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Statistical identification of chilling and heat requirements for apricot flower buds in Beijing, China

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ABSTRACT

Instead of the commonly used approach of conducting controlled experiments to estimate chilling and heat requirements (CR and HR) of fruit trees, the statistical method of Partial Least Squares (PLS) regression was applied to identify the CR and HR of apricot (*Prunus armeniaca* L.) in Beijing, China by correlating first flowering dates of apricot with daily chilling and heat accumulation during 1963–2010. Three common chilling models (the 0–7.2 °C, Utah and Dynamic Models) and one forcing model (the Growing Degree Hour Model) were used to convert daily temperature data into daily chill and heat accumulation rates. The results indicated that PLS regression analysis is a useful approach to estimate the CR and HR of fruit trees wherever phenology and climate observations have been conducted for long periods. Use of all chilling models indicated similar chilling periods for apricot in Beijing (mid-September to early March), while the identified forcing period started in early January and extended to the first flowering date for each year. The Dynamic Model appeared to be the most accurate model with smallest year-to-year variation in chill accumulated during the chilling period (coefficient of variation of only 7.5%). Using the Dynamic Model for chill, and the Growing Degree Hour Model for heat quantification, the CR of apricot in Beijing was determined at 75 ± 6 Chill Portions (CP) and the HR at 3055 ± 938 Growing Degree Hours (GDH).

1. Introduction

Deciduous fruit trees in the temperate zone fall dormant every year to survive in cold and unfavorable winter environments (Jones et al., 2013; Luedeling et al., 2013b). Dormancy is commonly assumed to consist of an endodormancy phase, during which factors within the trees inhibit growth, followed by an ecodormancy period, when growth is limited by external factors (mainly temperature; Lang et al., 1987). The fulfillments of chilling and heat requirements (CR and HR) are the major driving factors in the breaking of both dormancy stages and initiation of growth in spring (Campoy et al., 2011a; Luedeling, 2012).

Knowledge of CR and HR is crucial for introducing new cultivars (Bassi et al., 2005; Luedeling et al., 2009c), for timing application of dormancy-breaking chemicals, for choosing appropriate parents for breeding early or late flowering cultivars, and even for predicting impacts of climate change (Gao et al., 2012; Luedeling et al., 2009d). It also has significant practical and economic impacts on the establishment, maintenance, control, and productivity of orchards (Fennell, 1999). Insufficient chilling can result in uneven leafing, bloom and pollination, and cause varying fruit sizes and maturity times. All these factors can reduce the quantity and quality of fruits (Lang et al., 1987; Luedeling et al., 2009b). After sufficient chilling is accumulated, the satisfaction of HR is essential for breaking ecodormancy and initiating growth and bloom in spring.

Horticultural scientists have developed several models for quantifying the CR. Among them, three chilling models are widely used around the world: the 0–7.2 °C Model (Weinberger, 1950), the Utah Model (Richardson et al., 1974), and the Dynamic Model (Fishman et al., 1987a,b). Many studies have been conducted to compare the accuracy of different chilling models for different species and cultivars across the world. To our knowledge, the

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Dynamic Model has always performed better or at least equally well as the two alternative models (Campoy et al., 2011a; Luedeling and Gassner, 2012; Luedeling et al., 2009d; Ruiz et al., 2007; Zhang and Taylor, 2011). However, other models (mainly the 0–7.2 °C and the Utah Model) are still widely used, because their chill metrics are much more easily calculated, and in some cases other models have appeared equally robust as the Dynamic Model (Alburquerque et al., 2008; Ruiz et al., 2007; Wang et al., 2003). Methods for quantifying the HR for plant flowering have been developed, with the Growing Degree Hour (GDH) Model most widely used across the world compared with other forcing models (Anderson et al., 1985; Darbyshire et al., 2013; Luedeling et al., 2009d).

However, even when appropriate models are adopted, estimating a cultivar's CR and HR remains a challenge. The main reason for this is that the chill and heat accumulation processes and the periods when they occur cannot easily be identified without detailed field observations or laboratory experiments (Luedeling et al., 2013b). Recently, based on long-term temperature and phenology records, Partial Least Squares (PLS) regression has successfully been used to delineate the chilling and forcing periods and to estimate the CR and HR of cherry in Germany (Luedeling et al., 2013b) and chestnut in China (Guo et al., 2013) by statistically correlating flowering dates of trees with daily temperatures. A refined version of the PLS procedure, in which bloom dates were related to daily chill and heat accumulation rates, has proven to provide better estimates of CR and HR than the original procedure (Guo et al., 2014; Luedeling et al., 2013a). However, in these studies, only one chilling model (the Dynamic Model) was used to convert daily temperatures into daily chilling units, while no data comparing different chilling models were presented.

