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ORIGINAL ARTICLE

Phenological models for blooming of apple in a mountainous region

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Abstract Six phenological series were available for 'Golden Delicious' apple blooming at six sites in Trentino, an alpine fruit-growing region. Several models were tested to predict flowering dates, all involving a "chilling and forcing" approach. In many cases, application of the models to different climatic conditions results in low accuracy of prediction of flowering date. The aim of this work is to develop a model with more general validity, starting from the six available series, and to test it against five other phenological series outside the original area of model development. A modified version of the "Utah" model was the approach that performed best. In fact, an algorithm using "chill units" for rest completion and a thermal sum for growing-degree-hours (GDH), whose efficiency changes over time depending on the fraction of forcing attained, yielded a very good prediction of flowering. Results were good even if hourly temperatures were reconstructed from daily minimum and maximum values. Errors resulting from prediction of flowering data were relatively small, and root mean square errors were in the range of 1–6 days, being <2 days for the longest phenological series. In the most general form of the model, the summation of GDH required for flowering is not a fixed value, but a function of topoclimatic variables for a particular site: slope, aspect and spring mean temperature. This approach allows extension of application of the model to sites with different climatic features outside the test area.

Keywords Apple · Phenology · Flowering models

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Introduction

In general, phenology can be considered as one possible approach with which to observe the effects of climatic change (Defila and Clot 2001; Menzel and Estrella 2001; Stampfli 2001; Walther et al. 2001; Menzel 2003; White et al. 2003; Wolfe et al. 2005). In this context, a frequent topic of discussion is the possible trend towards increased frost risk for trees in temperate climates (Cannel and Smith 1986; Cannel et al. 1989; Hänninen 1991; Kramer 1994; Zinoni and Antolini 2002). For most fruit-tree crops, the occurrence of blooming coincides with a dramatic increase in frost sensitivity. Phenological phases that define the flowering process can be taken as key points in bud development for the investigation of frost events. A flowering model that performs well is useful. In Italy, homogeneous phenological series seldom range over a time span suitable for climatological analyses, at least in the case of flowering records of fruit trees. An empirical model could make up for the lack of phenological records with simulated flowering dates. After applying the model to historical time series, pheno-climatic analyses could be carried out on the simulated series. Finally, as a general issue, a good phenological model would enable the reproduction of phenophases at sites not equipped with meteorological recording, paving the way for high-resolution GIS applications of the model over climatically complex terrain.

This study aimed to fine-tune a phenological model of flowering dates using a temperature series input. Several approaches have been proposed in phenological modelling. Empirical models that link phenophases to the time spent above a certain temperature have been proposed (Landsberg 1974); another simple approach consists of linear regression models based on phenological information of some autochthonous plant species (White 1979; Kajfez-Bogataj and Bergant 1998; Bergant et al. 2001). Following the early development of phenological models, based mostly on daily data, and the increase in high time-resolution meteorological recording, phenologists have progressively focussed on hourly algorithms (Floyd and Braddock 1984; Reicosky et al. 1989). This choice may offer improved accuracy in the estimation of both chilling and temperature forcing. The simplest models, having heat as the forcing agent, sum "growing units" starting from a fixed date [Bidabé 1967 (part A); Winter 1986]. Nevertheless, the common approach has shifted to splitting bud development into two stages (chilling and forcing models). The first phase is where "chilling units" (CU) are accumulated to break dormancy when a certain value ("requirement") is reached. The second stage, starting from the fulfilment of the CU requirement, is where "growing degree days or hours" (GDD or GDH) are accumulated, continuing the ontogenetic process that leads to flower bud burst (Bidabé 1967; Richardson et al. 1974; Anderson et al. 1986; Valentini et al. 2001). Both CU and GDD (or GDH) are cumulative, taking into account a threshold value below which no temperature contribution is effective. For fruit trees, the base values for GDH or GDD thermal sums usually range between 0°C and 9°C (Richardson et al. 1974; Anderson et al. 1986; Kronenberg 1983; Valentini et al. 2001; Cesaraccio et al. 2004). CU are cumulative when the temperature range is between −2°C and 13°C. Nonetheless, a sound model calibration needs to take into account several thresholds for GDD and CU in order to choose the best-performing values against experimental outcomes (Snyder et al. 1999).

Anderson et al. (1986) and Kajfez-Bogataj and Bergant (1998) used triangular, rectangular or sine-wave models for estimation of GDD. Good results have been obtained for fruit trees by models that use both maximum and minimum daily temperatures, by implicitly considering the dynamics of daily cycles of temperature (Cesaraccio et al. 2004).

Models often differ in the way in which the starting date for CU accumulation is fixed. Earlier studies suggested a fixed date [Bidabé 1967 (part B); Landsberg 1974]; others proposed algorithms for a minimum rate of CU accumulation (Ashcroft et al. 1977; Cesaraccio et al. 2001). Different types of temporal succession between chilling and forcing time have been tested by alternating, sequentialising or placing these two phases in parallel (Chuine et al. 1998, 1999; Chuine and Cour 1999). Also, a "unified model" has been proposed that considers the effects of this sequence between chilling and forcing time (Chuine 2000).

The effect of other factors has also been tested. In fact, despite its widespread use, the CU-GDD approach has been criticised because other variables, such as soil moisture and photoperiod, are not addressed. The actions of other factors can also be directly included in the CU-GDD approach; for example, by modifying GDD effectiveness in response to these other parameters (Wang 1960; de Lemos Filho et al. 1997; Masle et al. 1989; Jame et al. 1998). Modification of GDD effectiveness has also been proposed as a function of the current attained summation of GDD or of a parallel summation of CU (Chuine et al. 1998, 1999). In fact, not only can the simple sequence between the two stages be considered, but also the alternation and parallel action of chilling and forcing.

Typically, the requirement for GDD is fixed by calibrating the model, and is fixed as a "universal" value, depending only on plant species and cultivar. The challenging task, which we intend to pursue, is to investigate the association of the requirement with specific site-dependent variables, as already outlined by White et al. (1997). This approach should allow an extension of model validity, even to sites with climatic features slightly different from those of the Trentino fruit-growing area.

Materials and methods

Phenological data and survey sites

Trentino is in the eastern-central part of the Italian Alps (Fig. 1). The climate in its lower valleys, typical of the southern alpine area, is particularly favourable for apple growing. Climatic features for two sites, one on the Adige valley floor (Mezzolombardo, 210 m), the other in the Non valley (Cles, 650 m), are given in Fig. 2. 'Golden Delicious' is the most common apple cultivar in this region, and phenological series are available from six localities at different elevations ranging from 210 to 727 m a.s.l. As a result of this variability in elevation, the various sites show significant climatic differences.

