Int J Biometeorol (2011) 55:723–732
DOI 10.1007/s00484-010-0387-0

ORIGINAL PAPER

Predicting apricot phenology using meteorological data

Mirjana Ruml · Dragan Milatović · Todor Vulić · Ana Vuković

Received: 4 June 2010 / Revised: 28 October 2010 / Accepted: 28 October 2010 / Published online: 21 November 2010

Abstract The main objective of this study was to develop feasible, easy to apply models for early prediction of full flowering (FF) and maturing (MA) in apricot (*Prunus armeniaca* L.). Phenological data for 20 apricot cultivars grown in the Belgrade region were modeled against averages of daily temperature records over ten seasons for FF and eight seasons for MA. A much stronger correlation was found between the phenological timing and temperature at the very beginning than at the end of phenophases. Also, the length of developmental periods were better correlated to daily maximum than to daily minimum and mean air temperatures. Using prediction models based on daily maximum temperatures averaged over 30-, 45- and 60-day periods, starting from 1 January for FF prediction and from the date of FF for MA prediction, the onset of examined phenophases in apricot cultivars could be predicted from a few weeks to up to 2 months ahead with acceptable accuracy. The mean absolute differences between the observations and cross-validated predictions obtained by 30-, 45- and 60-day models were 8.6, 6.9 and 5.7 days for FF and 6.1, 3.6 and 2.8 days for MA, respectively. The validity of the results was confirmed using an independent data set for the year 2009.

Keywords Phenological model · Apricot · Full flowering · Maturing

M. Ruml (✉) · D. Milatović · T. Vulić · A. Vuković
Faculty of Agriculture, University of Belgrade,
Nemanjina 6,
11080, Belgrade, Serbia
e-mail: mruml@agrif.bg.ac.rs

Introduction

Mathematical models are the basic tools used to predict the timing of phenological events. There are two main approaches in designing such models. One is physiologically based and takes into account cause–effect relationships between biological processes and driving external forces—most often climatic (Schaber and Badeck 2003). Another approach is statistical, and uses correlations between phenophase onset of different species or correlations between phenological timing and meteorological variables (Črepinšek et al. 2006). Most phenological models are statistical, since our understanding of the physiological mechanisms involved in plant development is still very limited. A number of studies have found air temperature to be the dominant factor controlling the timing of spring phases. Some models consider only the action of forcing temperatures (Snyder et al. 1999; Nendel 2010) while others also consider the action of chilling temperatures (Egea et al. 2003; Ruiz et al. 2007). In some studies, inter-annual variability in phenology is linked to other variables, such as photoperiod (Črepinšek et al. 2006) and rainfall (Peñuelas et al. 2003), or to large-scale weather features, such as the North Atlantic Oscillation (Menzel 2003).

The complexity and design of phenological models depend on their purpose, but also on the practical problem of providing data for driving variables. Since phenological timing is often extremely sensitive to inter-annual variations in thermal conditions, we have tried to develop simple but accurate models based on air temperature to predict phenological development of apricot cultivars grown under given environmental conditions. Generally, the apricot has a limited area of adaptation, and leading cultivars are different in each apricot-producing region. In Serbia, the dominant apricot cultivar is Hungarian Best, while other cultivars, both foreign and new Serbian ones, are distributed to a lesser extent. A specific knowledge of the influence of local climatic conditions on the phenology of different cultivars would offer producers information about possibilities of growing new and non-native cultivars in a given area, especially ones that can be sold in the more profitable early market. Phenological predictions can help to get more stable crop yields and quality through improved crop management, providing dates for timely irrigation, fertilizing, and crop protection. Apricot production in Serbia is characterized by high year-to-year yield oscillations, caused mostly by late spring frost damage. Thus, it is of particular importance for farmers to know, during a growing season, whether frost protection is needed. The timing of initial growth in spring affects the risk of frost damage to orchard crops, which is more likely when crops have an early bud-burst. Maturing prediction, if effective, could improve market delivery of fruits.

In order to address these issues, 20 apricot cultivars of diverse geographical origin and different flowering and maturing time were selected from the experimental orchard located in the vicinity of Belgrade. A relationship between phenophase appearance and air temperature was examined and periods when temperature had the most significant influence on apricot development were identified. Finally, aiming to forecast the onset of full flowering and maturing of apricot cultivars as early as possible with acceptable accuracy, we developed prediction models based on the responsiveness of phenological timing to the preceding thermal conditions.

Materials and methods

Site

The study was carried out at Radmilovac, the experimental station of the Belgrade Faculty of Agriculture, situated near Belgrade (44°45′ N, 20°35′ E, 112 m a.s.l.). This region has a mid-latitude moderate continental climate (Koeppen's Cfw) with mean annual air temperature of 10.8°C and mean annual precipitation of 640 mm. The warmest month is July with an average temperature of 20.8°C and the coldest month is January with an average temperature of −0.5°C.

Data

Two phenological stages of apricot were examined: full flowering (FF) and maturing (MA). The FF date was the date when about 80% of flowers were fully open. The beginning of the harvest was recorded as the MA date.

A group of 20 cultivars (Tables 1, 2), spanning the range of apricot FF and MA time in the Belgrade region, was selected from the first, older collection orchard to built prognostic models. All cultivars were represented by five trees of the same age, planted in the spring of 1993. The trees were grafted on myrobalan (*Prunus cerasifera* Ehrh.) seedlings and planted with a spacing of 4.5×4.5 m. Phenological observations were performed from 1995 to 2004. Years 1998 and 2002 were excluded from the MA data set, because of severe spring frost damage that occurred after very warm winters.