In this analysis, the refined PLS regression procedure was used to correlate flowering dates of apricot in Beijing to daily chilling and heat accumulation rates calculated with three common chilling models and one forcing model. Based on regression results, the chilling and forcing period, as well as CR and HR for apricot in Beijing were identified. The objectives of the present study were to statistically estimate the CR and HR of apricot flower buds instead of relying on experiments, and to compare the accuracy of different chilling models. A separate objective was to present an overall methodological summary on the determination of chilling and forcing periods, and the estimation of CR and HR for fruit trees.

2. Materials and methods

2.1. Study site

In Beijing, species-level phenological observations of plants were mainly conducted at the Summer Palace (39°54′38″N, 116°8′28″E, 50 m a.s.l.), a famous royal garden, which has the longest and most abundant records of phenology in China (Zhang et al., 2005). Most phenological stages for plants (e.g., bud sprouting, leaf unfolding, first and peak bloom, leaf coloring and leaf drop) have meticulously been recorded. The phenology dataset was collected by the Chinese Phenological Observation Network (CPON), a nationwide system of monitoring stations that has conducted standardized and systematic phenological observations across China since 1963. Uniform observation criteria and guidelines have been followed since the network's inception. This systematic dataset with high reliability and long history has played an important role in phenological and climatic research in recent years.

2.2. Phenology and climate data

First flowering data of three apricot trees (*Prunus armeniaca* L.) of similar age (ca. 70 years) and origin collected between 1963 and 2010 were obtained from the CPON. The dataset contains data for 39 years (no observations were available for 1969–1971, and 1997–2002). In the present analysis, the first flowering phase of apricot was registered when 10% of flowers were open, corresponding to stage 61 on the BBCH ('Biologische Bundesanstalt Bundessortenamt und Chemische Industrie') scale (Meier et al., 1994). Detailed phenological observation standards and methods have been described by Lu et al. (2006) and Wan and Liu (1979).

Daily minimum and maximum temperatures in Beijing during 1963–2010 were acquired from the Beijing Meteorological Station, which is located only 2.5 km from the Summer Palace (Lu et al., 2006), so that temperatures recorded there should closely represent conditions at the observation site. Since most common chilling and forcing models require hourly temperature data, idealized daily temperature curves with an hourly resolution were constructed from daily temperature extremes as proposed by Linvill (1989, 1990). Required inputs for these calculations were sunrise and sunset times, as well as daylength, which were computed according to procedures described by Almorox et al. (2005) and Spencer (1971).

2.3. Chilling and forcing models

The most commonly used chilling model is the 0–7.2 °C Model, also referred to as Weinberger Model (Weinberger, 1950). It interprets temperatures between 0 and 7.2 °C as effective for chilling accumulation and defines one Chilling Hour (CH) as one hour with temperature between these thresholds. CHs are then accumulated throughout the dormancy period.

The Utah Model (Richardson et al., 1974) assigns differential weights to different temperature ranges, and it includes negation of previously accumulated chill by high temperatures. This model, which quantifies chill in Chill Units (CU), has performed well in the cool temperate zone, but it has been shown to have deficiencies in warm temperate and subtropical climates. Modified Utah Models such as the Low Chilling Model (Gilreath and Buchanan, 1981), the North Carolina Model (Shaltout and Unrath, 1983), and the Positive Utah Model (Linsley-Noakes and Allan, 1994) have been developed subsequently. Since these modified Utah models are only intended for certain regions or species, we did not test them in the present study.

The Dynamic Model (Fishman et al., 1987a,b) assumes chilling accumulation occurs as a two-step process. In the first step, an intermediate product is formed, but this can be destroyed by heat. Prevalence of moderate temperatures can then convert this intermediate product into a permanent Chill Portion (CP) once a sufficient amount of intermediate product has accumulated. This second process is irreversible. CPs are then summed up until the end of the dormancy period. Similar to the Utah Model, the Dynamic Model also considers varying chill effectiveness for different temperatures. Compared to earlier models, the Dynamic Model includes some innovative traits, such as consideration of the chill-enhancing influence of moderate temperatures and the effects of temperature cycles. The mathematical functions of all above-mentioned chilling models are given in Luedeling et al. (2009c).

The forcing model used in the present analysis is the Growing Degree Hour (GDH) Model (Anderson et al., 1985). It assumes that heat accumulates when hourly temperature ranges between a base temperature (4 °C) and a critical temperature (36 °C), with maximum accumulation at optimum temperature (25 °C) for fruit trees. While estimation of parameters for the GDH model is necessary for different species and varieties, most studies on the HR for apricot have used the above threshold temperature values (Campoy et al., 2011b; Ruiz et al., 2007). We recognize that different temperature thresholds have been reported for pistachio (Zhang et al., 2015), and similar efforts for apricot may help refine our understanding of