Phenological series have been collected over different periods and using two different approaches (Table 1). At four of the six sites (Denno, Romallo, Sarche and Borgo Valsugana), phenological observations consisted only of the recording of the date on which a certain phenophase, based on Fleckinger's scale (Fig. 3), first occurred; these series are 8–12 years long. At the two other sites (Mezzolombardo and Cles), the series range over a much longer period (1979–2003) and represent two key sites for investigation. These sites represent well the typical environmental conditions of the apple-growing areas in Trentino, the former in the bottom of the large, plain Adige valley (at 210 m) and the latter on a gentle valley side, at 650 m in the Non valley, a noted European apple production district. For these sites, phenophases for any bud were recorded once or twice a

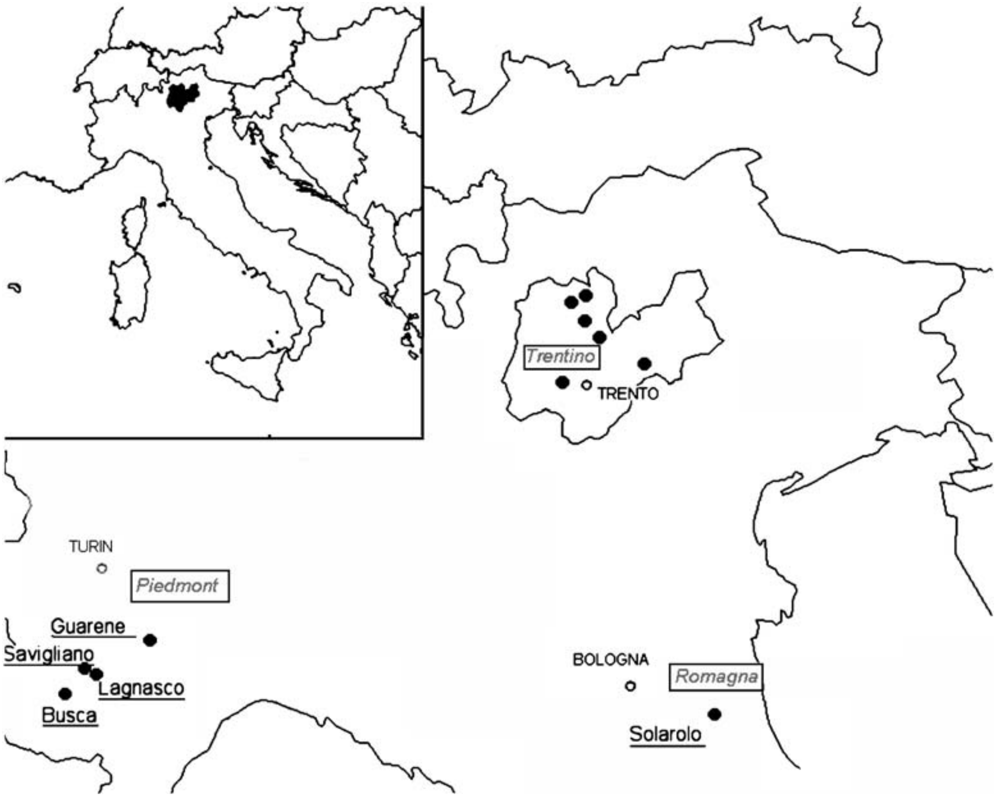

Fig. 1 Area of intensive study in Trentino (*shaded black* in inset) and phenological survey locations (*black dots*, names underlined—see Table 1 for names and details on Trentino area). The main town in each region is in *capitals*

week over the period 1983–2000. Before and after this period, the dates of initial, full and end flowering were also recorded at these sites as well as at the other four sites. The phenological models were tested and developed on data from Mezzolombardo and Cles; for the other sites in Trentino only the calibration of the forcing requirement was carried out, while the series outside Trentino were used as tests, with no new calibration.

Data have been standardised to the same format over all six sites. The "Phenagri" database (Brunetti and Zinoni 1999; Mezzolombardo and Cles sites, 1983–2000) is "bud oriented": it reports, at a fixed frequency (once a week), the phenophase attained by every bud within those belonging to the trees and branches selected at the beginning of the survey period. The other database (a "technical assistance service" database) is "phase oriented": it reports only the date of attainment of any phase; the date is valid, on average, for a specific orchard as a whole. Since the phenological models yield dates, it is necessary to identify the date of attainment of the stages of interest for each year. In the "technical assistance service" database the day is reported, whereas in the "Phenagri" database an identification of the "sensitive phase" representing blooming in the orchard as a whole, starting with observations relating to single buds, is required. The date of "initial flowering" was then inferred from calibration with the "technical assistance service" database, by comparing the partial overlap of the two phenological series involved in the Phenagri project (Mezzolombardo and Cles sites), which were also surveyed in the "technical assistance service" database. In the "bud oriented" (Phenagri) database, for both sites, the date of initial flowering was fixed when a variable rate of buds (in 5% increments) achieved the "F1" phase. Usually, the latter represents the general opening of the central flower—the earliest of the five composing the flower cluster, and also the most valuable. For each year, residuals were calculated by subtraction to the corresponding initial flowering date in the "phase oriented" database. For each rate of buds in the "F1" stage, the root mean square residual (RMSR) was calculated for the overlapping series, and the rate displaying the lowest RMSR was chosen as the best representative of the initial flowering stage. A rate of 30% of buds in Fleckinger's "F1" stage yielded the best match between the two databases, and the corresponding date for each year was chosen as the day of achievement of the initial flowering stage. The BBCH scale sets the initial flowering

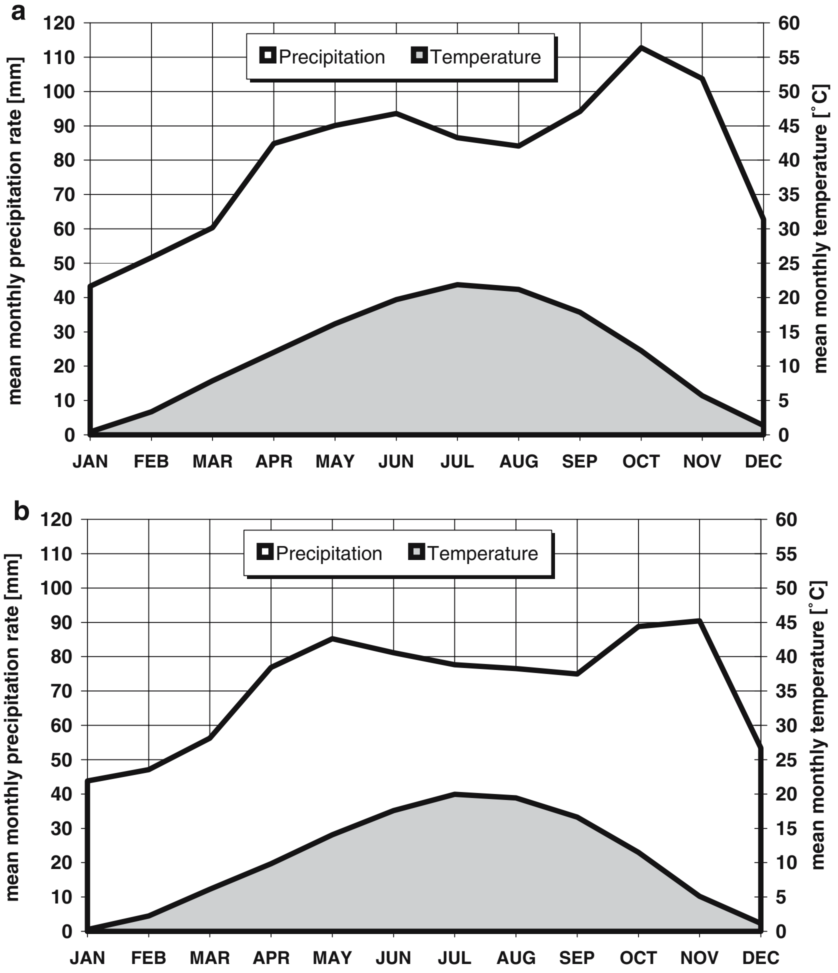

Fig. 2a,b Bagnouls-Gaussen climograph for the two model development sites. **a** Mezzolombardo, Adige Valley floor, 210 m a.s.l. **b** Cles, Non Valley side, 650 m a.s.l

stage to “61”; this stage correctly corresponds to 10% of flowers open, i.e. an average of 50% of floral clusters in Fleckinger’s “F1” stage, since the floral clusters consist of five flowers, and one flower per cluster represents 20% of the total. The condition of 30% of buds in phase F1 corresponds roughly to 30%×20% (i.e. 6%) of flowers open, so, in our “phase oriented” database, the two scales match at stage “60” of the BBCH scale. Finally, for the six localities, a phenological database reporting the yearly dates of initial flowering was set up.

