Validation of development models for winter cereals and maize with independent agrophenological observations in the BBCH scale

Article *in* Italian Journal of Agrometeorology · October 2009

Francesca Ventura
University of Bologna

Vittorio Marletto
Arpae (Environment and Energy Agency of Emilia-Romagna, Italy)

Fausto Tomei
Arpa Emilia-Romagna

VALIDATION OF DEVELOPMENT MODELS FOR WINTER CEREALS AND MAIZE WITH INDEPENDENT AGROPHENOLOGICAL OBSERVATIONS IN THE BBCH SCALE

CONVALIDA DI MODELLI DI SVILUPPO PER CEREALI VERNINI E MAIS CON RILEVAZIONI AGROFENOLOGICHE INDIPENDENTI NELLA SCALA BBCH

Francesca Ventura[1]*, Vittorio Marletto[2], Simon Traini[1], Fausto Tomei[2], Lucio Botarelli[2], Paola Rossi Pisa[1]

[1]*DiSTA, Dipartimento di Scienze e Tecnologie Agroambientali, Università di Bologna, via Fanin 44, 40127 Bologna*
[2]*Arpa-Simc, Arpa Emilia-Romagna, Servizio IdroMeteoClima, v.le Silvani 6, 40122 Bologna*
* *Corresponding author e-mail: fventura@agrsci.unibo.it*

Abstract
Phenological observations of four cereals (soft and durum wheat, barley and maize), carried out with the BBCH centesimal scale for three to four years in Cadriano, Italy, were compared with the numerical output of independently developed and calibrated phenological models taken from an operational agrometeorological software. The comparison produced rather stable and satisfactory results and so it was used to produce empirical translation functions from the model scale to the more widely used BBCH scale.

Keywords: *Triticum durum, Triticum aestivum, Ordeum vulgaris, Zea mays* L., crop phenology, phenological models

Riassunto
Le osservazioni fenologiche condotte con la scala centesimale BBCH su quattro cereali (grano tenero e duro, orzo e mais) per tre o quattro anni a Cadriano, Italia, sono state messe a confronto con i risultati numerici di modelli fenologici sviluppati e calibrati in maniera indipendente, tratti da un applicativo agrometeorologico operativo. I confronti hanno prodotto risultati piuttosto stabili e soddisfacenti, quindi sono stati usati per produrre delle funzioni empiriche di traduzione dalla scala del modello alla più diffusa scala fenologica BBCH..

Parole chiave : Triticum durum, Triticum aestivum, Ordeum vulgaris, Zea mays*, fenologia delle colture, modelli fenologici*

Introduction
Plant phenology is the science studying the relationships between climatic factors, seasonal changes and plant development cycles. Periodical and seasonal plant development phases (e.g. emergence, blossoming, fruit ripening, etc.) are defined as phenological stages or phenophases (Defila and Conedera, 2000). Phenology regards not only the knowledge of plant development, but also the understanding of the relationships between ambient temperature and biological development, considering how the climate and its elements, in a certain area, can influence habitat, morpho-physiology and the capacity of plants to adapt to environmental conditions.
The science of phenology needs the definition of clear keys (classification codes) in order to make comparable observations and surveys of phenological stages, carried out in different places and times. One of the most commonly used and efficient plant development scales for agricultural crops is the BBCH (Biologische Bundesanstalt, Bundessortenamt and CHemical Industry), adopted in Italy during the national research project Phenagri (Botarelli *et al.*, 1999). It is a two-digit decimal scale, allowing the description of every monocotyledon or dicotyledonous crop. It consists of one hundred stages, each describing a well determined level of development of the plant or of one of its organs. Therefore this scale describes both main development stages (numbered from 0 to 9) and secondary stages using the same digits (00 to 99; Meier, 2001).
Updated information regarding the current stage of crops and their development forecast is very important for agrometeorological bulletins, agricultural scheduling and technical assistance. Data can derive from agrophenological survey networks, whose maintenance is quite expensive because of the cost of human resources. Moreover, field data are difficult to get in real time and observations cannot be extrapolated to the area of interest with an acceptable level of accuracy (Borin *et al.*, 1996). In order to avoid these inconveniences, knowing meteorological conditions and forecasts, properly calibrated mathematical models can be used to simulate plant development with computers, allowing to produce reliable and updated regional phenological information (Pasquini *et al.*, 2006).
Phenological stages are determined by air temperature but there are also other factors, like vernalization and daylength, that strongly influence biological development (Marletto, 1999).
For this reason the operational phenological simulation system, developed and used by the Arpa-Simc agrometeorological office to produce weekly phenological bulletins, instead of the usual growing degree days approach, makes use of more complex phenological models. From

the practical point of view, these models are implemented within Praga, an operational software tool (Antolini and Tomei, 2006) providing spatially interpolated meteorological data and enabling both simulation and mapping of crop phenophases. Simulation maps are updated weekly and complemented with data and photographs of crops taken in the Cadriano agrophenological station. Such procedure is followed by Arpa-Simc, in cooperation with DiSTA, to produce phenological maps (Fig. 1) and weekly bulletins published on the web (http://tinyurl.com/22ovv4; http://tinyurl.com/2726wd). Complex phenological models output and observations carried out with the international scale BBCH are interesting to compare because they are both conceived to follow onthogenetic development of plants (e.g. the appearance of leaves) and not only macro events like emergence or flowering. The main aim of this work was to validate with phenological observations on four crops (durum wheat, soft wheat, barley and maize), carried out in an agrophenological station and codified using the BBCH scale, the output of the already independently calibrated operational phenological simulation models (Nerozzi *et al.*, 1998) included in the Praga operational system. Secondarily, as Praga uses its own codification of phenophases, empirical functions to translate them in the more common BBCH values were looked for.

