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# Evaluation of three modelling approaches for almond blooming in Mediterranean climate conditions

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ABSTRACT

Chilling and heat requirements for breaking dormancy and flowering were studied in seven almond cultivars in Southern Italy. Chilling portions (CP), computed through the Dynamic model, and growing degree hours (GDH) were used to determine chill and heat accumulation, respectively. Then, using full bloom dates and temperature data from nine seasons (2003/2004-2007/2008 and 2009/2010-2012/2013), three sequential methods for the estimation of thermal requirements were compared: 1) the Ashcroft Method (AM), where chilling and heat requirements were selected considering the lowest variability of the GDH at several intervals of CP, and two variations: 2) modified Ashcroft Method (AMm) that took into consideration the lowest variability in both CP and GDH, and 3) reverse Ashcroft Method (AMr) opposite to AM. All methods were effective in predicting full bloom dates; however the modified Ashcroft method was the most accurate under Mediterranean conditions and allowed to classify almond cultivars for their thermal requirements. The results from AMm, showed chilling requirements ranging between 24–62 CP and heat requirements between 3263 and 6699 GDH, respectively.

## 1. Introduction

The definition of the chilling requirements of temperate deciduous fruit species and of the amount of winter chill available at any given location represent central issues in horticulture, all the more so since the cultivation of these species is expanding beyond their traditional growing regions (Luedeling et al., 2009b). The negative effects of the lack of chill for breaking dormancy in temperate fruit species, both in vegetative and reproductive growth are well known, as in the case of high chilling requirement cultivars grown in warm-winter areas failing to flower at the proper time (Gianfagna and Mehlenbacher, 1985; Erez and Couvillon, 1987). On the other hand, in temperate regions, chilling requirements can be largely satisfied before the end of the cold season (Razavi et al., 2011), therefore flowering could occur too early, if the heat requirement is satisfied, enhancing the risk of loss of yield by late frosts (Balandier et al., 1993; Faust et al., 1997). Understanding the phenology of dormancy and blooming would provide not only an assessment of the performance and adaptation of genotypes to certain growing areas, but also reliable information for breeding programs and better scheduling of cultural techniques, such as pest management and frost protection (Maulión et al., 2014).

Bud dormancy in deciduous fruit trees of temperate zones occurs annually and enables trees to survive cold winters (Razavi et al., 2011). The minimum amount of chill necessary to exit endodormancy is known as chilling requirement. Several models have been proposed to quantify chill requirements: Chilling hours (Weinberger, 1950), Utah model (Richardson et al., 1974), North Carolina model (Shaltout and Unrath, 1983), Low Chilling model (Gilreath and Buchanan, 1981), Positive Chilling model (Linsley-Noakes and Allan, 1994) and the Dynamic model (Fishman et al., 1987a,b; Erez et al., 1988). All these models have been developed under different climatic conditions and fruit tree species (Ramirez et al., 2010). The minimum amount of heat necessary to re-start growth (i.e. bud burst, blooming) is known as heat requirement. Heat requirement is generally expressed as Growing Degree Hours (Richardson et al., 1974; Anderson et al., 1986). Both chill and heat requirement are species and cultivar specific (Westwood, 1993) and play a key role for the selection of genetic materials able to adapt to specific geographic regions (Bassi et al., 2006).

Besides temperature data, some methods (Ashcroft et al., 1977; Alonso et al., 2005; Funes et al., 2016) require three chronological dates for the estimation of chill and heat requirements: the chill accumulation start date (SD), the endodormancy breaking date (BD), and

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*Abbreviations:* CP, chilling portion; GDH, growing degree hour; AM, Ashcroft Method; AMm, modified Ashcroft Method; AMr, reverse Ashcroft Method; SD, start date chill accumulation; BD, endodormancy breaking date

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the full bloom date, with 50% of opened flowers (Couvillon and Erez, 1985; Alonso et al., 2005; Funes et al., 2016). The full bloom date is determined directly in the field. The start of dormancy is not defined by a calendar date, as it is deeply linked to the plant physiology. However, several studies suggested the same key dates to start the count for the accumulation useful for plant to exit endormancy (Luedeling et al., 2009b; Luedeling and Brown, 2011; Gannouni et al., 2017; Jarvis-Shean et al., 2015). Generally SD is determined empirically and varies according to the model of chill accumulation. Unfortunately, the BD cannot be observed easily from field observations (Funes et al., 2016). This complicates quantification of thermal requirements. *Forcing* and *modelling* approaches are normally used for estimating chilling and heat requirements (Pope et al., 2015). Several *forcing* approaches have been developed to assess the BD under controlled conditions, including biological, anatomical and biochemical methods (Marquata et al., 1999; Szabó et al., 2002; Bartolini et al., 2004; Bassi et al., 2006; Chuine et al., 2016; Chmielewski et al., 2017; Chmielewski and Götz, 2017). Once the BD is identified, chill requirement can be calculated from temperatures between SD to BD; the heat requirement for blooming can be computed as the heat accumulation from BD to full bloom (Richardson et al., 1974; Richardson et al., 1975; Guerriero and Scalabrelli, 1991; Mahmood et al., 2000). However quantification of chilling and heat requirements under laboratory conditions must be considered with caution because the environmental variables are unnaturally constant (Dennis, 2003; Luedeling et al., 2009b; Hawerroth et al., 2013), and these procedures are expensive and time consuming when analysing a large number of genotypes (Leida et al., 2012). The *modelling* approach relies on the analysis of historical blooming dates and hourly temperatures and has been developed to fit the responses of tree species to local weather conditions (Fan et al., 2010). Several *modelling* approaches have been proposed, such as the thermal time model (Cannell and Smith, 1983), the parallel model (Landsberg, 1974; Harrington et al., 2010), the sequential model (Sarvas, 1974; Ashcroft et al., 1977), and the alternating model, also named chill overlap (Cannell and Smith, 1983; Pope et al., 2014). Although the sequential approach could be considered a simplification of reality, it is widely applied as it is easy to handle from a statistical point of view and its results have practical implications (Cesaraccio et al., 2004; Legave et al., 2008; Ramirez et al., 2010; Campoy et al., 2012; Legave et al., 2013; Luedeling et al., 2009b; Luedeling and Gassner, 2012; Miranda et al., 2013; Funes et al., 2016; Zhang et al., 2015).

