenave and Buenos Aires locations for B1215, Danuta, MP1109, Q. Ayelén, Q. Painé and Scarlett cultivars. Environments were discriminated in dry and normal years.

Environment	Cultivar	*a*	*b*	r^2	*n*	RMSE (days)	RMSE (%)
Dry years	B1215	6.15	1.06	0.83	19	14	14.3
	Danuta	−1.83	1.11	0.96	27	12	10.7
	MP1109	9.87	1.09	0.99	9	19	19.4
	Q. Ayelén	−2.69	1.15	0.88	31	14	14.4
	Q. Painé	−1.21	1.14	0.87	26	14	14.9
	Scarlett	10.30	0.91	0.92	10	5	4.3
	All	9.29	1.02	0.86	122	14	13.3
Normal years	B1215	7.15	0.94	0.96	22	3	3.0
	Danuta	−3.47	1.05	1.00	2	3	2.3
	MP1109	6.38	0.98	0.97	12	5	4.1
	Q. Ayelén	0.15	1.02	0.95	45	4	4.1
	Q. Painé	−5.77	1.08	0.93	29	4	4.2
	Scarlett	9.51	0.92	0.97	10	4	3.7
	All	2.54	1.00	0.95	120	4	3.9
All years and cultivars		6.77	1.00	0.83	242	10	9.8

that behavior. Thus, we conclude that, similarly to other Argentine barley cultivars (Whitechurch et al., 2007), all commercial malting barley cultivars (including cultivars from Argentina, Brazil and Uruguay) analyzed in our study did not show vernalization requirements. Thereby, changes in the duration of phases Em-FVN and FVN-Hd depended on the cultivar thermo-photoperiodic response. FVN-Hd phase showed higher photoperiod sensitivity and intercepts values than the previous phase (Em-FVN). Those results are concurrent with previous works reported for photoperiod response throughout the crop cycle in barley. Kernich et al. (1997) and Miralles and Richard (2000) for Australian barley cultivars, and Slafer and Rawson (1996) and González et al. (2002, 2003, 2005) for Australian and Argentine wheat cultivars, all reported that immediate pre-heading/anthesis phases (i.e. around the stem elongation phase) tended to have a higher photoperiod sensitivity than previous phases. At the same time, changes in the duration of the phases in barley were associated with changes in photoperiod sensitivity rather than with optimum photoperiod or intrinsic earliness, similar to those reported for a wide range of Argentine commercial wheat cultivars (Miralles et al., 2007; Gomez et al., 2014). Except for BRS 195 and Scarlett, in the rest of the cultivars the late phase of FVN-Hd was more sensitive to photoperiod than the early phase of Em-FVN (Table 2). Thus, photoperiodic sensitivity was the main parameter that determined the variability in photoperiodic response among cultivars rather than optimum photoperiod or intrinsic earliness. This is in coincidence with previous evidence that demonstrated that photoperiodic sensitivity and optimum photoperiod are not related traits and the main difference between barley (or wheat) cultivars in their photoperiodic response is related to variations in photoperiodic sensitivity (Major, 1980; Slafer and Rawson, 1996; Whitechurch and Slafer, 2002; Gomez et al., 2014). BRS 195 and Scarlett showed slight variation in the

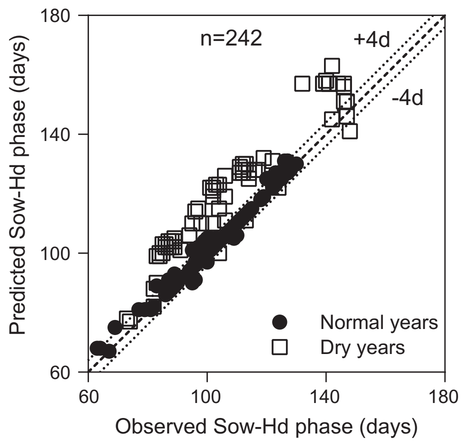

Fig. 5. Relationship between predicted and observed duration for the sowing-heading phase (Sow-Hd) for dry (empty squares) and normal years (full circles). Observed data were obtained from experiments carried out in Barrow, Bordenave and Buenos Aires from 1998 to 2008. The solid lines represent the 1:1 ratio and the dotted lines indicate a deviation of ±4 days.