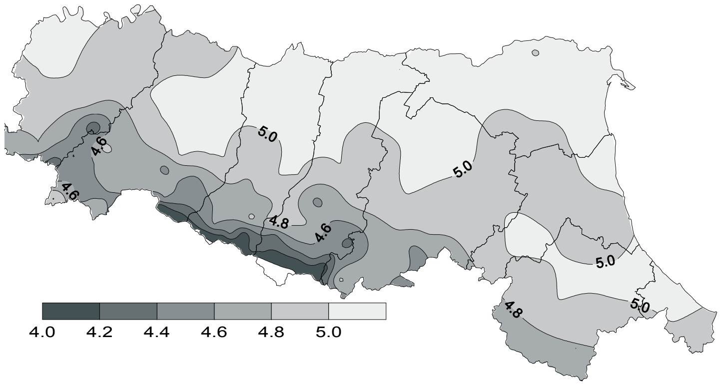


Fig. 1 - Example of agrophenological map generated with the Praga application program showing the simulated phenological stages of wheat in the Emilia-Romagna region, Italy. Stage 4 means *heading* and stage 5 means *physiological maturity*.

Fig. 1 - *Esempio di mappa agrofenologica generata con Praga: i livelli indicano lo stadio fenologico del frumento in Emilia-Romagna. Lo stadio 4 corrisponde alla* spigatura*, lo stadio 5 alla* maturazione fisiologica

Materials and methods

• *Agrophenological station in Cadriano (Bo)*

An agro-phenological station (Fig. 2), the first and only one of this type in Italy, was installed in 2003 in Cadriano (Bologna, Italy, 44° 33’ 03” N, 11° 24’ 36” E, 33 m a.s.l.), next to the University of Bologna agrometeorological station, in order to evaluate the effect of climate and its changes on plant development.

The soil and climate conditions of the area represent the environment of the Emilia-Romagna plains. The plots have the typical hydraulic arrangement of the area, their width and length are 30-50 m and 100-500 m respec-

Fig. 1 - View of the Cadriano agrophenological station, Bologna, Italy.

Fig. 2 - *Veduta della stazione agrofenologica di Cadriano, Bologna, Italia*

tively, with a light slope towards the long sides where the ditches are. These are 0.8 m deep and of small dimensions. Soil texture is sand 37%, silt 45%, clay 18% (F.C. 0.20 m^3/m^3; W.P. 0.11 m^3/m^3), with a shallow groundwater, ranging during the year between 0.80 and 2.40 m as an average (Rossi Pisa and Kerschbaumer, 1998).

The crops were selected on the base of the most common field varieties in Emilia-Romagna (Ventura *et al.*, 2006) and were sowed in isolated plots, one per plot; they were submitted to the normal agricultural practices, following the official regional guidelines (Disciplinari di produzione integrata, http://tinyurl.com/yt7z6y).

For every crop several rows were sowed, the number depending on the species, and the samples were selected only on the central rows, to minimize edge effects. Sowing was carried out with a mechanical sower. The cultivation of the crops was conducted under optimal water conditions especially at the beginning of the crop cycle. A water quantity suitable to stimulate germination and homogeneous emergence of the cotyledons was provided in case the soil humidity was a limiting factor. The weeds control was performed manually as soon as they emerged, to prevent possible ecophysiological competitions or damages caused by weed extraction.

During the first experimental year, starting in April 2003, the studied crops were: maize cv Cecilia (FAO class 500), potato cv Primura, soybean cv Sapporo, sunflower cv Proleic.

The phenological surveys were performed every week during the biological cycle using the BBCH centesimal scale (Meier, 2001), according to the operational protocol defined by the Italian Phenagri project (Botarelli *et al.*, 1999; Bernati *et al.*, 1999; Puppi and Zinoni, 1999). Of course, as the occurrence of consecutive BBCH stages can be very rapid only some of them were recorded, due to the weekly time step between observations.

Winter cereals have been studied from the second agricultural year (2003/2004), adding durum wheat, soft wheat, barley and oat. The scheme of the second experimental year has been used in the following years in order to keep the same sequence of surveys, following all the agricultural operations. From spring 2004 two other macrothermal crops - sorghum and tomato - have been added to the agrophenological station, while pumpkin was added in 2005. In this paper however only results from the winter cereals, durum wheat, soft wheat and barley, and from maize were considered.

The varieties used are widespread in Emilia-Romagna (Ventura *et al.*, 2004): for durum wheat Duilio, the second most common variety in Europe, for soft wheat Mieti, for barley Federal, for maize cv Cecilia in 2003 and the FAO class 500 variety PR34N43 in years 2004-2006.

For each species there are four or six rows and in order to minimize border effect, plant samples for observations were selected from the central rows. The sequence of the crops in the field and the respective sowing day during the years is shown in Tab. 1. More details about the agrophenological station and the used procedures are available in Ventura *et al.*, 2006.

Tab. 1 – Crops and sowing dates at the agrophenological station in Cadriano (Bologna).

Tab. 1 – *Colture e date di semina nella stazione agrofenologica di Cadriano (Bologna).*

Crop/Year	2003	2004	2005	2006
Barley	14-Nov	27-Oct	31-Oct	18-Oct
Oats	14-Nov	27-Oct	31-Oct	18-Oct
Soft wheat	14-Nov	27-Oct	31-Oct	18-Oct
Durum wheat	14-Nov	27-Oct	31-Oct	18-Oct
Potato	16-Apr	22-Mar	15-Mar	20-Mar
Sugarbeet	-	23-Mar	17-Mar	20-Mar
Sunflower	16-Apr	31-Mar	17-Mar	29-Mar
Maize	16-Apr	31-Mar	17-Mar	29-Mar
Tomato	-	01-Apr	01-Apr	05-Apr
Soybean	30-Apr	23-Apr	20-Apr	19-Apr
Sorghum	-	23-Apr	20-Apr	19-Apr
Pumpkin	-	-	28-Apr	27-Apr

- **Agrometeorological station and data**

For this work daily air temperature data were used. Data were recorded at the agrometeorological station of DiSTA, located in Cadriano, Bologna, next to the agrophenological station, in a fenced area of 30 x 40 m^2 covered by grass. For a complete description of the agrometeorological station see Ventura *et al.* (2002).

- **Biometric surveys**

Biometric surveys on winter cereals were carried out on 10 plants starting 30 days before the expected harvest date. Grain moisture was measured weekly. Plant height, number of plants per square meter, number of ears per plant, volumetric standard (hectolitre) mass, and yield were measured at harvest on a sample area.

For maize weekly surveys of plant height began when the tassel was completely emerged. Three ears were sampled every ten days starting from *stigmata completely dry* (BBCH69) to measure kernel moisture. When commercial moisture was reached the final survey was done, including plant dry weight, ear moisture and weight measured on a sample area.