With the aim of testing the model in a wider geographic and climatic context, some series collected outside Trentino were used (see map in Fig. 1): one site in Romagna (Padana Plain, 1996–2001) and four sites in Piedmont (flat landscape or close to foothills, 2003 only).

Meteorological data

The meteorological database stems from the agro-meteorological observational network of the Istituto Agrario di San Michele all’Adige (IASMA) and of the Hydrographic Service of the Autonomous Province of Trento. Temperature data were taken from the station closest to each phenological observation point. In most cases, phenological and meteorological observation sites coincided and so no adjustment was needed for meteorological data.

Both phenological and meteorological databases were checked to detect errors, and data were subjected to validation processes based on comparisons with nearby stations. In some cases, the series presented gaps or irregularities for two main reasons: (1) station malfunction-

Table 1 Recording periods and survey approach at the phenological recording sites

Site	Recording period	Survey approach
Model development series		
Mezzolombardo	1984–2000	Bud phenophases
Cles	1984–2000	Bud phenophases
In Trentino (all series)		
Mezzolombardo	1979–2003	Bud phenophases (1984–2000), flowering dates (1979–2003)
Cles	1979–2003	Bud phenophases (1984–2000), flowering dates (1979–2003)
Denno	1990–2001	Flowering dates only
Sarche	1994–2001	Flowering dates only
Romallo	1993–2001	Flowering dates only
Borgo Valsugana	1995–2002	Flowering dates only
Outside of Trentino (test)		
Solarolo	1996–2001	Flowering dates only
Lagnasco	2002–2003	Flowering dates only
Guarene	2003	Flowering dates only
Savigliano	2003	Flowering dates only
Busca	2003	Flowering dates only

ing, or (2) over certain periods, absence of a match between phenological observation site and location of the meteorological station, due to missing meteorological data.

Significant gaps in the meteorological dataset (full days) and missing periods were reconstructed by geostatistical methods on the basis of other stations in the network (Cressie 1993; Lennon and Turner 1995; Ashraf et al. 1997; Kitanidis 1997). “Kriging with drift” has proved to be a precise interpolation method for temperatures in our area, according to Rea and Eccel (2004), who tested several techniques for spatial interpolation; this method was applied to fill daily data gaps. Minor hourly gaps were filled by linear interpolation between existing records.

To cope with the frequent non-availability of hourly data in meteorological archives, particularly for past periods, an estimate can be performed using empirical models, starting from daily maximum and minimum temperature (Johnson and Fitzpatrick 1977; Wann et al. 1985; Worner 1988; Fernandez 1992; Cesaraccio et al. 2001). In our case, with the ability to apply phenological models to hourly data, but with hourly temperatures not always being available for a particular site and period, the precision of the “TM model” (Cesaraccio et al. 2001) in reconstructing hourly data from daily values was tested. Necessary input data are minimum and maximum daily temperature and an estimation of times of dawn and sunset, but the model was also tested with the additional information of the times of occurrence of minimum and maximum temperature.

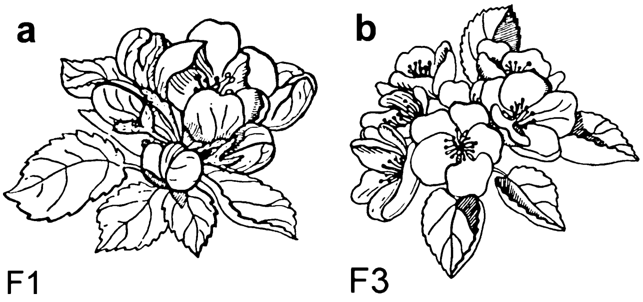

Fig. 3a,b Flowering stages for apple (Fleckinger scale). **a** F1 initial flowering. **b** F3 full flowering

The performance of the TM model was verified by (1) applying the Utah model (see next section for details of model) to approximated GDH and CU, and to the respective measured quantities, in periods with available hourly data, and (2) evaluating the different responses of the best-performing phenological model run with measured daily data, measured hourly data and estimated hourly data, respectively. The hypothesis is that the time of occurrence of daily minimum and maximum temperatures can be estimated from a yearly series of hourly recorded data for the same meteorological station. This represents a case of a model applied to a past period when only maximum and minimum temperatures were recorded, but at a place where more recent hourly observations are available.

Choice of existing phenological models

Three existing flowering models—Bidabé (1967), “Utah” (Ashcroft et al. 1977) and Anderson et al. (1986)—were calibrated and tested with our hourly data. Furthermore, we proposed a new version of the “Utah” model, which will be described in full in “Results”. All the models tested make use of “chilling and forcing” algorithms with different parameterisations of the CU and GDH summation. They were calibrated for chilling and forcing requirements and for the chilling start date, where required. Other parameters remained the same as proposed by the authors. The calibration of both CU and GDD-GDH requirements was carried out separately for each of the six phenological sites in Trentino. The calibration algorithm (described in detail in Ashcroft et al. 1977) consists in varying CU requirement and observing the effect on the assessment of the GDH requirement. For every trial value of CU requirement, the GDH requirement is estimated as the average of values calculated at every recorded flowering date in the available series; for each CU requirement value, the corresponding standard deviation in GDH is calculated. The optimum value for CU is that which yields the minimum standard deviation value in GDH requirement. The latter is then fixed as the average on the series, with the CU requirement calculated as described above. The three models are detailed in the following sections. A synopsis of the equations involved is given in Table 2.

Bidabé model

In his early work, Bidabé (1967) proposed two types of CU and GDD/GDH accumulation: (1) a summation with threshold, and (2) a summation of exponential terms; we used the exponential, hourly formulation for the chilling stage:

$$\mathrm{CU}(k) = \sum_{i=k.st}^{k}\sum_{h=1}^{24}\frac{1}{24}Q_{10}^{-\frac{T_h(i)}{10}} \tag{1}$$

where k is a generic day, k.st is the starting day for the chill summation (a fixed date), Q_{10} is a base ranging from 2 to 3, and $T_h(i)$ is the hourly temperature at time *h* and day *i*. Q_{10} represents the ratio of the measurable effects of a physiological activity occurring at two temperatures, the second 10°C higher than the first. For the forcing phase, Bidabé (1967) proposed two daily models, both using daily minimum and maximum values. We used the exponential model in both a daily (Eq. 2) and an hourly (Eq. 3) formulation:

$$\mathrm{GDD}(k) = \sum_{i=k.st}^{k}\left(Q_{10}^{\frac{T_{n,i}}{10}} + Q_{10}^{\frac{T_{x,i}}{10}}\right) \tag{2}$$

where $T_{n,i}$ and $T_{x,i}$ are the minimum and maximum daily temperature of day *i*, respectively;

$$\mathrm{GDH}(k) = \sum_{i=r}^{k}\sum_{h=1}^{24}\frac{1}{24}Q_{10}^{\frac{T_{h,i}}{10}} \tag{3}$$

For the whole model, the parameters to calculate are the starting date for chilling, the chilling requirement, and the forcing requirement.