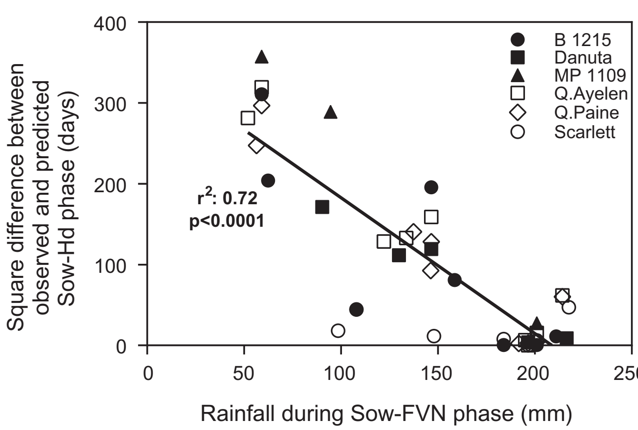

Fig. 6. Relationship between square difference of observed and predicted data (days) and rainfall during sowing to first visible node phase (mm), for the barley cultivars B1215 (full circles), Danuta (full squares), MP1109 (full triangles), Q. Ayelén (empty squares), Q. Painé (empty rhombus) and Scarlett (empty circles) in experiments carried out in Barrow, Bordenave and Buenos Aires from 1998 to 2008.

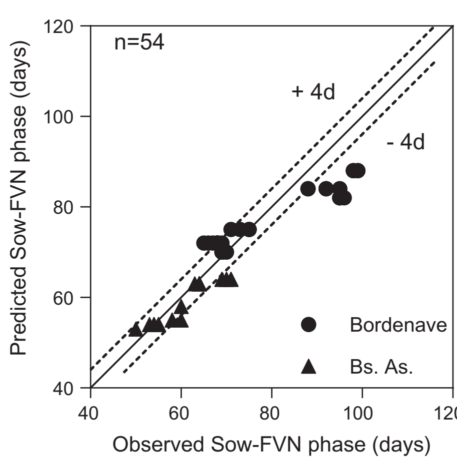

Fig. 7. Relationship between predicted and observed duration for sowing – first visible node phase (Sow-FVN). Observed data were obtained from experiments carried out in Bordenave (full circles) and Buenos Aires (full triangles) from 2006 to 2008. The solid line represents the 1:1 ratio and the dotted lines indicate a deviation of ±4 days.

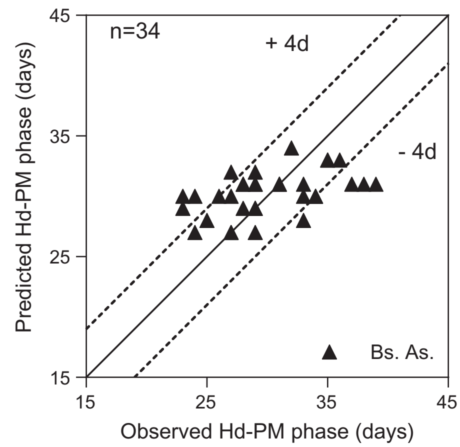

Fig. 8. Relationship between predicted and observed duration for heading – physiological maturity phase (Hd-PM). Observed data were obtained from experiments carried out in Buenos Aires from 2006 to 2008. The solid line represents the 1:1 ratio and the dotted lines indicate a deviation of ±4 days.

duration of FVN-Hd phase with changes in photoperiod, which determined a low photoperiodic sensitivity (i.e. values of $-20\,°C\,h^{-1}$ in BRS 195 and $-3\,°C\,h^{-1}$ in Scarlett in FVN-Hd phase) and a low r^2 adjustment, not being possible to estimate optimum photoperiod for those two cultivars (Table 2). In accordance to Slafer and Rawson (1994), some wheat cultivars are characterized by not showing an optimum photoperiod.

The grain filling phase, when measured in thermal time units, showed slight variations due to changes in sowing dates, similarly to those reported for wheat (Calderini et al., 1999). However, when Hd-PM phase was measured in days, the latest sowing date drastically reduced this phase duration, mostly associated with the higher temperatures experimented by the crop during the grain filling period (18 °C for the first sowing date and 23 °C for the last two sowing dates; supplementary data), which was widely described in the literature (Stone and Nicolas, 1994; Savin et al., 1996; Panozzo and Eagles, 1999; Passarella et al., 2002, 2005).

4.2. Benefits and limitations of the model

Crop phenology can be predicted by functional or mechanistic models, which use complex genetic coefficients for determining the crop response to temperature, vernalization and photoperiod (Weir et al., 1984; Otter-Nacke et al., 1991; Goyne et al., 1996; Jamieson et al., 1998a,b). Different simulation models developed for barley (CERES-Barley, Otter-Nacke et al., 1991; QBAR, Goyne et al., 1996) and wheat (ARCWHEAT1, Weir et al., 1984; CERES-Wheat, Ritchie and Otter, 1985; AFRCWHEAT2, Porter, 1993; Sirius, Jamieson et al., 1998b) can be used to predict phenology and other attributes related to crop yield generation. However, those models are complex because they need (i) several inputs (i.e. detail of the crop management, soil description, climate series and genetic coefficients), (ii) a demanding training for the user and (iii) important number of observations for their validation (Johnen et al., 2012). Thus, most of those models are not commonly used by consultants and/or technicians for crop management decisions due to complexity in their operation and calibration. The model proposed in the present study was built based on equations relating the duration of different crop phases with the DOEm based on the thermo-photoperiodic characterization of the cultivars.