- **The Praga phenological routines**

A set of operational routines based on mathematical models from the literature, was developed at Arpa-Simc and calibrated with field survey data (Nerozzi *et al.*, 1998) to simulate the phenological development stages of wheat, maize and other field crops. The routines describe the whole development cycle of crops from sowing to harvest, passing through the most important phenological phases. The wheat model routine starts at *sowing* (phase 1) and foresees the dates of *emergence* (2), *double ridge stage* (3), *heading* (4) and *physiological maturity* (5). For maize the model is the same except for stage 4 corresponding to *stigmata emergence* or female flowering. Details on the models are reported in the Appendix.

Calibration and validation of the two models were performed using observations from the period 1987-1996, obtained by surveys carried out in the framework of the

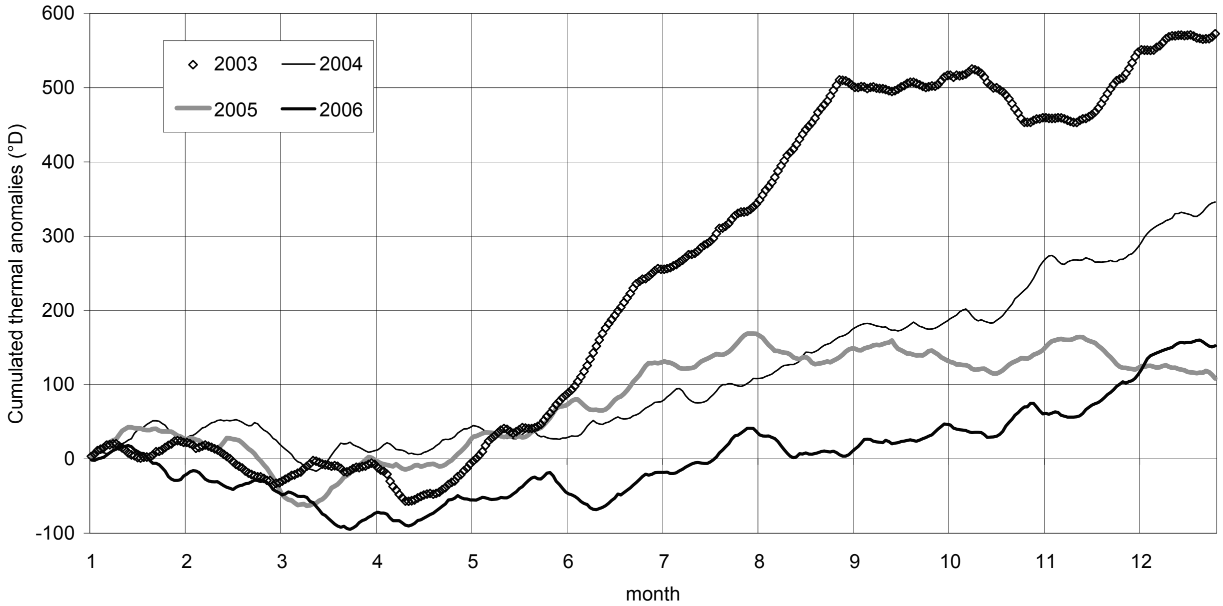


Fig. 3 - Comparison of cumulated thermal daily anomalies of years 2003 to 2006 with respect to the mean temperatures computed from 1961 to 1990.

Fig. 3 *– Confronto tra le anomalie termiche cumulate degli anni dal 2003 al 2006 calcolate rispetto alla temperatura media del periodo 1961-1990.*

Tab. 2 – Final biometric surveys for durum wheat during the 3 years of experimentation.

Tab. 2 – Rilievi biometrici finali del grano duro nei tre anni di sperimentazione.

				Final biometric surveys – Durum wheat							
harvest	**investment** plants m^{-2}	**h (cm) main stem**	**N° spikes**	**wFn (g) stems**	**wSn (g) stems**	**wFn (g) spikes**	**wFn (g) grains**	**wDn (g) grains**	**humidity (%) grains**	**yield ($t\ ha^{-1}$) grains**	**Weight ($kg\ hl^{-1}$) grains**
2004	491	83.90	2.90	4.26	3.90	6.47	4.95	4.42	10.76	5.31	83.1
2005	644	80.50	1.80	2.00	1.80	2.77	2.20	1.97	10.39	7.87	64.8
2006	371	83.30	2.90	6.54	4.41	8.37	6.95	6.16	11.38	8.34	80.0
average	502	82.57	2.53	4.26	3.37	5.87	4.70	4.18	10.84	7.17	76.0

w: weight; F: fresh; n: net; D: dry.

then existing Emilia-Romagna agrophenological network (Botarelli, 1990).

The phenological simulations used in this work were performed using daily minimum and maximum temperatures recorded in Cadriano between April 16th, 2003, and December 31st, 2006.

Results and discussion

- **Thermal data**

In order to present the thermal differences between years Fig. 3 shows the cumulated daily anomalies of each year of the study period (2003 to 2006), with respect to the 1961-1990 average.

All years resulted in final positive cumulated thermal anomalies, with year 2003 showing a very high anomaly, mainly cumulated from April to August. Year 2006 resulted negatively anomalous in the first semester, with consequent delays on crop phenology.

- **Biometric results at harvest**

The biometrical values recorded for all crops during the experimentation always showed normal crop behaviour and final yields. As an example data from durum wheat (Tab. 2) are presented and discussed.

Durum wheat final humidity values (H) were always below the commercial value of 13% (10.84% as an average in the 3 years). With such humidity a yield of 5.31 t/ha was calculated in 2003/04, which is a quite good value for Emilia-Romagna. The grains standard mass (kg/hl) was excellent, showing the high quality of grain filling, assuring that there were no physiological alterations during *milk* and *dough ripening*. In the second year density was 644 plants/m^2 but the effective spikes for plant were 1.8 on average, less then the previous year. In spite of that, the yield was high, with an average of 7.87 t/ha. In the last year the yield was the highest (8.34 t/ha), positively influenced by a good standard hectolitric mass, and the number of the spikes was almost 3 per plant, with around 370 plants/m^2

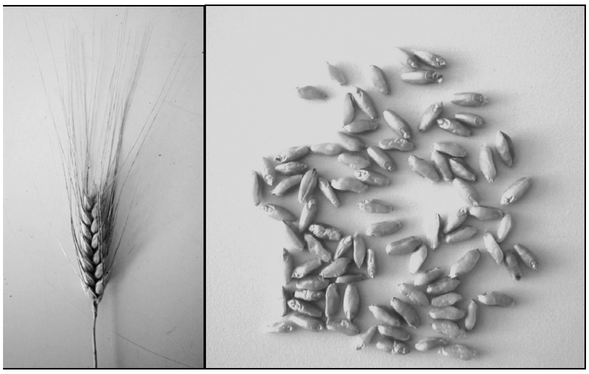


Fig. 4 – Durum wheat ear and grains at harvest (BBCH 99). The final biometric surveys were carried out on the whole plant and on the grains.