Utah model

We jointed two algorithms, proposed in 1974 and 1977, to define a “Utah model”. Richardson et al. (1974) proposed an accumulation of CU based on a table (Table 3, Fig. 4) that sets the efficiency of CU according to a temperature-dependent broken line. At the end of summer, CU accumulation is negative, owing to the prevailing action of high temperatures. The start date of CU accumulation is fixed as the day in autumn when the largest negative value of CU is attained. After the chilling phase, which is required to release dormancy, Ashcroft et al. (1977) proposed the application of an hourly, linear forcing model, expressing heat accumulation as GDH. The forcing stage is based on a fixed threshold and its equation is:

$$\mathrm{GDH}(k) = \sum_{i=r}^{k}\sum_{h=1}^{24}\max[0, T_h(i) - T_b] \tag{4}$$

where k is a generic day (k≥r), r is the day of rest completion (fulfilment of chilling requirement), $T_h(i)$ is the hourly mean temperature at hour *h* and day *i*, and T_b is the threshold (or base) temperature. The “Utah” approach used a value of 4.4°C for T_b. An equivalent daily model (Eq. 5) has been tested, which cumulates daily temperatures above the same 4.4°C threshold:

$$\mathrm{GDD}(k) = \sum_{i=r}^{k}\max\left[0, \overline{T_i} - T_b\right] \tag{5}$$

where $\overline{T}_i$ is the average temperature of day *i*.

Anderson model

Continuing the experience of the “Utah school”, Anderson and Richardson (1982) and Anderson et al. (1986) proposed non-linear equations linking both CU and GDH to temperature. The chilling phase follows a curve (see Anderson et al. 1986 for details), which we interpolated by a 3rd-degree polynomial curve (see Fig. 5); its analytical form is the following:

$$\mathrm{CU} = 0.0022T_h^3 - 0.0879T_h^2 + 0.9129T_h - 2.1 \tag{6}$$

The forcing phase follows an “ASYMCUR” line in a certain temperature range, described by two cosine equations for temperatures lower or higher than optimum, respectively. The equations are the following:

$$\mathrm{GDH}(k) = \sum_{i=r}^{k}\sum_{h=1}^{24}\frac{T_u - T_b}{2}\left[1 + \cos\left(\pi + \pi\frac{T_h(i) - T_b}{T_u - T_b}\right)\right]$$

$$T_b \le T_h \le T_u \tag{7a}$$

Table 2 Synopsis of model features. *CU* Chilling units, *GDD* growing degree days, *GDH* growing degree hours, *k* generic day, *k.st* starting day for the chill summation (a fixed date), $T_h(i)$ hourly temperature at time *h* and day *i*, T_u optimum temperature, T_b base temperature, T_c critical temperature

Model	Calibrated parameters	Values		Non-calibrated parameters Original values
		Original propositions	Calibration results	
Bidabé				
Chilling phase:	Q_{10} CU requirement	3 90	3 10÷60	k.st=15 December
$\mathrm{CU(k)} = \sum_{i=k.st}^{k} \sum_{h=1}^{24} \frac{1}{24} Q_{10}^{-\frac{T_h(i)}{10}}$				
Forcing phase-daily:	Q_{10} $\mathrm{GDD}_{\text{in flower}}$	3 600	3 480÷533	
$\mathrm{GDD(k)} = \sum_{i=r}^{k} \left(Q_{10}^{\frac{T_{n,i}}{10}} + Q_{10}^{\frac{T_{x,i}}{10}} \right)$				
Forcing phase-hourly:	Q_{10} $\mathrm{GDH}_{\text{in flower}}$	= =	3 520÷542	
$\mathrm{GDH(k)} = \sum_{i=r}^{k} \sum_{h=1}^{24} \frac{1}{24} Q_{10}^{\frac{T_{h,i}}{10}}$				
Utah				
Chilling phase: see Table 3	CU requirement	1,234	1,000÷1,150	
Forcing phase-daily:				
$\mathrm{GDD(k)} = \sum_{i=r}^{k} \max\left[0, \overline{T_i} - Tb\right]$	$\mathrm{GDD}_{\text{in flower}}$	=	235÷474	T_b=4.4°C
Forcing phase-hourly:				
$\mathrm{GDH(k)} = \sum_{i=r}^{k} \sum_{h=1}^{24} \max[0, T_h(i) - T_b]$	$\mathrm{GDH}_{\text{in flower}}$	6,933	5,850÷7,600	T_b=4.4°C
Anderson				
Chilling phase: interpolated by the equation: $\mathrm{CU} = 0.0022T_h^3 - 0.0879T_h^2 + 0.9129T_h - 2.1$	CU requirement	954[a]	780÷950	
Forcing phase:				T_u=25°C
$T_b \leq T_h \leq T_u$:	$\mathrm{GDH}_{\text{in flower}}$	5,380[a]	500÷8600	T_b=4°C
$\mathrm{GDH(k)} = \sum_{i=r}^{k} \sum_{h=1}^{24} \frac{T_u - T_b}{2} \left[1 + \cos\left(\pi + \pi \frac{T_h(i) - T_b}{T_u - T_b}\right)\right]$				T_c=36°C
$T_u \leq T_h \leq T_c$:				
$\mathrm{GDH(k)} = \sum_{i=r}^{k} \sum_{h=1}^{24} \frac{T_u - T_b}{2} \left[1 + \cos\left(\frac{\pi}{2} + \frac{\pi}{2} \frac{T_h(i) - T_u}{T_c - T_u}\right)\right]$				
$T_h < T_b$ or $T_h > T_c$: GDH(k)=0				
Progressive Utah				
Chilling phase: see Table 3	CU requirement		1,075	
Forcing fase				
$\mathrm{GDH(k)} = \sum_{h=1}^{24} \max\left\{0, (T_h(k) - T_b)\left[1 + \left(\frac{\mathrm{GDH(k-1)}}{\mathrm{GDH}_{\text{in. flow.}}}\right)^2\right]\right\}$	GDH $_{\text{in flower}}$		7,850÷9,350[b]	T_b=4.4°C

[a] Original model refers to ‘Montmorency’ sour cherry
[b] Non-fixed values-see Eq. 14

Table 3 Values of CU as a function of hourly temperature (from Richardson et al. 1974)

Temperature [°C]	CU
$T<1.4$	0
$1.5<T<2.4$	0.5
$2.5<T<9.1$	1
$9.2<T<12.4$	0.5
$12.5<T<15.9$	0
$16<T<18$	−0.5
$T>18$	−1

$$\mathrm{GDH}(k)=\sum_{i=r}^{k}\sum_{h=1}^{24}\frac{T_u-T_b}{2}\left[1+\cos\left(\frac{\pi}{2}+\frac{\pi}{2}\,\frac{T_h(i)-T_u}{T_c-T_u}\right)\right]$$

$$T_u\leq T_h\leq T_c \tag{7b}$$

$$\mathrm{GDH}(k)=0 \qquad T_h<T_b\ \text{or}\ T_h>T_c \tag{7c}$$

where T_u is the optimum temperature (25°C), T_b is the base temperature (4°C) and T_c is the critical temperature (36°C). In the alpine region, even at low elevation, it is unlikely that temperature exceeds the 25°C "optimum" before flowering, so Eq. 7b seldom applies, and with our data only the ascending branch of the "ASYMCUR" was used.