Phenological data for the year 2009, used for validation of models, were collected in the second, newer collection orchard that was planted in three consecutive years from 2005 to 2007 at the same experimental station. The trees were grafted on myrobalan (*Prunus cerasifera* Ehrh.) seedlings and planted with a spacing of 4×3 m. Only cultivars that were present in both orchards, older and newer, were considered. For testing the FF model, there were seven such cultivars. Unfortunately, for MA model validation, data for only three cultivars were available, because the cultivars that were planted latterly did not fruit in their 2nd year.

Daily maximum (T_x) and minimum (T_n) air temperatures were measured with standard National Weather Service thermometers at 2 m above the soil surface at a climatological station located 200 m from the experimental orchards. Thermal conditions varied considerably over the studied period, with very warm winters in 1998 and 2002. The average annual temperature for the period considered (1995–2004) was 1.2°C higher than the mean value for a preceding 45-year period (1951–1995).

Statistical methods

In order to build statistical models correctly, a standard statistical analysis of phenological data was carried out: averages, minima and maxima were calculated. Phenological data were subjected to analysis of variance (ANOVA) in order to examine cultivar effect on the length of phenophases.

Periods during the temperature had the most significant influence on apricot development were determined using Pearson's correlation coefficient (R). Examined phenophases were divided into several sub-periods and averages of daily T_n, T_x and mean temperatures $[T_m = (T_n + T_x)/2]$ over each sub-period were calculated. The length of phenophases was defined as the number of days from starting date to FF (NDFF) and to MA (NDMA). We considered the 30-, 45- and 60-day sub-periods after the starting date, and sub-periods of the same length before the ending date of phenophase. For the NDFF, the starting date was arbitrary, since we did not take into account the chilling

Table 1 Observed number of days from 1 January to full flowering (NDFF) for the 1995–2004 period. *Average* Averaged values, *Amplitude* difference between largest and smallest NDFF, *Diff* difference between the cultivar's mean NDFF and average value for all cultivars. There were no significant differences in averaged values among cultivars at P=0.05 according to Duncan's multiple range test

Cultivar	Year										Average	Amplitude	Diff
	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004			
Bergeron	75	113	89	67	86	88	74	65	99	83	83.9	48	0.2
Cacak's Gold	78	114	89	66	86	89	75	65	99	84	84.5	49	0.8
Detskyi	73	112	88	63	86	89	74	65	96	82	82.8	49	-0.9
Drjanovska Kasna	77	113	89	66	86	89	74	66	98	83	84.1	47	0.4
Harcot	76	113	89	63	86	89	74	65	99	83	83.7	50	0.0
Hungarian Best	78	114	91	65	87	89	75	65	100	84	84.8	49	1.1
Kecskemet Rose	79	113	89	66	87	89	75	65	100	84	84.7	48	1.0
Kisiniev Early	76	113	90	67	86	89	75	65	96	86	84.3	48	0.6
Ligeti Orias	75	113	88	62	84	88	73	63	94	82	82.2	51	-1.5
Melitopol Early	74	113	89	64	85	88	74	65	96	82	83.0	49	-0.7
Mramornyi	75	113	88	62	85	88	73	63	97	82	82.6	51	-1.1
NJA-1	73	111	88	61	84	89	72	63	95	81	81.7	50	-2.0
Nugget	73	113	88	63	84	88	73	63	96	82	82.3	50	-1.4
Roxana	81	114	94	69	89	91	77	67	102	88	87.2	47	3.5
Senetate	75	112	88	65	85	88	75	64	95	82	82.9	48	-0.8
Silistrenska Kompotna	81	114	93	68	88	90	76	65	100	84	85.9	49	2.2
Stark Early Orange	74	113	88	63	84	88	73	63	94	82	82.2	50	-1.5
Stella	83	115	96	71	90	93	78	68	104	91	88.7	47	5.0
Szegedi Mammut	74	113	88	62	84	88	73	63	94	82	82.1	51	-1.6
Tyrinthos	69	111	84	57	83	88	70	63	94	80	79.9	54	-3.8
Average	76	113	89	65	86	89	74	65	97	83	83.7	50	
Amplitude	14	4	12	14	7	5	8	5	10	11	8.8		

requirements. We performed correlation analysis for several starting dates: 1 December, 15 December, 1 January, 15 January and 1 February in order to choose the most suitable one for given climatic conditions. For the NDMA, the starting date was the date of FF.

Linear regression functions based on temperature averages for selected sub-periods were used to develop prediction models for FF and MA of apricot cultivars. Parameters were fitted using 10 years of observations for FF and 8 years for MA from the 1995–2004 dataset.

To obtain a more reliable estimation of the accuracy of the models, a cross-validation procedure was carried out, where the models were, in turn, developed with all the included years but one. In this procedure, the regression coefficients were re-estimated using 9 out of 10 years for FF and 7 out of 8 years for MA; the remaining year was modeled by these re-estimated coefficients. In this way, we provided independent data sets for testing, 10 for FF and 8 for MA. From the predictions of all data sets, the predictive quality of the models was estimated by computing the following performance measures: (1) mean absolute error (MAE) to inform about the actual size of the error produced by the model on an average level; (2) index of agreement (IA), a relative and bounded measure that compares the predictions and observations on an individual level (0 indicates complete disagreement and 1 perfect agreement). The MAE and IA (Willmott 1981) were calculated using Eqs. 1 and 2, respectively:

$$MAE = \frac{\sum_{i=1}^{N} \left| n_i^p - n_i^o \right|}{N} \tag{1}$$

$$IA = 1 - \frac{\sum_{i=1}^{N} \left(n_i^p - n_i^o \right)^2}{\sum_{i=1}^{N} \left(\left| n_i^p - n_{mean}^p \right| + \left| n_i^o - n_{mean}^o \right| \right)^2} \tag{2}$$

where n_i^p and n_i^o are the predicted and observed number of days within the development period in the ith year, n_{mean}^p and n_{mean}^o are the means of the predicted and observed number of days for all years, and N is the number of years.