Fig. 4 – *Spiga di grano duro e granella alla raccolta (BBCH 99). I rilievi biometrici finali sono stati fatti sulla pianta intera e sulla granella.*

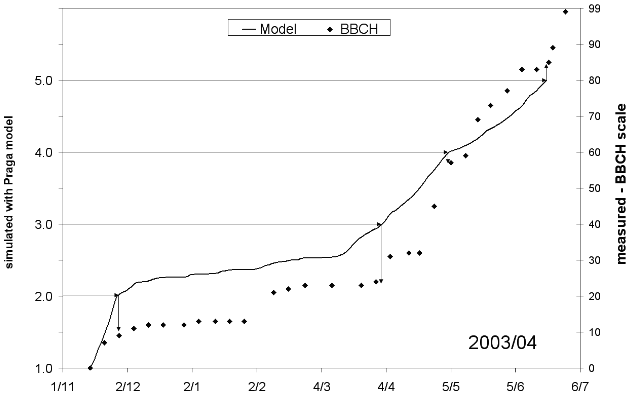


Fig. 5 – Correspondences between model output (scale 1-5 on the left) and observations (BBCH scale, 00-99 on the right) for durum wheat phenology in the Cadriano station, Bologna. The arrows lead from model main values to the closest in time BBCH observed values.

Fig. 5 – *Corrispondenze tra i risultati del modello (scala da 1 a 5, sulla sinistra) e le osservazioni fenologiche (scala BBCH da 00 a 99, sulla destra) per il frumento duro nella stazione di Cadriano, Bologna. Le frecce collegano le fasi principali del modello con quelle osservate in campo più vicine nel tempo.*

- **Model results**

Winter cereals

Fig. 5 shows the correspondences between simulated (model scale, left) and observed (BBCH scale, right) phenological stages for durum wheat in the agrarian year 2003/04. The shape of the two curves looks quite similar for both scales. For instance, following the arrows one can notice that there is a clear correspondence between the simulated stage 5 (*physiological maturity*) and the corresponding BBCH phase 85 (*soft dough ripening*).

A complete comparison between model output and field observations is available in Tab. 3, where model stages 2 to 5 are compared with BBCH stages in the three years for the three winter cereals. Model stage (MS) 2 (*emergence*) results practically coincident with BBCH stages 9 (*emergence*) to 11 (*first leaf unfolded*), while MS3 (*double ridges*) comes slightly before or coincident with BBCH 31 (*first node*), MS4 (*heading*) is comparable with *end of heading* (BBCH 59) for wheat or tends to coincide with *full flowering* (BBCH 65) for barley. Note that in the field stages 59 and 65 are always separated only by a few days, less than the time interval between observations at the agrophenological station, usually one week. MS5 coincides with BBCH 85 for durum wheat, appearing a little late for soft wheat, and moving towards *senescence* (BBCH 92-93) for barley.

The results presented before are satisfactory from the practical point of view, indicating that numerical model output and the related maps can be represented in BBCH scale. Fig. 6 presents a graphical comparison between the BBCH observed values and model output at the observation dates, showing a clear non linear relationship. Curvilinear regressions were fitted to quantify the relationship and the figure presents a 4th degree polynomial showing a very high determination coefficient. The degree of the polynomial ensures the three inflection points needed to satisfactorily fit the data.

In Fig. 7, data include three years of observations (2003/4 to 2005/6) for all three winter cereals. The graph shows again a 4th degree polynomial with $R^2 = 0.97$ and a RMSE = 4.9 arbitrary BBCH units, indicating that this type of function could reasonably be used for all the winter cereals with good reliability. Model outputs were linearly transformed in order to have an equation fitting exactly the point (1 , 00), representing the starting point of both models. Thus a simple operational relationship was found between model output and the corresponding BBCH observed data for winter cereals and for all phenological phases.

Tab. 3 - Correspondence between model output and field observations at Cadriano, Bologna, for three cereals and in three years. The dates refer to model reaching stages 2 to 5, while Δ represents the difference in days between the BBCH observation closest in time with model stage date.

Tab. 3 – *Corrispondenza tra i risultati del modello e le osservazioni fenologiche a Cadriano, Bologna, per tre cereali in tre anni. Le date si riferiscono al raggiungimento da parte del modello degli stadi da 2 a 5, il Δ è la differenza in giorni tra il modello e l'osservazione BBCH più vicina nel tempo.*

Model stage	date	Durum wheat		Soft wheat		Barley	
		BBCH	Δ (days)	BBCH	Δ (days)	BBCH	Δ (days)
2	23/11/03	09	0	09	1	10	1
	04/11/04	10	0	10	0	10	0
	10/11/05	11	0	11	0	11	0
3	02/04/04	31	4	31	4	30	0
	26/03/05	30	5	30	5	28	5
	10/04/06	31	0	31	0	31	0
4	04/05/04	57	1	57	1	59	1
	02/05/05	59	2	58	2	65	-1
	09/05/06	58	5	65	2	69	-2
5	19/06/04	85	2	87	-4	89	-4
	16/06/05	85	0	85	0	92	0
	23/06/06	85	-3	89	-3	93	-3

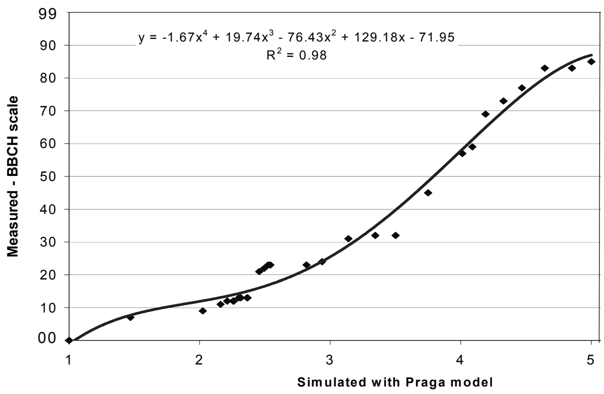


Fig. 6 – Comparison between Praga model output (scale 1-5) and observations (BBCH scale, 00-99) for durum wheat phenology for the year 2003/04, in the Cadriano station, Bo-logna.