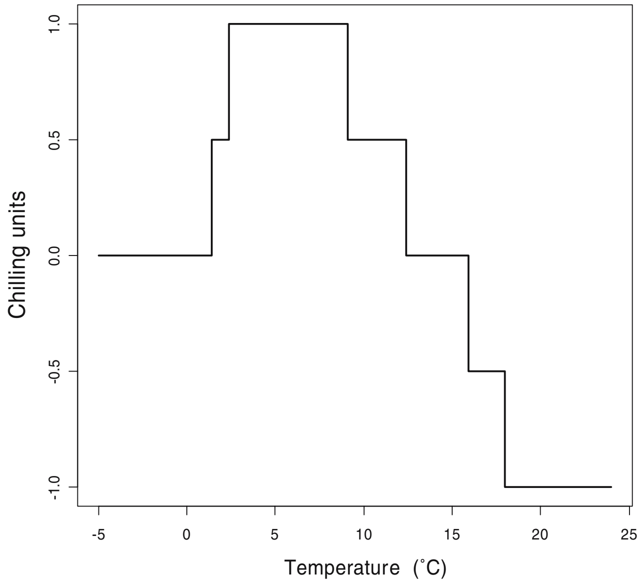

Fig. 4 Utah model: chilling units (CU) as a function of temperature

Extension to photoperiod effects

Even if the influence of temperature on bud phenology is predominant, some authors have underlined the role of photoperiod, at least in crops other than fruit trees (Wang 1960; de Lemos Filho et al. 1997; Jame et al. 1998; Caffarra et al. 2005; Crepinsek et al. 2006). Modifications of "Utah" and "Progressive Utah" models were produced to take into account any possible enhancement due to day length. Multiplicative functions of photoperiod $f_p(\mathrm{k})$ were applied to the forcing term of the Utah model; they can be written in the general form:

$$f_p(\mathrm{k})=\left[\frac{H_s(\mathrm{k})}{H_{s(\mathrm{in.flow.})}}\right]^{x} \tag{8}$$

where k is a generic day during the forcing stage, $H_s(\mathrm{k})$ is the length of day k (sun hours), $H_{s(\mathrm{in.flow})}$ is the day length at the "initial flowering" phenophase, and x is an exponent whose value has been set equal to ±1 and ±2 for testing purposes.

Towards a new formulation of the Utah model

The concept of a changeable threshold temperature, used by authors such as Kronenberg (1983), Winter (1986), and Črepinšek et al. 2006, can be seen in terms of a varying weighting of heat effect along the forcing stage. By considering this assumption, and by re-examining the review of modelling approaches given by Chuine et al. (1998), a model was developed in which GDH weighting at any time is a function of the summation attained at that

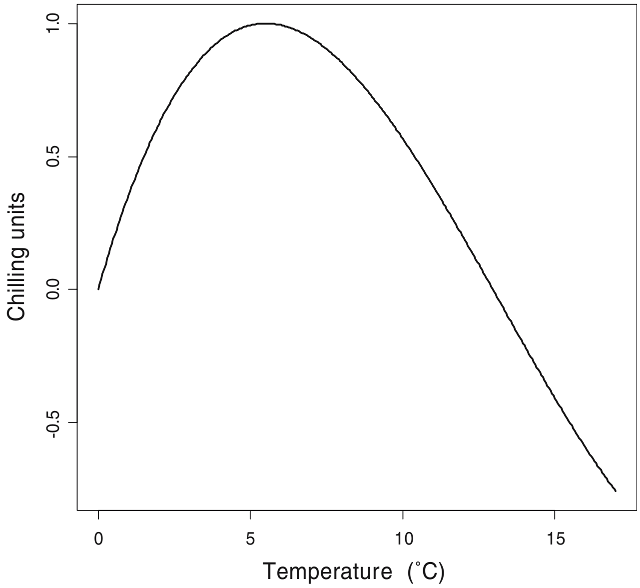

Fig. 5 Anderson model: CU curve (fitted by 3rd degree function of temperature)

time. A more complex form of the Utah model has been set up with a GDH weighting as a function of the forcing achieved; the forcing phase starts only after rest completion, i.e. with reference to the definition given in Chuine et al. (1998), our model follows a "sequential" rather than a "parallel" approach.

The combination of "actual GDH summation" and photoperiod effects has been tested, obtaining the following general equation for GDH:

$$\mathrm{GDH(k)} = \sum_{\mathrm{i=r}}^{\mathrm{k}} f_f(\mathrm{T_h(i)}) f_a(\mathrm{GDH(i-1)}) f_p(\mathrm{i}) \tag{9}$$

where $f_f(\mathrm{T_h(i)})$is the Utah model forcing function (Eq. 4), $f_p(\mathrm{i})$ is the photoperiod (day length) function for day i (Eq. 8), and $f_a(\mathrm{GDH(i-1)})$ is the function of "actual GDH summation". The general form for this weighting function is

$$f_a(\mathrm{GDH(i-1)}) = \left[\frac{\mathrm{GDH(i-1)}}{\mathrm{GDH_{in.flow.}}}\right]^{\mathrm{a}} \tag{10}$$

where $\mathrm{GDH_{in.flow.}}$ is the requirement for initial flowering phase (Fleckinger F1, or BBCH 60) and a is an exponent whose value has been set equal to ±1, ±2 and ±3. The equation for the definitive forcing model, shown from the tests to be optimum, will be given in the "Results" section.

The need for one model encompassing different climatic conditions suggested taking into account flowering records from more localities, even those adapted from other sources (Chuine et al. 1998). The new version of the Utah model that we proposed was applied, with no site-specific calibration, to two "external" data sets (see section on "Phenological data and survey sites" above) to test its adaptability. Indeed, even if estimates derived from single phenological series were good, the model was still only poorly adaptable, since forcing requirements in GDH were generally different for each of the six sites. Some effect of other variables is expected, which, up to now, had not been explicitly included in the model. In a roughly homogeneous climatic context, one site distinguishes itself from another according to physical characters, which are, to a large extent, explained by topographic features, such as slope, aspect and elevation. To improve model adaptability, the required value of GDH has been assumed to be a function of site-dependent variables, easily obtainable for any locality (White et al. 1997), namely the topographic variables, added to mean yearly or spring temperature.

Model evaluation and testing

Model performances were determined by an evaluation of two statistical indices on the differences between simulated and recorded flowering dates: root mean square error (RMSE) and the Pearson determination coefficient (r^2).

First, the usefulness of hourly data was tested. Tests on the performance of the "Utah" hourly model, in comparison with the same model employing daily data, were carried out on the two best phenological series—Mezzolombardo and Cles—which also display the longest observation period. Day length effects on the Utah model were then estimated. Finally, the four hourly models (Bidabé, Utah, Anderson and "Progressive Utah") were compared with one another.

Results

Use of hourly models

The first, general, outcome is that a better estimation of flowering dates was obtained with hourly than with daily models. Since, as discussed further below, among the three models tested the Utah model approach yielded the best results, effects of the use of hourly values and of photoperiod functions are reported for this model. Values of forcing requirement ($\mathrm{GDH_{in.flow.}}$) obtained after reconstruction of hourly data with the "TM model", are similar to those obtained with measured values (Table 4). In fact, in this case, hourly models respond better than daily models to forcing situations, even when the latter foster either premature or late flowering (Fig. 6).