Additional validation was performed with data for 2009—the year not used to fit the models. This data set

Table 2 Observed number of days from full flowering to maturing (NDMA) for the 1995–2004 period (years 1998 and 2002 excluded). *Average* Averaged values, *Amplitude* difference between largest and smallest NDMA, *Diff* difference between the cultivar's mean NDMA and average value for all cultivars. Means within the *Average* column not sharing a common following letter are significantly different at P= 0.05 according to Duncan's multiple range test

Cultivar	Year								Average	Amp	Diff
	1995	1996	1997	1999	2000	2001	2003	2004			
Bergeron	126	92	122	115	95	117	92	115	109.3 abcd	34	12.1
Cacak's Gold	116	82	109	104	87	111	83	104	99.5 abcd	34	2.3
Detskyi	114	77	103	98	83	101	79	102	94.6 abcd	37	-2.5
Drjanovska Kasna	124	99	125	117	97	123	95	120	112.5 a	30	15.3
Harcot	106	74	104	103	76	106	75	101	93.1 abcd	32	-4.0
Hungarian Best	114	80	108	101	83	108	82	105	97.6 abcd	34	-0.5
Kecskemet Rose	126	97	122	115	99	126	91	119	111.9 a	35	14.7
Kisiniev Early	98	66	94	86	73	94	80	90	85.1 cd	32	-12.0
Ligeti Orias	118	86	109	109	92	112	89	109	103.0 abcd	32	5.8
Melitopol Early	96	59	90	86	72	95	70	91	82.4 d	37	-14.8
Mramornyi	104	70	97	94	79	98	76	99	89.6 bcd	34	-7.5
NJA-1	110	76	102	107	79	104	76	103	94.6 abcd	34	-2.5
Nugget	116	79	103	109	79	106	82	102	97.0 abcd	37	0.2
Roxana	119	88	106	114	87	120	84	109	103.4 abcd	36	6.2
Senetate	94	60	90	92	72	91	67	89	81.9 d	34	-15.3
Silistrenska Kompotna	118	90	113	110	92	119	91	112	105.6 abcd	29	8.5
Stark Early Orange	110	75	101	103	75	104	80	100	93.5 abcd	35	-3.7
Stella	109	82	101	98	82	106	77	98	94.1 abcd	32	3.0
Szegedi Mammut	123	89	110	110	94	115	92	112	105.6 abcd	34	8.5
Tyrinthos	104	70	99	91	73	101	75	97	88.8 bcd	34	-8.4
Average	112	80	105	103	84	108	82	104	97.2	34	
Amplitude	32	40	35	31	27	35	28	31	30.6		

was considered separately, since it contained observations for fewer cultivars than the 1995–2004 dataset. Finally, in order to gain wider insight into the prediction-observation discrepancy, predicted vs observed values of NDFF and NDMA for all cultivars over all years were plotted.

Results

Phenological data analysis

The average time of apricot FF in the Belgrade region was the third decade of March (Table 1). The mean NDFF differed from 80 to 89 days among cultivars. A much greater variation in NDFF was found between years for a single cultivar (47 to 54 days) than among cultivars within individual years (4 to 14 days). The mean NDMA ranged from 82 to 112 days (Table 2). Differences in the NDMA among cultivars were 27 to 40 days within a year, while inter-annual variation of NDMA for the single cultivar ranged from 29 to 37 days. ANOVA showed that the cultivar had a significant influence on the NDMA, but not on the NDFF (Tables 1 and 2). In years with late FF, the NDMA was smaller than in years with earlier FF. In the year with the latest FF and the smallest NDMA (1996), the least variation of FF time (4 days) and the greatest variation of NDMA (40 days) among cultivars were recorded.

Pheno-climatic correlation analysis

Preliminary correlation analyses indicated that FF time was correlated much more strongly with the mean monthly temperatures after than before 1 January. The variables that had the most significant effect on the NDMA were FF date and post flowering temperatures. While the correlation between the NDMA and FF time was significant, the correlation between the MA and FF time was non-significant.

The values of R between phenophase length averaged over all cultivars, and T_x, T_n and T_m averaged over different sub-periods, are shown in Table 3. For NDFF, correlations are given using 1 January as the starting date, since the best results in terms of correlation with phenological observations were obtained for that date, while 15 January showed the next best performance (data not shown).

Table 3 Pearson's correlation coefficients (R) between the phenological and temperature data (1995–2004, years 1998 and 2002 excluded for maturing). *NDFF* Number of days from 1 January to full flowering, averaged over all cultivars; *NDMA* number of days from full flowering to maturing, averaged over all cultivars; T_x daily maximum, T_n daily minimum, T_m daily mean air temperature averaged over first and last 30, 45 and 60 days of the phenophase and over the entire phase

Temperature	First			Last			Entire phase
	30 days	45 days	60 days	30 days	45 days	60 days	
	NDFF						
T_x	-0.59 *	-0.90 ***	-0.92 ***	0.11 ns	-0.29 ns	-0.42 ns	-0.88 ***
T_n	-0.33 ns	-0.61 *	-0.72 **	0.33 ns	-0.10 ns	-0.27 ns	-0.56 *
T_m	-0.50 ns	-0.81 **	-0.86 ***	0.29 ns	-0.25 ns	-0.38 ns	-0.77 **
	NDMA						
T_x	-0.90 **	-0.98 ***	-0.99 ***	-0.50 ns	-0.48 ns	-0.40 ns	-0.97 ***
T_n	-0.78 *	-0.86 **	-0.88 **	-0.09 ns	-0.32 ns	-0.07 ns	-0.82 **
T_m	-0.86 **	-0.95 ***	-0.96 ***	-0.42 ns	-0.43 ns	-0.28 ns	-0.95 ***