The sequential approach is based on the assumption that chilling and heat requirements are constants (Ashcroft et al., 1977) and are consecutive and independent of each other to determine the flowering date (Darbyshire et al., 2016). According to Ashcroft et al. (1977) flowering is a phenological phase that results from sequential exposure to two temperature stimuli: 1) the dormant flower bud accumulates exposure to low temperatures up to a predetermined level; 2) the flower within the bud develops at a rate influenced by temperature until flowering. The chilling requirement for breaking dormancy (considered as the first constant) and heat requirement for floral development (second constant) are thus satisfied. They can both be estimated selecting the values showing the minimum variability among years (Ashcroft et al., 1977, Rattigan and Hill, 1986). Different chilling accumulations (hypothetical chilling requirement) obtained with this method showed the same variability, making the choice of the proper chilling requirement and the corresponding heat requirement difficult (Alonso et al., 2005). In addition, some sequential approaches that used the Partial Least Squares Regression (PLS) to identify the timing of budburst needed more than 20 years of observed data for the statistical analysis (Luedeling and Gassner, 2012).

Almond is considered a low chilling requirement species, being early flowering. Only a limited number of studies, in comparison with other species, have evaluated its chill and heat requirements (Alonso et al., 2005, 2010; Benmoussa et al., 2017; Egea et al., 2003; Pope et al., 2014; Ramirez et al., 2010; Rattigan and Hill, 1986). There is no agreement on its chilling and heat requirements, as studies have been conducted using different methods and systems (Alonso et al., 2005; Melke, 2015; Razavi et al., 2011).

The objective of this work was to assess, compare and evaluate 3 sequential models predicting the chilling requirement for breaking dormancy and heat requirement for blooming in seven almond cultivars characterised by diverse flowering time and different origin.

**Table 1**

Average flowering time of the seven almond cultivars; means of the 1982–1992 period (De Giorgio et al., 1996) expressed as days before (−) or after (+) full bloom (50% flower opened) of Tuono cultivar, considered as reference.

| Cultivar (Origin) | Flowering time |
|---|---|
| Pizzuta d'Avola (Italy) | −26 |
| Malaguena (Spain) | −21 |
| Ne Plus Ultra (USA) | −19 |
| Tribuzio (Italy) | 0 |
| Tuono (Italy) | 0 |
| Cristomorto (Italy) | +2 |
| Rana Gentile (Italy) | +9 |

## 2. Materials and methods

### 2.1. Site, experimental material and data collection

The study was carried out at the almond germplasm collection of the experimental farm, Council for Agricultural Research and Economics – Research Centre for Agriculture and Environment (CREA-AA), located in the Apulia Region (Southern Italy), under Mediterranean climate conditions (altitude 126 m a.s.l., latitude 41°20′ N, longitude 16°45′ W). The annual mean maximum and minimum air temperature and rainfall for the experimental site calculated over a 30 year period (1976–2006), are 21.6 °C, 10.5 °C and 409.17 mm, respectively. The experiment was conducted on seven almond cultivars (Table 1). Trees were planted in 1968, grafted on seedling, spaced 3.5 × 7 m and trained as classic vase. Each cultivar received similar cultural practices.

Full bloom dates (50% of bloom, Richardson et al., 1974), were recorded on ~4 trees per cultivar and averaged. Hourly temperatures between October 1st and March 31st were recorded by a weather station located on the farm. The meteorological and phenological data for the 13 seasons under investigation were divided in two groups: nine seasons (2003/2004-2012/2013, except 2008/2009) were used to assess the thermal requirements of the seven cultivars with the three methods (data n = 63). Data from four seasons (1990/1991-1992/1993 and 2001/2002) were used to evaluate (test, verify) their reliability by comparing predicted and observed blooming dates (data n = 28).

### 2.2. Models to evaluate chilling and heat accumulations

Chilling requirement to exit endodormancy was calculated by hourly temperatures using the Dynamic model (Erez and Couvillon, 1987; Fishman et al., 1987a,b; Erez et al., 1988). The equations used were in accordance with Fishman et al. (1987a, 1987b) and Darbyshire et al. (2011). This model performs best in regions with warm and subtropical climates (Erez et al., 1988,1990) and is considered the most robust chilling model for temperate winter areas (Luedeling et al., 2009a,b; Luedeling and Gassner, 2012; Guo et al., 2014; Melke, 2015). In the same region where the present trial was conducted, the Dynamic model outperformed the chill hours ≤ 7.2 °C model, the Utah and Low Chilling models on sweet cherry cultivars (Palasciano and Gaeta, 2017).

Growing degree hours (GDH) were calculated from hourly temperatures using the model proposed by Richardson et al. (1974).