Fig. 6 – *Confronto tra risultati del modello Praga (scala 1-5) e osservazioni (scala BBCH, 00-99) per frumento duro nell'anno 2003/2004, nella stazione di Cadriano, Bologna.*

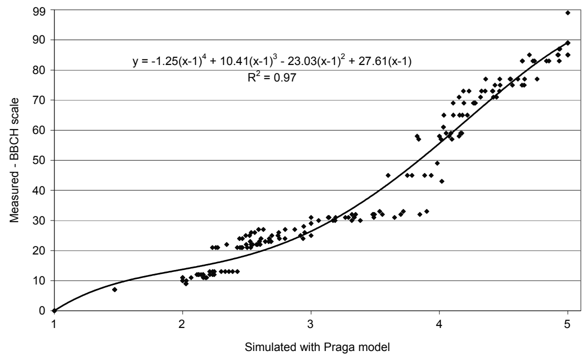


Fig. 7 – Comparison between Praga model outputs (scale 1-5) and observations (BBCH scale, 00-99) for durum wheat, soft wheat and barley phenology for the three years, in the Cadriano station, Bologna.

Fig. 7 – *Confronto tra risultati del modello Praga (scala 1-5) e osservazioni (scala BBCH, 00-99) per frumento duro, tenero e per l'orzo, nei tre anni di sperimentazione. nella stazione di Cadriano. Bologna.*

Maize

The Praga model was applied to the maize crop using the same procedure. The model enables to choose the FAO hybrid, in our case a 500 class maize was sowed during the 4 years of experimentation, and the output obtained were compared to experimental data.

A complete comparison between model output and field observations is available in Tab. 4, where model stages 2 to 5 are compared with BBCH stages in the four years for maize. Model stage (MS) 2 (*emergence*) coincides with BBCH stages 9 (*emergence*) to 11 (*first leaf unfolded*) with the exception of 2006 when these latter stages were not observed and MS almost coincides with stage 7 (*coleoptile emerged from caryopsis*). MS3 (*double ridges*) comes close to 4 to 7 *leaves unfolded* (BBCH 14 to 17). MS4 (*stigmata emergence*) resulted better comparable to *beginning to middle tassel emergence* (BBCH 51 and 55) instead of with female flowering (BBCH principal stage 6). Note that in 2005 the latter stages were not observed so MS4 comes close to stage 37 (*seven nodes detectable*). MS5 is close to BBCH 85 (*dough stage*) or 87 (*physiological maturity*); the high temperatures recorded in 2003 strongly influenced the ripening stages; the comparison of model output with observed data shows about a week of delay of the model (August 5th, 2003 instead of July 30th, 2003) and a coincidence of MS5 with BBCH 89 (*fully ripe*).

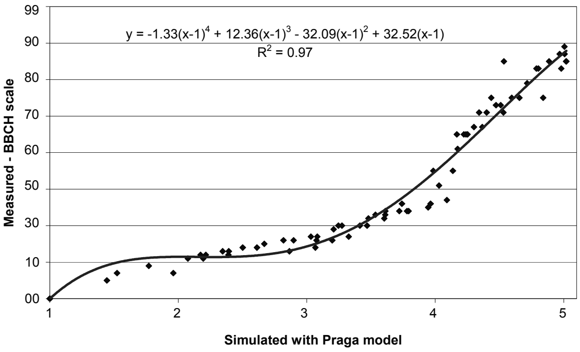
Summarizing, also for maize the behaviour of the model resulted quite stable compared to the experimental data, though less than for winter cereals. As it was done for the winter cereals, Praga model data and experimental BBCH observations of the four years were compared, as a single dataset (Fig. 8). For maize, though, principal stages 2 and 4 are not defined in the BBCH scale so observed stages above 30 were reduced by 10 and values above 50 where reduced by 20.

As for winter cereals a simple relationship between data produced by the model for every phenological phase and the BBCH data expressing the field observations was obtained. Also for maize the 4th degree polynomial regression equation was tested, as shown in Fig. 8, resulting in a quite satisfactory determination coefficient (R^2 = 0.97) and a good RMSE (3.4 arbitrary BBCH units). This allows the practical translation of the Praga maize model output in the widely used BBCH codification.

Tab. 4 - Comparison between model output and field observations at Cadriano, Bologna, for maize in four years. The dates refer to model reaching stages 2 to 5, while Δ represents the difference in days between the BBCH observation closest in time with model stage date.

Tab. 4 - *Confronto tra risultati del modello e osservazioni a Cadriano, Bologna, per il mais nei 4 anni di sperimentazione. Le date si riferiscono al raggiungimento da parte del modello degli stadi da 2 a 5, il Δ è la differenza in giorni tra il modello e l'osservazione BBCH più vicina nel tempo.*

Model stage	Date	Maize	
		BBCH	Δ (days)
2	26/04/03	09	-2
	13/04/04	11	2
	29/03/05	11	2
	11/04/06	07	-1
3	18/05/03	16	2
	11/05/04	17	1
	26/04/05	14	2
	07/05/06	17	4
4	18/06/03	51	0
	23/06/04	55	6
	12/06/05	37	2
	21/06/06	55	-1
5	05/08/03	89	1
	13/08/04	85	0
	03/08/05	85	5
	12/08/06	87	5



ig. 8 – Comparison between Praga model outputs (scale 1-5) and observations (BBCH scale, 00-99) for maize phenology during the four experimental years. Notice that principal stages 2 and 4 are not defined for maize in the BBCH scale.

ig. 8 *– Confronto tra risultati del modello Praga (scala 1-5) e osservazioni (scala BBCH, 00-99) per mais nei quattro anni di sperimentazione. Si noti che gli stadi principali 2 e 4 nella BBCH del mais non sono definiti.*

Conclusions

In this research, the phenological observations of some microthermal and macrothermal cereals were compared with an independently calibrated phenological model suite (Praga), currently used by Arpa-Simc to simulate crop phenology for the production of phenological weekly bulletins. Model outputs are in a different scale from the widely used BBCH, often chosen as a standard. The results obtained simulating crop development and comparing model outputs with field observed BBCH phenophases of durum wheat, soft wheat, barley and maize were quite interesting. The models appear reliable, especially for the simulation of ripening (BBCH 85 to 87); for example for the winter cereals in 2005 the dates of model stage 5 and BBCH 85 coincide. In maize the results of the model produced more discontinuous but still valid values.