*$P<0.05$, **$P<0.01$, ***$P<0.001$, ns non significant

The results showed that NDFF and NDMA in apricot were better correlated to T_x than to T_n and T_m. A much stronger correlation was found between the phenological timing and temperature at the beginning than at the end of examined phenophases. The mean T_x for the first 60 days in the developmental period was best correlated with the observed data for both phenophases. Stronger correlations were obtained for 45- and 60-days means than for the means over the whole developmental period.

Statistical models and validation

Since the onset of the selected phenophases was best correlated with mean T_x, the forecasting models were built using this variable. The fact that phenological timing, especially the onset of MA, differed considerably among cultivars suggests that the same regression equation could not be applied to all apricot cultivars. Instead of determining the best-fitting model equations for each cultivar, the general model equations, obtained by using phenological data averaged over all cultivars, were adjusted for each cultivar by adding a correction factor. The correction factor equals a difference between the mean length of phenophase for cultivar in question and average value for all examined cultivars (given in Tables 1 and 2) rounded to the nearest whole number. The correction factor was used only if its value was greater than 2 days. The general regression equations based on T_x averaged over 30-, 45- and 60-day periods, together with the coefficients of determination (R^2) are given in Fig. 1.

The computed performance measures MAE and IA for the 1995–2004 dataset are presented in Table 4. Differences between the observations and predictions for the year 2009, characterized by rather late FF and smaller than average NDMA, are shown in Table 5. Scatter plots of predicted vs observed NDFF and NDMA for all cultivars over all years are shown in Fig. 2 (1:1 line indicates the perfect fit).

According to MAE and IA, the MA models performed better than FF models. Variation of MAE among cultivars was greater for NDMA than NDFF predictions, which concurs with the greater variation of the NDMA itself among cultivars. A much larger cultivar effect on NDMA predictions and greater year effect on NDFF prediction are illustrated clearly in the scatter plots. In the NDFF plots, dots representing different cultivars are clustered by year, while in the NDMA plots, they are distributed evenly along the 1:1 line.

Although the 60-day models gave the best results for both phenophases according to performance measures, and the 30-day models the worst, it should be pointed out that the 60-day model will not give the most accurate prediction in all instances, and that the 45-day model will always outperform the 30-day model. The performance of the models depends on the meteorological conditions of a particular year. Unusual weather that departs considerably from the average during the modeled period lessen model accuracy. This is particularly true for FF models. In 1996, the year with the latest FF date, all models considerably underestimated the observations (Fig. 2a–c), because of exceptionally unusual weather—a not so cold winter followed by a very cold March, especially during its first half. The 45-day model performed worst among the FF models in 2001 (Fig. 2b), as well as in 2009 (Table 5). The poor performance of the 45-day model in both years was due to a very warm first half of February (30th to 45th day) followed by much colder weather up to the end of the month. When the years 1996 and 2001 were eliminated from the FF data set, a better correlation between the phenological and temperature data was obtained for the 45-day model (R=0.96) than for the 60-day model (R=0.94).

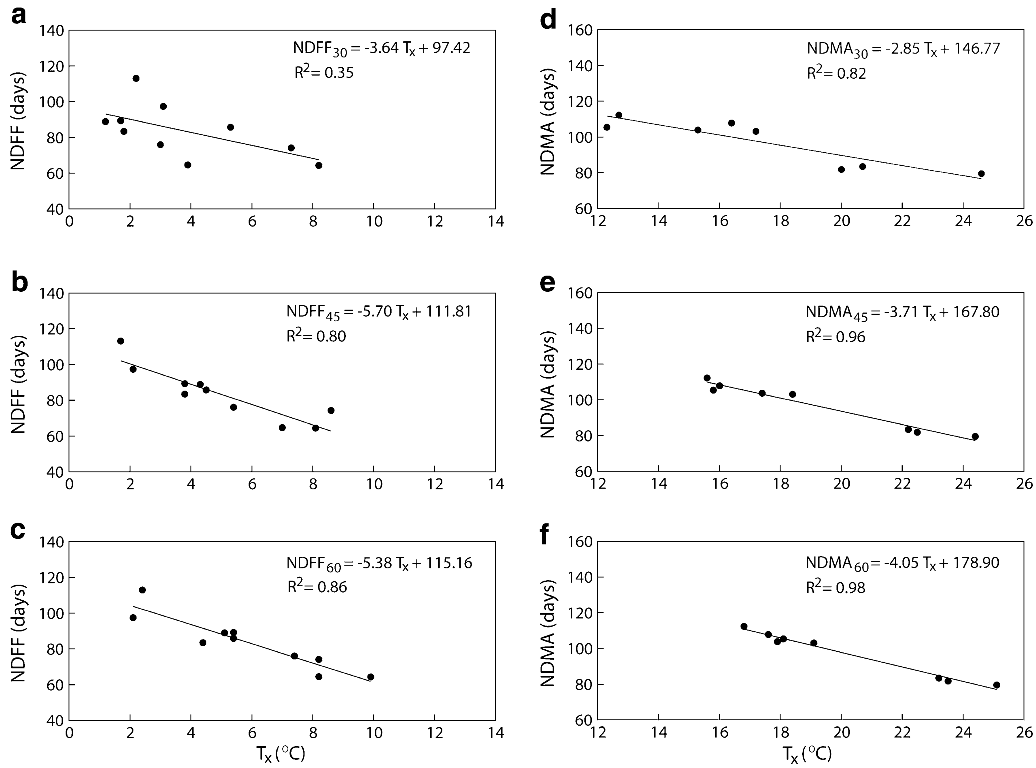

Fig. 1 Relationships between the number of days from 1 January to full flowering (NDFF) and number of days from full flowering to maturing (NDMA) and daily maximum temperature (T_x) averaged over 30 days (**a**, **d**) 45 days (**b**, **e**) and 60 days (**c**, **f**)

Thus, it can be concluded that the 45-day FF model better simulated the observed data than the 60-day model in years with thermal conditions close to normal during the modeled period.