Table 4 Performances of daily and hourly models compared. Pearson's r^2 coefficient and root mean square errors (*RMSE*) of flowering dates for the two sites with the best phenological series (modelled vs measured)

	Mezzolombardo		Cles	
	r^2(n=18; P<0.001)	RMSE (days)	r^2(n=18; P<0.001)	RMSE (days)
Best results with hourly measured data	0.92	2.2	0.95	2.3
Best results with hourly reconstructed data (TM model)	0.90	3.2	0.92	2.8
Best results with daily measured data (daily minimum and maximum temperature)	0.81	2.9	0.76	3.0

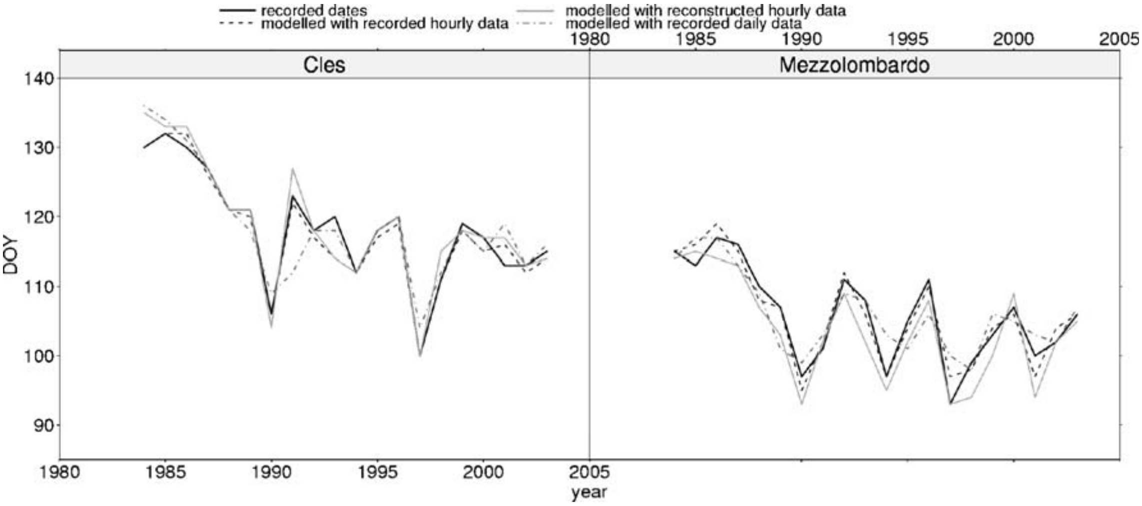

Fig. 6 Modelled and recorded initial flowering dates (30% of buds in Fleckinger's "F1" stage) for the two model development sites

Photoperiod effects

No effects of photoperiod were evident in our series: the different functions tested for day length gave no real improvement in flowering prediction. The application of the best performing form of Eq. 8 (exponent x=2), case by case, to the two "optimum" sites of Mezzolombardo and Cles, increased the forecasting RMSE of 0.1÷0.4 days and lowered the r^2 value of 0.0÷0.2. This outcome is not surprising, confirming findings by other authors (White 1979; Caffarra et al. 2005; Črepinšek et al. 2006) and general convictions concerning fruit trees (Guerriero and Scalabrelli 1991).

Formulation of the "Progressive Utah" model

An attempt to generalise the Utah model described in "Materials and methods", gave rise to a new formulation that we called "Progressive Utah". The model has the following features: the chilling phase is carried out as in Ashcroft et al. (1977), with a threshold temperature of 4.4°C, the starting of chill determined by the search for the minimum of the chilling function, as described under the heading "Towards a new formulation of the Utah model" in "Materials and methods". The chilling phase is completed when the requirement is attained; its value comes from a calibration performed as described in the aforementioned section. A forcing phase then begins; every term in the summation contains a multiplication by a weight, which is a function of the forcing attained:

$$\mathrm{GDH(k)} = \mathrm{GDH(k-1)} + \sum_{\mathrm{h}=1}^{24} \max\left\{0, (\mathrm{T_h(k)} - \mathrm{T_b})\left[1 + \left(\frac{\mathrm{GDH(k-1)}}{\mathrm{GDH_{in.flow.}}}\right)^2\right]\right\} \tag{11}$$

It can be seen that no correction for day length has been considered.

"Progressive Utah" is compared with other models in Table 5; all models are applied to the two localities with the longest and best phenological series (Mezzolombardo and Cles). Table 6 lists the statistics of the application of "Progressive Utah" for each site. The model yielded an RMSE of less than 2 days when applied to the two best sites; applied to the others, errors ranged from 4.0 to 6.3. The fit is good, even for years with a pronounced advance or delay in flowering (Figs. 7, 8).

Table 5 Performances of hourly models compared. Ranges refer to applications of models to two sites (Mezzolombardo and Cles)

Hourly model	r^2(n=18; P<0.001)	RMSE (days)
Bidabé	0.75÷0.85	3.0÷4.0
Anderson	0.50÷0.70	5.0÷7.0
Utah	0.90÷0.93	2.0÷3.0
Progressive Utah	0.93÷0.95	1.2÷1.5

$\mathrm{GDH_{in.flow}}$ for the "Progressive Utah" model was calibrated site by site. As expected, the value was different for each site (Table 7). For example, $\mathrm{GDH_{in.flow}}$ is 9,350°C h at Mezzolombardo and 7,850°C h at Cles (−16%). An overall application of the model would require a priori knowledge of forcing requirement. The second part of the

Table 6 Performance statistics of the "Progressive Utah" model

Site	Sample size	r^2	*P*-value	RMSE [days]	Regression line residuals Minimum [days]	 Maximum [days]
Mezzolombardo	25	0.93	$3.98\ 10^{-11}$	1.5	−3.0	3.9
Cles	25	0.95	$1.44\ 10^{-12}$	1.2	−5.3	3.6
Denno	12	0.64	0.002	4.0	−5.9	6.3
Sarche	8	0.73	0.007	6.3	−6.1	6.2
Romall	9	0.60	0.015	4.7	−4.8	5.0
Borgo Valsugana	8	0.57	0.031	4.7	−8.4	4.8

model consists of determining the links between the forcing requirement of a site and its topo-climatic features, as outlined in the description of the existing phenological models in "Materials and methods".

Linear functions were tested, at first using variables one by one, and then by means of indices created by different combinations of the variables; all the information contributed one index (I_{site}), defined for each site:

$$GDH_{in.flow.} = f(\text{slope, aspect, climatic mean T}) = f(I_{site}) \tag{12}$$

Mean temperatures averaged over different periods were tested, and the best performing were: yearly, MAM (March-April-May) and AM (April-May). Best results were obtained by the inclusion in I_{site} of April-May mean temperature and its linear composition with slope and aspect (known by means of the GIS GRASS function "r.slope.aspect"):

$$I_{site} = C_{SC} \cdot T_{AM} + I_{slope} + I_{aspect} \tag{13}$$

where T_{AM} is climatic mean temperature from 1 April to 31 May, I_{slope} is an index ranging from 0.5 to 2 depending on slope and aspect, I_{aspect} is an index ranging from 0.5 to 2 depending on aspect, and C_{sc} is a "spring-climate" coefficient, equal to 0.4 (Table 8). Eq. 13 was calibrated as the best performing linear function. Higher values of I_{slope} and I_{aspect} correspond to localities where availability