Model outputs, on a truly continuous numerical scale, are not fully comparable with discrete BBCH values, that in effect are coding symbols, but enough correspondence between model output and observations was found to think that there was a clear possibility to produce model outputs directly in BBCH scale, in order to improve its interpretative use. The fitting of translation functions from the model scale to BBCH, resulted in very high determination coefficients. In this way, at least for the winter cereals and maize, the Praga phenological models can provide output directly in the BBCH scale.

Based on the elaborations and the obtained results, the authors intend to further apply the phenological models from the Praga suite to other crops, and to make them publicly available. In the near future application of the models will also be extended to climate change scenario analysis and to seasonal predictions. Farmers and extensionists could possibly use this tool as a useful support for agricultural planning and technical assistance.

Aknowledgements

The authors are deeply indebted with Nicola Gaspari and Fiorenzo Salvatorelli for their help in the setup and maintenance of the agrophenological station and also with numerous students that helped with field observations. This work was carried out with the financial support of Regione Emilia-Romagna, Assessorato Agricoltura, within the PhD thesis of Simon Traini in herbaceous crops, coordinated by Prof. Giovanni Toderi.

Appendix 1 - The phenological models

Winter cereals

The model simulates the following stages and the phases in between:

1. sowing, 2. emergence, 3. double ridge, 4. heading and 5. physiological ripening.

Phase 1-2 (Sowing – Emergence)

Under a controlled atmosphere, where it is possible to keep air temperature at constant values higher than the threshold temperature T_b, the development speed (defined as the inverse of phase duration) is linearly related with air temperature.This is consistent with the existence of a hyperbolic relationship between the duration of the germination period and the average temperature of the air (Summerfield *et al.,* 1991):

$$\frac{1}{f} = b(T - T_b)$$

where f is the number of the days between sowing and emergence of the plants, while b is a coefficient.

In field conditions, where the temperature of the air is not constant, the necessary thermal time θ for emergence is calculated by the following function:

$$\theta = \sum_{i=1}^{f} \max\{0; b(T_i - T_b)\}$$

where T_i is the mean temperature of the i-th day.

Emergence happens when θ value reaches 1. The coefficient b and the threshold temperature T_b were calibrated on the basis of phenological observations carried out in the former Emilia-Romagna agrophenological network (Nerozzi *et al.*, 1998).

The mean temperature has been calculated as the relationship between the sum of the daily mean temperatures and the number of the days between the date of sowing and the date of germination.

In this way some errors can occur if the daily mean temperature is, for a few days, lower then the threshold temperature (1 °C). Nevertheless, very low mean temperatures are rather rare in Emilia-Romagna during the autumn and the possible errors can be neglected.

Phase 2-3 Emergence – Double ridge
To simulate the date of the double ridge stage (when the vegetative apex stops the production of leaf primordia and switches to the production of the ear; Kirby and Appleyard, 1984) and the date of appearance of the last leaf, a model developed by Miglietta (1991a, b) has been used.
After emergence this model foresees a formation rate of the leaf *primordia* as a linear function of the mean temperature of the air, when this is higher than 2 °C, and increases the number of vegetative *primordia P* beginning from a number of 4 already in the seed:

$$\frac{dP}{dt} = \max\{0; 0.0149(T-2)\}$$

The number of the emerged leaves L_e is calculated by the following empirical function:

$$L_e = \frac{1}{\alpha}\left\{1-\exp\left[-\alpha\sum\frac{dP}{dt}\delta t)\right]\right\}$$

where α value is 0.03 and δt is the unitary interval. The model considers the difference of synchronization between the date of sowing and the coldest period of the year, or rather, for Emilia-Romagna, when the 5-day mobile mean of mean air temperature gets lower than 2 °C.
The total number of leaves of the crops sowed in the coldest period of the year is calculated in correspondence of the phase of germination L_p as a function of the photoperiod φ (Goudriaan and Van Laar, 1978) and a coefficient σ dependent on the latitude, in this case equal to 32,1 (Miglietta, 1991b):

$$L_p = 6.5 + \sigma\exp(-0.25\varphi)$$

For anticipated sowing, the total number of the leaves (L_t) is given by the sum of L_p with the number of the leaves already appeared on the main stem (L_e) when the sowed crops germinate in the coldest period of the year:

$$L_t = L_p + 0.65L_e$$

The coefficient L_e has been set equal to 0,65 as proposed by Miglietta (1991b). The double ridge stage is reached when the number of the initiated *primordia* is equal to the total number of the leaves L_t.

Phase 3-4 Double ridge - Heading
The *heading* phase is observed in field after the last leaf gets out and the booting stage. The criterion used to simulate the duration of the period between the last leaf and heading has been proposed by Grant (1989) in a model of maize. This criterion defines the duration as a function of the phyllochron (see below).

Phase 4-5 Heading - Physiological ripening
The degree days sums with threshold temperature of 9 °C (Weir *et al.,* 1984; Porter, 1984) were used to simulate the duration from heading to physiological ripening. Nevertheless, this model foresees the physiological ripening after 350 °D from flowering and, therefore, the level of the needed degree days to complete the heading-physiological ripening cycle has been estimated from data of the former agrophenological network of the region Emilia-Romagna.

Maize
The model simulates the following stages and the phases in between:
1. sowing, 2. emergence, 3. double ridge, 4. stigmata emergence, and 5. physiological ripening.

Phase 1-2 Sowing - Emergence
This phase is simulated considering thermal time, as in the wheat model (see above) but with a base temperature of 9.8 °C.