In order to examine the correctness of our approach in developing general models, we established specific equations for each cultivar for both examined phenophases. The MAE of these fits (data not shown) was very similar to that obtained by using general equations.

Discussion

Phenological data

Findings obtained by phenological data analysis agree with the results of some other studies conducted at sites with mid-latitude continental climate. Szabó and Nyéki (1999) in Hungary, and Vachůn (2003) in the Czech Republic also found much greater variation of blooming time between years for single apricot cultivars than between cultivars within individual years. A greater variation of blooming time among cultivars was found in regions with a warmer climate, e.g., in Italy (Della Strada et al. 1989) and Spain (Ruiz et al. 2007). Vachůn (2003) also reported less inter-annual variation of MA than FF time of apricot and, interestingly, he found that the year with very late FF and small NDMA was the same year as in our data (1996). The similarities found in our data and the phenological data analysis of other authors indicate that the results from this study could be applicable to other regions with similar climatic conditions.

Pheno-climatic correlations

A number of studies have found good correlation between the onset of phenological stages and air temperature. The periods of the year that best correlate with phenological timing differ. Also, there is no consensus whether T_n, T_x or T_m is the most influential in plant development.

According to Due et al. (1993), who modeled grapevine phenology (budburst, flowering and harvest), averages of meteorological data taken 3 weeks or more prior to phenological events were significantly associated with their occurrence in different climatic regions of Australia. Ahas et al. (2000) found good correlation between the starting dates of phenophases and the temperature of the previous 2–3 months for different tree species. Peiling et al. (2006)

Table 4 Mean absolute error (*MAE*) and index of agreement (*IA*) between the observations and cross-validated predictions of number of days from 1 January to full flowering (NDFF) and from full flowering to maturing (NDMA) for 30-, 45- and 60-day models (1995–2004, years 1998 and 2002 excluded for maturing)

Cultivar	NDFF						NDMA					
	30-day		45-day		60-day		30-day		45-day		60-day	
	MAE (days)	IA	MAE (days)	IA	MAE (days)	IA	MAE (days)	IA	MAE (days)	IA	MAE (days)	IA
Bergeron	8.3	0.74	7.3	0.87	5.9	0.91	5.1	0.93	3.1	0.97	1.6	0.99
Cacak's Gold	8.6	0.74	7.2	0.88	5.8	0.92	4.6	0.94	1.9	0.99	1.4	1.00
Detskyi	9.5	0.72	7.5	0.88	5.4	0.93	5.6	0.93	3.4	0.97	2.4	0.99
Drjanovska Kasna	8.4	0.74	6.4	0.88	5.8	0.92	3.5	0.96	2.1	0.99	2.9	0.97
Harcot	8.8	0.74	7.4	0.88	5.4	0.92	5.0	0.94	2.7	0.98	1.3	1.00
Hungarian Best	8.4	0.74	7.8	0.87	6.0	0.91	6.9	0.90	4.3	0.96	3.3	0.98
Kecskemet Rose	8.7	0.76	7.9	0.88	5.7	0.92	7.5	0.89	4.8	0.95	3.3	0.98
Kisiniev Early	8.9	0.74	6.7	0.89	5.2	0.93	6.9	0.90	3.4	0.98	3.2	0.98
Ligeti Orias	8.8	0.74	7.4	0.88	5.6	0.92	5.5	0.93	3.4	0.98	2.5	0.98
Melitopol Early	8.7	0.74	7.7	0.88	5.9	0.92	7.7	0.89	5.1	0.95	4.3	0.96
Mramornyi	9.0	0.72	6.0	0.89	5.8	0.93	5.7	0.93	3.4	0.97	2.2	0.99
NJA-1	8.0	0.78	6.1	0.91	5.1	0.94	6.8	0.86	4.6	0.95	3.2	0.96
Nugget	8.5	0.73	6.3	0.88	5.8	0.92	6.0	0.92	3.1	0.98	2.5	0.98
Roxana	8.4	0.74	7.8	0.87	5.8	0.91	5.5	0.92	3.5	0.97	2.4	0.99
Senetate	8.5	0.74	7.9	0.87	5.9	0.91	6.0	0.90	3.6	0.96	2.6	0.98
Silistrenska Kompotna	8.1	0.76	5.8	0.90	5.4	0.94	9.1	0.81	5.3	0.95	5.4	0.95
Stark Early Orange	8.5	0.74	6.2	0.89	6.1	0.92	6.1	0.89	3.3	0.97	2.2	0.98
Stella	8.5	0.74	6.4	0.89	5.5	0.93	5.5	0.93	3.1	0.98	3.4	0.98
Szegedi Mammut	8.3	0.74	6.3	0.89	5.6	0.93	6.2	0.90	2.9	0.97	2.9	0.97
Tyrinthos	8.6	0.73	5.9	0.89	5.7	0.93	6.7	0.88	4.0	0.95	3.2	0.98
Average	8.6	0.74	6.9	0.88	5.7	0.92	6.1	0.91	3.6	0.97	2.8	0.98

reported that the significant period of temperature influence on the flowering in four tree species was 30 days before flowering in a monsoon climate of the Beijing region. According to their results, flowering of *Prunus davidiana* and *Prunus armeniaca* was better correlated to T_m than to T_n and T_x, while flowering of *Robinia pseudoacacia* and *Syringa oblata* were better correlated to T_x. Wielgolaski (2001) noted that night temperature is generally the most