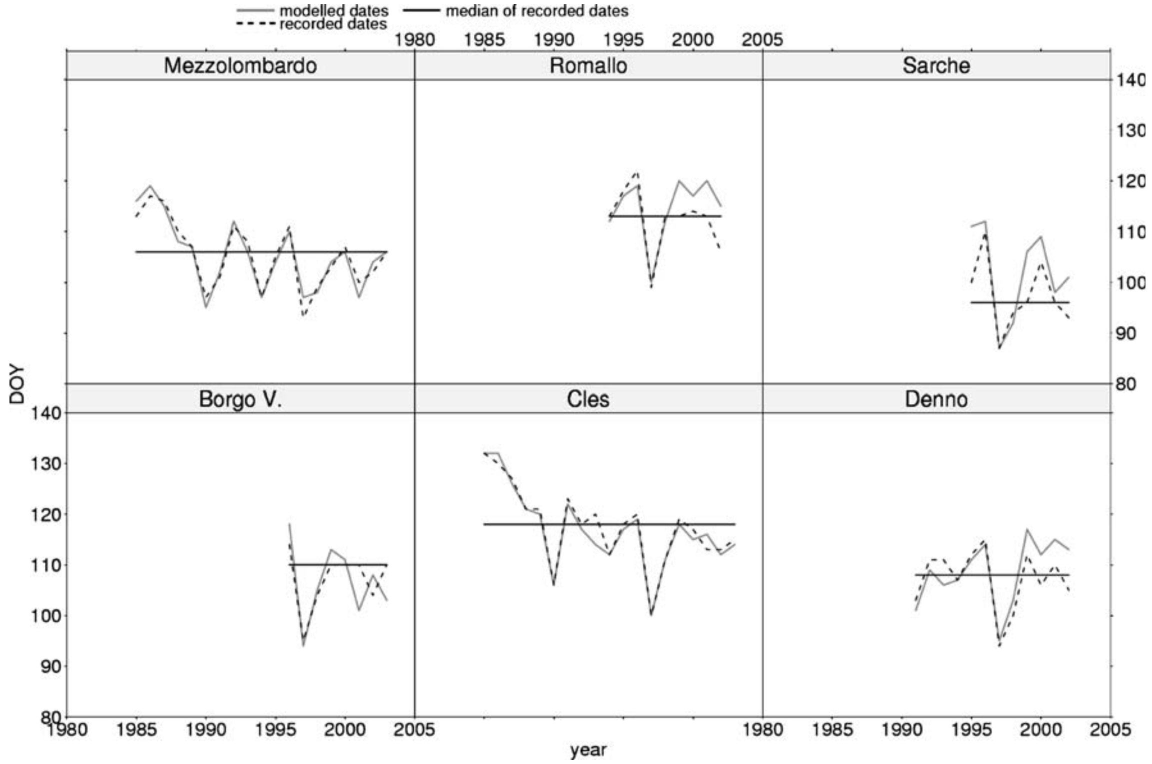

Fig. 7 Initial flowering dates (30% of buds in Fleckinger's "F1" stage or BBCH 60) modelled with the "progressive Utah" model for six sites in Trentino

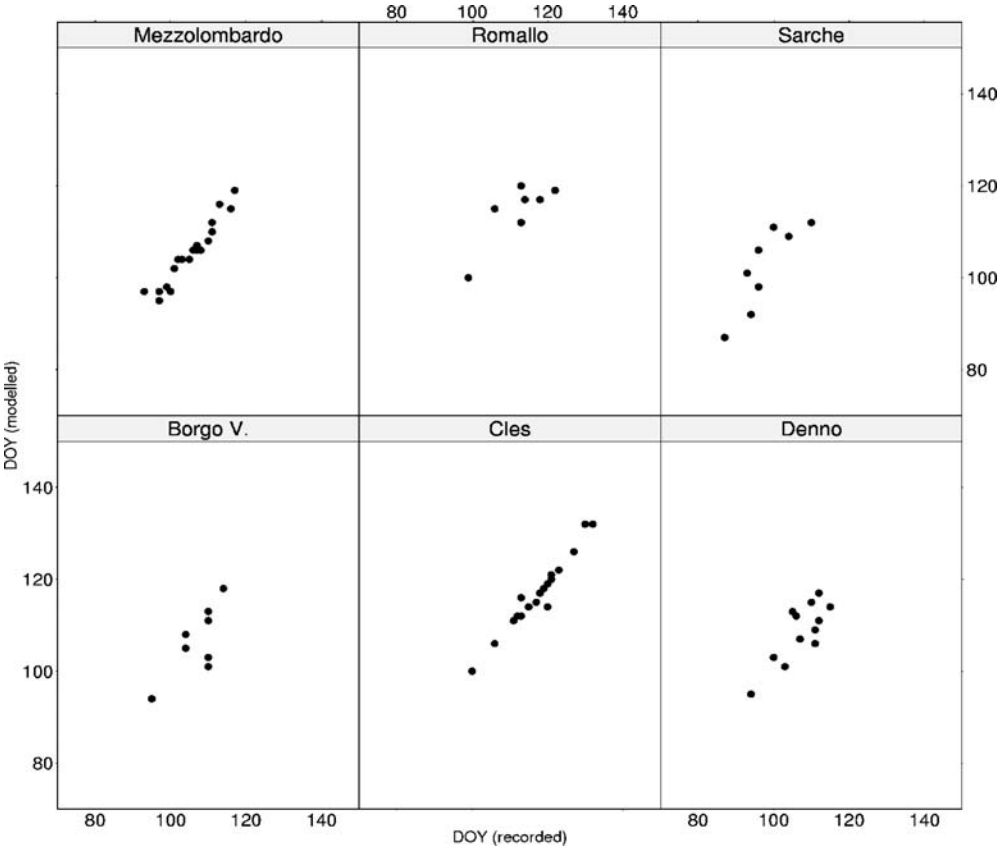

Fig. 8 Scatterplots of modelled vs recorded initial flowering dates with the "Progressive Utah" model for six sites in Trentino

of solar radiation is enhanced (sites on a sloping terrain, facing south).

By interpolating pairs of values of $GDH_{in.flow.}$, assessed site by site, and I_{site} calculated for the relevant sites, a relationship linking the two was inferred (Eq. 14); r^2 was >0.996 (Fig. 9).

$$GDH_{in.flow.} = 1302 \cdot I_{site} - 1371 \tag{14}$$

Poorer relationships were detected when other existing indices (Regniere 1996) or single variables were used.

As far as "external validation" is concerned, with a site-dependent GDH requirement, the model proved able to easily encompass different climatic conditions, both for valley bottom and hillside situations, and it yielded good or acceptable results when applied to localities external to the model development area. In Romagna (one site) for the period 1996–2001, the RMSE was, on average, 5.5 days over the period, with a maximum error of 11 days (Table 9); in the Piedmont region (four sites) better results were obtained, with a mean absolute error of 2.2 days for the only available year (2003), and a maximum of 4 days (Table 10).

Table 7 Geomorphologic (elevation, aspect and slope), climatic [mean yearly/mean March-April-May (*MAM*)/mean April-May (*AM*) temperature] and forcing requirements at the phenological recording sites

Site	Elevation [m a.s.l.]	Aspect [°]	Slope [°]	Yearly mean temperature [°C]	MAM mean temperature [°C]	AM mean temperature [°C]	GDH requirement [°C h]
Mezzolombardo	210	–	0.0	11.7	12.5	14.5	9,350
Cles	652	360	5.7	9.6	9.6	11.5	7,850
Denno	321	270	2.9	10.8	11.5	13.4	8,850
Sarche	245	333	3.2	12.0	11.8	13.5	8,500
Romallo	727	360	2.9	9.3	9.5	11.4	7,100
Borgo Valsugana	419	90	5.7	11.0	11.3	13.2	7,400

Table 8 Values of I_{aspect} and I_{slope} for assessment of index I_{site}

Aspect	Slope	I_{aspect}	I_{slope}
Undefined	Slope=0°	1.75	0.75
SW-S-SE	0°<slope<3°	2	0.75
SW-S-SE	3°≤slope<6°	2	1
SW-S-SE	6°≤slope	2	2
SE-E-NE	0°<slope<3°	1.5	0.5
SE-E-NE	3°≤slope<6°	1.5	1
SE-E-NE	6°≤slope	1.5	1.5
NE-N-NW	0°<slope<3°	0.5	0.5
NE-N-NW	3°≤slope<6°	0.5	1
NE-N-NW	6°≤slope	0.75	1.25
NW-W-SW	0°<slope<3°	1.5	0.5
NW-W-SW	3°≤slope<6°	1.5	1
NW-W-SW	6°≤slope	1.5	1.5