Phase 1-3 Emergence – Double ridge – Stigmata emergence
The dates of the *double ridge stage* and of *stigmata emergence* are calculated by the model of Grant (1989). For every FAO classes (from 200 to 700), the model sets a maximum number of leaves, that increases during the season as a function of photoperiod and soil temperature:

$$L_t = L_j + L_\varphi + L_T$$

L_j is the number of the *primordia* specific for each precocity class at the beginning of the production of the *flowering ridges* (juvenile phase), while L_φ and L_T are the terms that express the photoperiod and temperature effects, which value is, respectively:

$$L_\varphi = 0.1(L_j - 10)(\varphi - 12.5)$$

$$L_T = 13.6 - 1.89T_s + 0.081T_s^2 - 0.001T_s^3$$

Ts represents the calculated soil surface temperature.
In the next equation the rate of the primordial leaf formation is:

$$\frac{dP}{dt} = -0.00065 - 0.0139T_s + 0.00372T_s^{\ 2} - 0.000072T_s^{\ 3}$$

P represents the number of the vegetative *primordia*, while T_s is the superficial soil temperature. The number of the vegetative *primordia* grows during the season from a number of 5, already present in the seed, up to the total number of leaves.
The number of the *primordia* is daily calculated and constantly compared with the average value of L_t calculated from the germination up to the current day.
The *double ridge stage* happens when the daily value of the *primordia* is equal to the mean value of L_t, corresponding to the total number of the leaves.
The rate of leaves emergence is calculated using the function described by Tollenaar and Hunter (1983):

$$\frac{dL}{dt} = -0.0997 - 0.0360T + 0.00362T^2 - 0.0000639T^3$$

T represents the value of the soil surface temperature until the *double ridge stage*, then it assumes the value of the air temperature.
The daily rate of leaves emergence is the average of the values respectively calculated with the minimum and maximum air temperature considering that the function is

Appendix 2. BBCH phenological stages for cereals and maize (Meier, 2001).

Principal stage	Winter Cereals	Maize (Zea mays L.)
0 Germination	00 Dry seed (caryopsis) 01 Beginning of seed imbibition 03 Seed imbibition complete 05 Radicle emerged from caryopsis 06 Radicle elongated, root hairs and/or side roots visible 07 Coleoptile emerged from caryopsis 09 Emergence: coleoptile penetrates soil surface (cracking stage)	00 Dry seed (caryopsis) 01 Beginning of seed imbibition 03 Seed imbibition complete 05 Radicle emerged from caryopsis 06 Radicle elongated, root hairs and/or side roots visible 07 Coleptile emerged from caryopsis 09 Emergence: coleoptile penetrates soil surface (cracking stage)
1 Leaf development	10 First leaf through coleoptile 11 First leaf unfolded 12 2 leaves unfolded 13 3 leaves unfolded 1 . Stages continuous till ... 19 9 or more leaves unfolded	10 First leaf through coleoptile 11 First leaf unfolded 12 2 leaves unfolded 13 3 leaves unfolded 1 . Stages continuous till ... 19 9 or more leaves unfolded
2 Tillering	20 No tillers 21 Beginning of tillering: first tiller detectable 22 2 tillers detectable 23 3 tillers detectable 2 . Stages continuous till ... 29 End of tillering.Maximum no.of tillers detectable	
3 Stem elongation	30 Beginning of stem elongation: pseudostem and tillers erect, first internode begins to elongate, top of inflorescence at least 1 cm above tillering node 31 First node at least 1 cm above tillering node 32 Node 2 at least 2 cm above node 1 33 Node 3 at least 2 cm above node 2 3 .Stages continuous till ... 37 Flag leaf just visible, still rolled 39 Flag leaf stage: flag leaf fully unrolled, ligule just visible	30 Beginning of stem elongation 31 First node detectable 32 2 nodes detectable 33 3 nodes detectable 3 . Stages continuous till ... 39 9 or more nodes detectable
4 Booting	41 Early boot stage: flag leaf sheath extending 43 Mid boot stage: flag leaf sheath just visibly swollen 45 Late boot stage: flag leaf sheath swollen 47 Flag leaf sheath opening 49 First awns visible (in awned forms only)	
5 Inflorescence emergence, heading	51 Beginning of heading: tip of inflorescence emerged from sheath, first spikelet just visible 52 20% of inflorescence emerged 53 30% of inflorescence emerged 54 40% of inflorescence emerged 55 Middle of heading: half of inflorescence emerged 56 60% of inflorescence emerged 57 70% of inflorescence emerged 58 80% of inflorescence emerged 59 End of heading: inflorescence fully emerged	51 Beginning of tassel emergence: tassel detectable at top of stem 53 Tip of tassel visible 55 Middle of tassel emergence: middle of tassel begins to separate 59 End of tassel emergence: tassel fully emerged and separated
6 Flowering, anthesis	61 Beginning of flowering: first anthers visible 65 Full flowering: 50% of anthers mature 69 End of flowering: all spikelets have completed flowering but some dehydrated anthers may remain	61 Male: stamens in middle of tassel visible. Female: tip of ear emerging from leaf sheath 63 Male: beginning of pollen shedding. Female: tips of stigmata visible 65 Male: upper and lower parts of tassel in flower. Female: stigmata fully emerged 67 Male: flowering completed. Female: stigmata drying 69 End of flowering: stigmata completely dry.
7 Development of fruit	71 Watery ripe: first grains have reached half their final size 73 Early milk 75 Medium milk: grain content milky, grains reached final size, still green 77 Late milk	71 Beginning of grain development: kernels at blister stage, about 16% dry matter 73 Early milk 75 Kernels in middle of cob yellowish-white (variety-dependent), content milky, about 40% dry matter 79 Nearly all kernels have reached final size
8 Ripening	83 Early dough 85 Soft dough: grain content soft but dry.Fingernail impression not held 87 Hard dough: grain content solid.Fingernail impression held 89 Fully ripe: grain hard, difficult to divide with thumbnail	83 Early dough: kernel content soft, about 45% dry matter 85 Dough stage: kernels yellowish to yellow (variety dependent), about 55% dry matter 87 Physiological maturity: black dot/layer visible at base of kernels, about 60% dry matter 89 Fully ripe: kernels hard and shiny, about 65% dry matter
9 Senescence	92 Over-ripe: grain very hard, cannot be dented by thumbnail 93 Grains loosening in day-time 97 Plant dead and collapsing 99 Harvested product	97 Plant dead and collapsing 99 Harvested product

not linear. The number of the emerged leaves is calculated starting from an initial leaf value.