Table 5 Observed and predicted number of days from 1 January to full flowering (*NDFF*) and number of days from full flowering to maturing (*NDMA*) for 30-, 45- and 60-day models for the year 2009; *MAE* absolute error between the observed and predicted values averaged over all cultivars

Cultivar	NDFF				NDMA			
	Observed (days)	n			Observed (days)	Predicted by model (days)		
		30-day	45-day	60-day		30-day	45-day	60-day
Bergeron	94	97	100	95	96	98	97	97
Harcot	94	97	100	95				
Hungarian Best	93	97	100	93	84	87	85	85
Mramornyi	92	96	99	92				
Roxana	93	93	96	96	90	92	90	91
Senetate	94	98	101	94				
Stark Early Orange	94	96	99	96				
MAE (days)		2.9	5.9	1.0		2.3	0.7	1.0

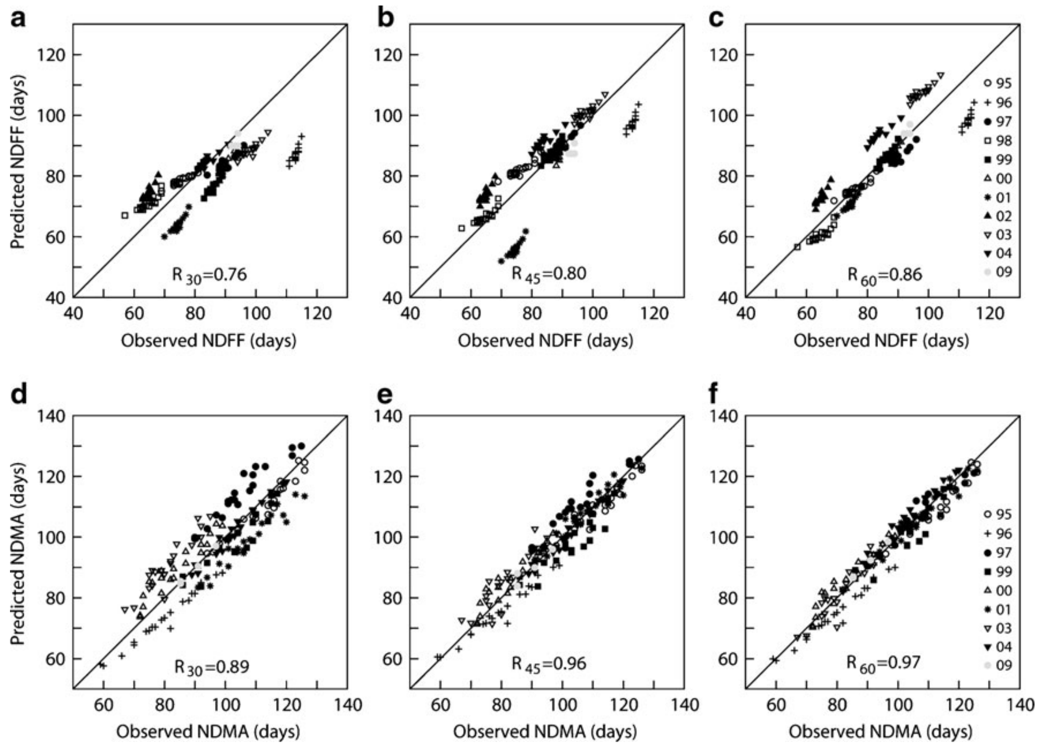

Fig. 2 Observed vs predicted number of days from 1 January to full flowering (NDFF) and number of days from full flowering to maturing (NDMA) using 30-day (**a**, **d**) 45-day (**b**, **e**) and 60-day (**c**, **f**) models

important factor during mainly vegetative periods, while day temperature affects the more generative phases. Similarly, Mimet et al. (2009) reported that the pre-flowering phases of *Platanus acerifolia* and *Prunus cerasus* in western France are best correlated with the mean T_n for the 15-day period before the observation, whereas flowering appears to be more dependent on the mean of the daily diurnal temperature range for 8 days preceding the observation. Considering fruit maturation, there have been suggestions that the length of the fruit development period is related to early spring temperatures in peach (Weinberger 1948) and in apricot (Brown 1952).

Reported differences in the periods of the year that have the most effect on the phenological timing and differences in the most influential temperature variable (T_n, T_x or T_m) could be assigned to many factors, such as climatic conditions, lateness of the species, differences among species in response to daylight (maximum) and to nighttime (minimum) temperatures, and different growth response to temperature in various developmental periods.