Discussion

Results from the identification and application of an optimum model (“Progressive Utah”), fully satisfy the aims of this study. Errors are smaller than with existing models and, when “Progressive Utah” is applied to sites with accurate and long phenological series, they are less than 2 days, i.e. within the uncertainty implicit in the identification of the exact initial flowering date. Larger errors, yet still acceptable for most purposes, have been obtained at sites with poorer phenological series, owing to both a limited survey length and approximate survey methods, consisting of simple observation of a specific phenophase for the orchard. Moreover, at some sites the reference meteorological station was only in the neighbourhood rather than exactly at the phenological survey site, thus introducing an effect of local microclimatic conditions. This is true for the site at Mezzolombardo (210 m), for which the meteorological reference series was adapted from San Michele, at a distance of about 3 km and at the same elevation. The performance of the model for this series, even if generally good, is not quite as good as for the Cles series (650 m), where the meteorological station is inside the farm itself. In this case, the phenological and meteorological survey protocols were identical for the two sites, as well as the length of the series. This suggests that particular attention should be paid to the choice of reference meteorological series, and invokes the application of corrections when temperature series are inferred from data recorded at another site.

Table 9 Maximum error and RMSE obtained with the “Progressive Utah” model for the external site in Romagna

Site	Maximum error(days)	RMSE(days)
Solarolo (Romagna)	11	5.5

The algorithm introduced in the Utah model for the determination of the beginning of rest phase is likely to improve model performances. When the starting time was a fixed date (Bidabé model), our calibration of CU required to break dormancy led to values remarkably different from the original values. This is probably a consequence of a late starting date (15 December), when full winter temperatures are often ineffective in accumulating CU. If this is true, CU requirement would partly lose its importance as a calibration parameter.

The testing of the “progressive Utah” model with a site-dependent GDH requirement gave positive results, even on series collected outside the geographic and, to some extent, climatic context of their original calibration. This is

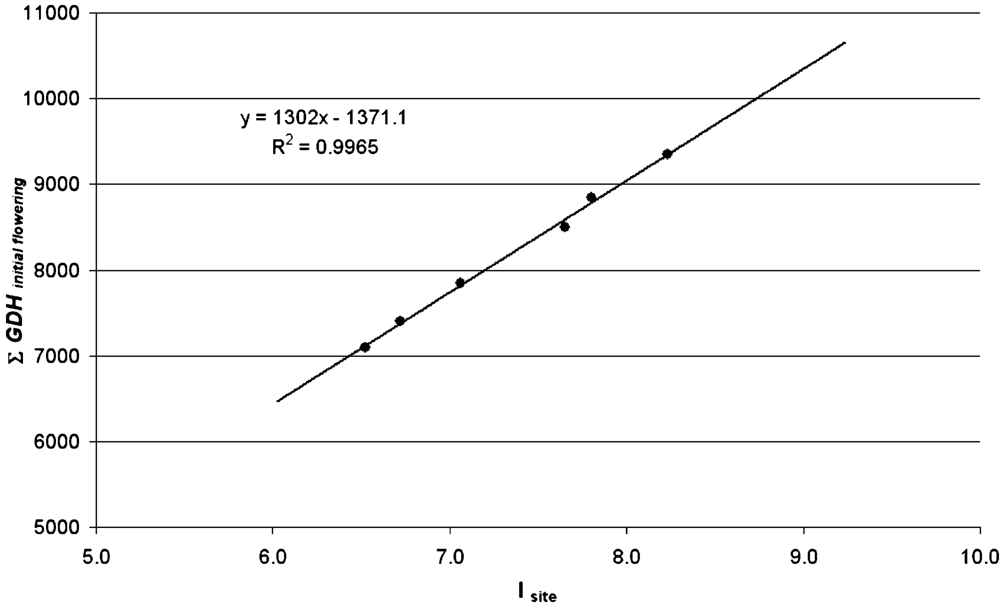

Fig. 9 Relationship between growing degree hours (*GDH*) requirement for initial flowering and index I_{site}

Table 10 Absolute error values for the four Piedmont stations (year 2003)

Site	Absolute error (days)
Lagnasco	1
Guarene	1
Savigliano	4
Busca	3
Mean of four Piedmont sites	2.2

particularly important for the general applicability of the model. The definition of the I_{site} index seems to fully meet the requirements of simplicity and completeness for bioclimatic discriminants among sites.

Some comments need to be made about the use of hourly data. The availability of hourly temperature series exerted a positive effect on model performance. Even when hourly data were reconstructed by the TM model (Cesaraccio et al. 2001), hourly models performed better than daily ones. Yet, test results show that, for the optimal use of the TM model, 1 year of hourly observations is required, resulting in a limitation of the application of hourly models. Secondly, any gap in the data, if not filled, acts towards a reduction of chill (or heat) accumulation; in this way, a "mean effect", counterbalancing the lack of "cold" with the lack of "warm" hours (having the same probability of happening) in a long series, does not apply. Therefore, there is a clear need for a continuous hourly series, often requiring data reconstruction by time and space interpolation, or by the application of models such as the TM itself.

In general, day length is thought to potentially affect the phenologic evolution of plants; nevertheless, no improvement was detected when day length was added to the model. In our investigation, no relationship was found and results were even worse when duration of sunlight was taken into account. On the other hand, the positive or negative anomaly in solar radiation is indirectly taken into account when the forcing quantity is temperature, the two variables being strongly linked, at least when working on seasonal series. In any case, allowing for solar radiation would weigh down the model with a variable often not readily available for any locality (especially when past records are examined), and could affect the performance of a model that is certainly attractive in its present formulation.

As far as operational applications of the "Progressive Utah" model are concerned, at least two are envisaged: blooming prediction and climatology. In the first case, it must be acknowledged that blooming does not immediately follow the winter bud stage. On the contrary, four or five other phenophases occur between the two, and the two previous phenophases follow each another in the approximately 2 weeks before initial flowering. Moreover, the flowering stage is not an unexpected event and can probably be better predicted by direct field observation; the practical use of a phenological model for blooming prediction is then questionable.

Of wider interest is the climatological use of the model. In most regions in the world, minimum temperature is known to be increasing more than maximum temperature. This could decrease the risk of damage by spring frost, since the general temperature increase would push forward phenological development; however, on the other hand, higher minimum temperatures would expose orchards to less severe frost risk. Nevertheless, this rule is not valid for every site. Particularly in northern Italy, cases are reported where the increase in minima and maxima are more or less equal, and there are even localities where the general temperature increase is driven by maxima rather than by minima (Simonini 1995; Cacciamani et al. 2001). Schwartz et al. 2006 found that, in Europe, the change in frost damage risk shows a mixed pattern (in northern Italy cases of both slight increase and slight decrease have been reported). Moreover, in central Europe, scenarios are envisaged where higher winter–spring temperatures would quicken phenological development until flowering, but the inhomogeneous temperature trend for full-spring months would then expose buds to temperatures no higher than the present ones, so that frost risk would increase (Chmielewski 2005).

The application of a flowering model to sites or, more frequently, for periods with no phenological observations, could generate flowering date series to be used for climatological purposes. Since frost sensitivity sharply increases when flowers open, the blooming model allows the identification, for any year or locality, of a period at which trees go through a frost-prone stage. This information can be coupled to a climatic series encompassing past or future periods, when phenological surveys are not available. The general effectiveness of the "progressive Utah" model makes it a valuable tool in cases of local climatic downscaling, i.e. in areas encompassing different elevation zones, where the phenological model must differentiate outcomes according to microclimatic features.

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