The phase of stigmata emergence happens after the emission of all the leaves and follows the male flowering or tassel emergence. Grant's model simulates this phenological phase after a period of time from the last leaf emission, similar to the fictitious emission of two further leaves.

Phase 4-5 Stigmata emergence - Physiological ripening

The physiological ripening happens after a certain quantity of Maize Heat Units calculated by the Ontario method (Desiderio and Monotti, 1979) from the date of female flowering:

$$\theta_x = \max(0; T_x - 10)$$

$$\theta_n = \max(0; T_n - 4.4)$$

$$CHU = 0.5(1.85\theta_x - 0{,}047\theta_x^{\ 2} + \theta_n)$$

The necessary quantity of the Maize Heat Units at the ripening depends on the FAO class.

References

Antolini, G., Tomei, F., 2006. Praga - programma di analisi e gestione di dati agrometeorologici (poster). Atti del convegno Aiam 2006, Torino, 6-8 giugno 2006, RiAM 11(suppl. 1), 79-82.

Bernati, E., Botarelli, L., Cosentino, S., Ferraresi, A., Nieddu, G., Sirca, C., 1999. La conduzione agronomica ed il rilevamento agrofenologico nelle prove sperimentali. In: Botarelli et al. *(eds.). Aspetti generali delle osservazioni agrofenologiche. Collana di Agrofenologia, volume 1, Progetto finalizzato Mipaf PHENAGRI, Roma, 48-64.*

Borin, M., Palchetti, C., Schiavon, A., 1996. La rete fenologica del mais (Zea mays L.) nella Pianura Veneta. I. Caratteristiche e rappresentazione spaziale. Riv. di Agron., 30 (3 Suppl.), 500-505.

Botarelli, L., 1990. La rete agrofenologica. Agricoltura, Regione Emilia-Romagna, 12/90: 64-65.

Botarelli, L., Brunetti, A., Pasquini, A., Zinoni, F. (a cura di), 1999. Aspetti generali delle osservazioni agrofenologiche. Collana di Agrofenologia, MiPAF, P.F. Phenagri, Fenologia per l'Agricoltura. Vol. 1, pp 110.

Defila, C., Conedera, M., 2000. Il contributo della fenologia alla discussione sul clima: potenzialità e limiti presentati all'esempio del sud delle Alpi della Svizzera. Boll. Soc. Ticin. Sci. Nat. 88: 29-39.

Desiderio, E., Monotti, M., 1979. La definizione di precocità degli ibridi. L'Italia Agricola, 116, 225-234.

Goudriaan, J., van Laar, H.H., 1978. Calculation of daily totals of the gross CO2 assimilation of leaf canopies. Neth. J. Agric. Sci. 26, 373-382.

Grant, R.F., 1989. Simulation of maize phenology. Agron. J. 81:451-457.

Kirby, E.J.M., Appleyard, M., 1984. Cereal Development Guide, 2nd edn. Arable Unit, National Agricultural Centre, U.K.

Marletto, V., 1999. Fenologia vegetale. In "Aspetti generali delle osservazioni agrofenologiche" a cura di A. Brunetti e F. Zinoni. Progetto finalizzato PHENAGRI. Roma, Volume 1, 7-13.

Meier, U., (ed.) 2001. Growth stages of mono-and dicotyledonous plants. BBCH Monograph. 2nd Edition. Federal Biological Research Centre for Agriculture and Forestry, http://tinyurl.com/26j3b3.

Miglietta, F., 1991a. Simulation of wheat ontogenesis: I. Appearance of main stem leaves in the field. Clim. Res., 1, 145-150.

Miglietta, F., 1991b. Simulation of wheat ontogenesis: II. Predicting dates of ear emergence and main stem final leaf number. Clim. Res, 1, 151-160.

Nerozzi, F., Zinoni, F., Marletto, V., 1998. Calibrazione e validazione di due modelli fenologici operativi per il frumento e per il mais in Emilia-Romagna. Riv. Agron. 32: 112-123.

Pasquini, A., Botarelli, L., Dal Monte, G., Traini, S., 2006. Il rilevamento agrofenologico: dall'osservazione in campo alla registrazione dei dati, Collana di Agrofenologica, Vol. 2, CRA – UCEA, Roma, 142 pp.

Porter, J.R., 1984. Modelling stage development in winter wheat. Aspects of Applied Biology, 4, 449-455.

Puppi, G., Zinoni, F., 1999 - La fenologia in agricoltura.In: "Aspetti generali delle osservazioni agrofenologiche" a cura di Botarelli et al. *Collana di Agrofenologia, MiPAF, P.F. Phenagri. Vol. 1, 14-18.*

Rossi Pisa, P., Kerschbaumer, A., 1998. Rappresentazione spazio temporale di dati di profondità di falda. Quad. Georgofili III, 173-186.

Summerfield, R.J., Roberts, E.H., Ellis, R.H., Lawn, R.J., 1991. Towards the reliable prediction of time to flowering in six annual crops. I. The development of simple models for fluctuating field environments. Expl. Agric., 27, 11-31.

Tollenaar, M., Hunter, R.B., 1983. A photoperiod and temperature sensitive period for leaf number of maize. Crop Sci., 23, 457-460.

Ventura, F., Gaspari N., Traini S., Rossi Pisa, P., Guarise M., 2004. Rilievi fenologici come indicatori del cambiamento climatico. Atti Convegno Aiam2004, "Gli agroecosistemi nel cambiamento climatico", Matera, 22-23 Aprile 2004, 80-81 (http://tinyurl.com/25gzra).

Ventura, F., Rossi Pisa, P., Ardizzoni, E., 2002. Temperature and precipitation trends in Bologna (Italy) from 1952 to 1999. Atmospheric Research 61, 203-214.

Ventura, F., Traini, S., Gaspari, N., Rossi Pisa, P., Marletto, V., Zinoni, F., 2006. La prima stazione agrofenologica italiana: installazione e risultati preliminari. Riv. Ital.Agromet. 11 (1), 41-45.

Weir, A.H., Bragg, P.L., Porter, J.R.E., Rayner, J.H., 1984. A winter wheat crop simulation model without water or nutrient limitations. J. Agric. Sci., Camb., 102, 371-382.