In our study, temperature was better correlated with NDMA than NDFF (Table 3). A possible reason is that we used an arbitrary starting date for NDFF instead of the end date of the previous phenological phase, and/or because the year effect is more pronounced in the case of NDFF than NDMA. In contrast, Schwartz et al. (1997) reported that MA of peach cultivars in the southeastern United States is less predictable than FF, at least in terms of the temperature variables used in the study. The results of this study indicate that, under our climatic conditions, a 30-day period after 1 January is not long enough for a reliable forecast of FF (Table 4, Fig. 1a). Prediction of MA using a 30-day temperature record following FF is much more reliable (Table 4, Fig. 1d). Litschmann et al. (2008) investigated the relationship between the sum of hourly active temperatures above 7°C (SAT7) and phenological phases of peach grown in the Czech Republic. The correlation (R=0.53) between the SAT7 1 month after blossom and NDMA was much weaker than in our study (R=0.90). For a 2-month period after blossom the correlation (R=0.91) was much stronger and closer to ours (R=0.98). Smith (1985) obtained an R value of 0.81 between the heat unit summation for 60 days past FF and NDMA for peach grown in the Niagara Peninsula, Canada.

The results of the correlation analysis and the fact that satisfactorily accurate predictions were obtained without the inclusion of chilling in the FF model, suggest that the chilling requirement of all examined apricot cultivars is generally satisfied by 1 January under the given climatic conditions, and that apricot flowering time is more influenced by heat than chill accumulation—most likely due to the early completion of chilling in the study region. Studies on *Juglans regia* (Mauget, 1977, 1980, cited in Chuine et al. 1999) strongly suggest that dormancy intensity does not influence the timing of budburst if dormancy is broken by the end of December. García de Cortázar-Atauri et al. (2009) came to the same conclusion when they evaluated several models for predicting budburst date of grapevine in France. However, there are opposing findings and opinions in the literature about the importance of chilling temperatures for early spring phenology in temperate trees. In almonds, according to Alonso et al. (2005), heat requirements were found to be more important for regulation of blooming time than chilling requirements in the cold climatic conditions of Zaragoza (north-east Spain). However, in south-east Spain, the almond flowering time was influenced more by chilling than by heat requirements (Egea et al. 2003). Chuine et al. (1999) have shown that thermal time models give more effective prediction of flowering phenology in some temperate-zone trees grown in southern France than models that also incorporate the effects of chilling. Although there is no common position applicable to all species in all climatic conditions, it seems that chilling plays only a minor role in spring phenology in colder climatic conditions and our study results support this hypothesis.

Statistical models and validation

The proposed phenological models have several plus points: the possibility of early predictions, satisfactory accuracy and simplicity.

Most existing phenological models are based on the heat accumulation required to reach a particular developmental stage. These models, to be predictive, have to use weather forecast products that are reliable up to at most 7 days ahead. In addition, a constraint of these models is the existence of threshold temperatures that may vary not only between locations and between species, but also between cultivars, in grafted material between stocks, and even between individuals (Wielgolaski 1999). There were similar attempts to ours to predict the onset of phenophase using heat sums for the first 30–80 days, but to the best of the authors' knowledge such models were developed only for harvest and none of them for apricot (Smith 1985; Ben Mimoun and DeJong 1999; Marra et al. 2002; Day et al. 2008; Litschmann et al. 2008).

Using the presented models, FF and MA in apricot cultivars can be predicted from a few weeks to up to 2 months ahead, depending on the thermal conditions in a particular year. Balancing between the accuracy and the range of the prediction, we find the 45-day model to be an optimal solution and recommend it as a base model for predicting apricot phenology. Generally, it provides more accurate forecasts than the 30-day model, but still early enough to have a practical use. Compared to the 45-day model, the 60-day model did not give considerably more accurate predictions, but in some cases the predictions obtained came too late. This is particularly true for FF because in some years apricot reached this phenological stage at the beginning of March. Another way to apply the proposed models is to use the 30-day model to estimate the FF or MA time and then, as time passes, improve the accuracy of the predictions by updating them using the 45-day and 60-day models.

Considering the high year-to-year variability of NDFF (49 days) and NDMA (34 days on average for all cultivars), the models provide satisfactorily accurate predictions. On the other hand, the calculated MAE (Table 4) is close to values obtained with other, often more sophisticated, phenology models (Schwartz et al. 1997; Chuine et al. 1999; Snyder et al. 1999; Črepinšek et al. 2006; Peiling et al. 2006; García de Cortázar-Atauri et al. 2009; Caffarra and Eccel 2010; Nendel 2010; Ruml et al. 2010). Our results also compare well with results obtained by the above-mentioned models for early prediction of harvest. Smith (1985), using prediction equations for the harvest of three peach cultivars based on growing degree-day simulation over different periods for different cultivars (40, 60 and 80 days past FF), predicted harvest dates within 6 days of actual dates. Ben Mimoun and DeJong (1999) established regression equations for the harvest of different peach and nectarine cultivars based on heat accumulation 1 month after bloom. The actual and predicted dates differed from 0 up to 18 days, depending on the cultivar and the method used to calculate heat accumulation. Non-linear models based on growing degree hours (GDH) were used by Marra et al. (2002) to predict the NDMA in five peach and nectarine cultivars. Taking into account the whole fruit developmental period, the MAE averaged over all cultivars was 3 days, while the MAE was 2 days when heat accumulated within 25–55 days after FF was used. The finding that early forecasting of the harvest was more accurate than that calculated from climatic data of the whole developmental period agrees with the results of our pheno-climatic correlation analysis (Table 3). It should be noted that all of these models for early prediction are cultivar-specific, except that proposed by Day et al. (2008). They developed a predictive model for estimating the NDMA based on GDH accumulated 30 days after bloom using a 5-year data series for four peach and four nectarine cultivars.

The results of this study are particularly encouraging given our effort to develop simple, easy to apply models. The advantage of our models is that they are based on daily temperature data that are readily available from most weather stations, and that calculation procedures are maximally simplified (even computation of heat sums are not required). Also, our models offer general regression equations for apricot as a fruit species that can be easily modified for a greater number of cultivars by using a single cultivar-specific parameter. Despite their simplicity, the models showed a high capacity for predicting the onset of FF and MA in different apricot cultivars in the studied region and, importantly, early enough to be useful for agricultural practices. Additional validation tests made with a greater number of observations (years) would be very valuable in their further evaluation.