The fact that the cultivars did not show vernalization requirements simplified the approach as the response of phenology to changes in DOEm was mainly associated with photoperiod sensitivity and temperature. Although the experiment to obtain the parameters to build the model was carried out in one growing season, the fact that cultivars were sown in a wide range of sowing dates (seven) ensured that the different genotypes explored a wide range of environments with different temperatures and photoperiods. These are the most relevant environmental variables that regulate barley development and thereby the duration of the phases evidenced a wide range of variation. This approach allows us to obtain the parameters (thermal-photoperiodic models) for a wide range of environmental conditions similar to those explored by the barley crop in the field.

The model predicted the occurrence of Hd with acceptable accuracy (i.e. within ±4 days) when water was not a limiting factor. Similar or lower accuracy values for heading and anthesis dates were observed in barley (±5.6 days, Travasso and Magrin, 1998) and wheat (±4.7 days, Jamieson et al., 1998b; ±7.0 days, Abeledo et al., 2008) using more complex models. However, the proposed model showed lower accuracy in dry years, showing a tendency to overestimate the duration of Sow-Hd phase. Although phenology is expected to be regulated by temperature, photoperiod and vernalization (Slafer and Rawson, 1994), evidence for wheat and barley (McMaster and Wilhelm, 2003), as well for triticale (Estrada-Campuzano et al., 2008), indicated shortening of the duration of crop growth phases (i.e. hastened development) when crops were grown under water stress. As the slope of the estimation for normal or dry years was not significantly different between both conditions, with a constant error estimation of 1 day per 10 days of duration of Sow-Hd phase (10%), a correction factor should be included in the model. Thus, the model could be improved to simulate crop development by considering the effect of water deficit as an initial input to be entered by the users (McMaster et al., 2011).

4.3. Utility of the model for crop management

The algorithms described above were included in a software with a simple structure and easy to use, such as wheat model PhenologyMMS (McMaster et al., 2011). The model named CRONOCEBADA© is free and available in www.agro.uba.ar/catedras/cerealicultura/servicios, and currently in use by professionals and farmers. The results demonstrated that, at least for barley cultivars without vernalization requirements (as used in the present study), a simple model can be built using the simple parameters required to create a thermo photoperiodic model exposing the crop to a wide range of environments (e.g. different sowing dates), allowing the cultivars to explore different temperatures and photoperiods during the whole cycle. Even when the thermo photoperiodic characterization was made from experiments carried out in one location (Buenos Aires, 34°35′S, 58°29′W), it can be extrapolated, using historical data series of temperature, to other more southern latitudes (as Barrow, 38°20′S, 60°17′W) and to northern locations with respect to that where the model was built, as demonstrated by the validation with independent data. A new version of the model with the latest cultivars released to the Argentine market will be available during 2014. In order to include parameters of new cultivars as well as other locations in the model, further experiments of sowing dates are required and it is necessary to repeat the exercise explained in this work, which is expensive and time consuming for the authors of the model but not for future users, contributing to expand the benefits of the model for farmers.

The proposed model allows determining the occurrence of different ontogenic stages in the most important commercial barley cultivars used in the region. The model allows to (i) determine the frost risk around heading (i.e. critical period for a frost event; Goyne et al., 1996) and (ii) the probability to escape from frost when different sowing dates or cultivars are used. The model is also a useful tool for farmers, for supporting crop management decisions, such as the occurrence of the critical period for yield determination (i.e. 40 days previous to Hd; Arisnabarreta and Miralles, 2008) or predict the window for hormonal herbicide application (e.g. 3–4 leaves until the first visible node).

In conclusion, this work confirmed that most of the widely distributed malting barley genotypes in Argentina (and other countries in South America) had a strong photoperiod response, but no detectable vernalization requirement. Thus, a simple model to predict phenology (with a friendly frame) was developed from the use of thermo-photoperiodic models and historical climatic series. It was successfully validated for different ontogenic stages and locations that included the malting barley belt of Argentina. At present, the model counts with two thousand registered users and it is a useful tool for planning malting barley sowing dates to establish frost risk, agrochemical applications and to predict when the field will be released to sow the following crop within the Argentine crop rotation diagram.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.compag.2014.05.011.

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