Acknowledgments This study was conducted within research project III 43007 supported by the Serbian Ministry of Science and Technological Development. The authors would like to thank anonymous reviewers for constructive comments and valuable suggestions that have helped improve this paper.

References

Ahas R, Jaagus J, Aasa A (2000) The phenological calendar of Estonia and its correlation with mean air temperature. Int J Biometeorol 44:159–166

Alonso JM, Ansón JM, Espiau MT, Socias i Company R (2005) Determination of endodormancy break in almond flower buds by a correlation model using the average temperature of different day intervals and its application to the estimation of chill and heat requirements and blooming date. J Am Soc Hortic Sci 130:308–318

Ben Mimoun M, DeJong TM (1999) Using the relation between growing degree hours and harvest date to estimate run-times for peach: a tree growth and yield simulation model. Acta Hortic 499:107–114

Brown DS (1952) Climate in relation to deciduous fruit production in California. V. The use of temperature records to predict the time of harvest of apricots. J Am Soc Hortic Sci 60:197–203

Caffarra A, Eccel E (2010) Increasing the robustness of phenological models for *Vitis vinifera* cv. Chardonnay. Int J Biometeorol 54:255–267

Chuine I, Cour P, Rousseau DD (1999) Selecting models to predict the timing of flowering of temperate trees: implications for tree phenology modelling. Plant Cell Environ 22:1–13

Črepinšek Z, Kajfež-Bogataj L, Bergant K (2006) Modelling of weather variability effect on fitophenology. Ecol Model 194:256–265

Day K, Lopez G, DeJong T (2008) Using growing degree hours accumulated thirty days after bloom to predict peach and nectarine harvest date. Acta Hortic 803:163–167

Della Strada G, Pennone F, Fideghelli C, Monastra F, Cobianchi D (1989) Monografia di cultivar di albicocco. Istituto Sperimentale per la Frutticoltura, Ministry of Agriculture, Rome, Italy

Due G, Morris M, Pattison S, Coombe BG (1993) Modeling grapevine phenology against weather-considerations based on a large data set. Agric For Meteorol 65:91–106

Egea J, Ortega E, Martinez-Gomez P, Dicenta F (2003) Chilling and heat requirements of almond cultivars for flowering. Environ Exp Bot 50:79–85

García de Cortázar-Atauri I, Brisson N, Gaudillere JP (2009) Performance of several models for predicting bud burst date of grapevine (*Vitis vinifera* L.). Int J Biometeorol 53:317–326

Litschmann T, Oukropec I, Křižan B (2008) Predicting individual phenological phases in peaches using meteorological data. Hortic Sci (Prague) 35(2):65–71

Marra FP, Inglese P, DeJong TM, Johnson RS (2002) Thermal time requirement and harvest time forecast for peach cultivars with different fruit development periods. Acta Hortic 592:523–529

Menzel A (2003) Plant phenological anomalies in Germany and their relation to air temperature and NAO. Clim Change 57:243–263

Mimet A, Pellissier V, Quénol H, Aguejdad R, Dubreuil V, Rozé F (2009) Urbanisation induces early flowering: evidence from *Platanus acerifolia* and *Prunus cerasus*. Int J Biometeorol 53:287–298

Nendel C (2010) Grapevine bud break prediction for cool winter climates. Int J Biometeorol 54:231–241

Peiling L, Qiang Y, Jiandong L, Xuhui L (2006) Advance of tree flowering dates in response to urban climate change. Agric For Meteorol 138:120–131

Peñuelas J, Fillela I, Zhang X, Llorens L, Ogaya R, Lloret F, Comas P, Estiarte M, Terradas J (2003) Complex spatiotemporal phenological shifts as a response to rainfall changes. New Phytol 161:837–846

Ruiz D, Campoy AA, Egea J (2007) Chilling and heat requirements of apricot cultivars for flowering. Environ Exp Bot 61:254–263

Ruml M, Vuković A, Milatović D (2010) Evaluation of different methods for determining growing degree-day thresholds in apricot cultivars. Int J Biometeorol 54:411–422

Schaber J, Badeck FW (2003) Physiology-based phenology models for forest tree species in Germany. Int J Biometeorol 47:193–201

Schwartz MD, Carbone GJ, Reighard GL, Okie WR (1997) A model to predict peach phenology and maturity using meteorological variables. HortScience 32:213–216

Smith RB (1985) Predicting the dates of first commercial harvest of selected Ontario peach cultivars. J Am Soc Hortic Sci 110:650–654

Snyder RL, Spano D, Cesaraccio C, Duce P (1999) Determining degree-day thresholds from field observations. Int J Biometeorol 42:177–182

Szabó Z, Nyéki J (1999) Floral biology and fertility of apricot. Int J Hortic Sci 5(3–4):9–15

Vachůn Z (2003) Phenophases of blossoming and picking maturity and their relationships in twenty apricot genotypes for a period of six years. Hortic Sci (Prague) 30(2):43–50

Weinberger JH (1948) Influence of temperature following bloom on fruit development period of 'Elberta' peach. J Am Soc Hortic Sci 51:175–178

Wielgolaski FE (1999) Starting dates and basic temperatures in phenological observations of plants. Int J Biometeorol 42:158–168

Wielgolaski FE (2001) Phenological modifications in plants by various edaphic factors. Int J Biometeorol 45:196–202

Willmott CJ (1981) On the validation of models. Phys Geog 2:184–194