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Research Paper

# Performance of pistachio (*Pistacia vera* L.) in warming Mediterranean orchards

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ABSTRACT

Woody perennial species from temperate regions fall dormant during the cold winter season to avoid unfavourable conditions. To break out of dormancy and eventually flower, they must fulfil cultivar-specific chilling and heat requirements. Phenology analysis can clarify the climatic requirements of tree cultivars and thus provide critical information to ensure the future viability of orchards in warm growing regions, where warmer winters are expected as a result of climate change. We used Partial Least Squares (PLS) regression to correlate first bloom dates of 4 local and 3 foreign pistachio (*Pistacia vera* L.) cultivars with daily chill and heat accumulation (quantified with the Dynamic Model and Growing Degree Hours Model, respectively) for 18-year records (1997–2016) from Sfax, Tunisia. PLS outputs allowed delineation of the chilling phase, during which high chill accumulation was correlated to early bloom, and the forcing phase, when this was true for high heat accumulation. Both phases showed discontinuities. During September and October, high heat accumulation appeared to first have a bloom-delaying effect, followed by a bloom-advancing effect, indicating that temperature during dormancy induction may affect bloom dates. Chilling requirements were estimated between 32.1 ± 2.3 and 33.3 ± 2.2 Chill Portions and heat requirements between 9974 ± 198 and 12,738 ± 235 Growing Degree Hours. This study revealed limitations of the Dynamic Model, which is often considered the most accurate among commonly used models, in the warm Tunisian climate. High temperatures during the chilling phase had a significant bloom-delaying effect on all pistachio cultivars. Low chill accumulation was related to very low yields and associated with zero production in 1995, 2001 and 2007. Low flowering percentage, high bud fall percentage, long and inhomogeneous bloom, and co-occurrence of several phenological stages on the same branch were symptoms of lack of chill in 2016.

## 1. Introduction

Pistachios are an important nut crop that is widely cultivated in Mediterranean climates. Even though the global production of in-shell pistachios dropped from 638 to 524 thousand metric tons between 2014 and 2015, growers have roughly doubled production since 2004 (International Nut and Dried Fruit Council, 2016, 2015). Much of this expansion has occurred in places where winter temperatures are substantially higher than in the species' centre of origin in Central Asia or in its traditional production regions. Expanding the production of temperate-zone tree species into warm climates may lead to a mismatch between tree physiology and climatic conditions (Erez, 2000). Woody perennial species that evolved in cold-winter regions fall dormant during the cold season to reduce exposure of sensitive growing tissue to unfavourable conditions (Atkinson et al., 2013; Campoy et al., 2011; Faust et al., 1997; Jones et al., 2013). In order to break out of their dormant state, most such species require fulfilment of a chilling requirement, which conditions them to resume growth, produce leaves and eventually bloom and develop fruits, as their environment warms (Jones et al., 2015). The timing of each of these developmental stages is understood to further depend on heat requirements that are specific to each stage and vary across tree cultivars (Luedeling, 2012). Especially the compulsory chilling requirements make temperate-zone tree species potentially vulnerable to climate change, because rising temperatures

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may reduce available chill (Luedeling et al., 2011), causing physiological disorders and threatening the productivity and economic viability of orchards (Erez, 2000).

While this challenge is a concern in many pistachio growing regions around the world, it is particularly daunting for Tunisia, which features some of the warmest pistachio orchards on the planet (Elloumi et al., 2013). Here, chill levels are likely already marginal for pistachio production, and climate projections for the coming decades indicate continued warming (Schilling et al., 2012). This is expected to further reduce available chill (Luedeling et al., 2011), which may jeopardize orchard productivity and sustainability (Darbyshire et al., 2011; Ghrab et al., 2014a). Lack of sufficient chill can have severe consequences (Atkinson et al., 2013), causing physiological symptoms such as shifts in the timing of developmental stages (Miller-Rushing et al., 2007; Ramírez and Kallarackal, 2015), irregular or delayed budbreak, abscission of floral buds, altered reproductive morphology, poor fruit set and changes in vegetative growth (Atkinson et al., 2013). Most of these effects reduce yield and fruit or nut quality (Legave et al., 2013; Lopez and Dejong, 2007). In pistachio, nut quality responds to climate conditions (Doster et al., 2001, 1999; Tajabadipour et al., 2006). Where low chill and changes in winter temperatures affect the timing of developmental stages, changing nutrient demand patterns may cause nutritional imbalances that can lead to early dehiscence, and empty or cracked shells (Hosseinifard and Panahi, 2006; Khezri et al., 2010). In dioecious species like pistachio, changing dormant-season conditions could reduce pollination rates, if male and female trees lose their flowering synchrony (Luedeling et al., 2009a). The large array of production problems that can arise from a mismatch between local climate and tree requirements makes the selection of appropriate cultivars a crucial prerequisite to economically viable fruit and nut production. In making such choices, orchard managers, especially those operating in warm climates, should consider the potential impact of climate change.

Plant phenology is a sensitive indicator of climate variation and change (Fu et al., 2015). Analysis of bloom and leafing dates may therefore allow insights into tree responses to climate and provide useful information for the development of adaptation strategies (Valentini et al., 2001). Such strategies may include the application of rest-breaking agents or shifts towards better-adapted species or cultivars. As a first step towards this goal, phenology analysis can help clarify the climatic requirements of tree cultivars (Benmoussa et al., 2017), which is critical information for preparing orchards in warm growing regions for warming winters (Gao et al., 2012; Jones et al., 2015; Naor et al., 2003).

Precise quantification of chilling requirements is hampered by the poor performance of commonly used chill models, such as the Chilling Hours Model (Weinberger, 1950) or the Utah Model (Richardson et al., 1974), in warm growing regions (Benmoussa et al., 2017; Elloumi et al., 2013; Ghrab et al., 2014a; Pérez et al., 2008). Chilling requirements determined with such models cannot be assumed to be valid across locations (Luedeling and Brown, 2011) or to remain accurate as temperature increases (Luedeling et al., 2009b). This makes it difficult to use information generated by past studies in regions with different climatic conditions. Among such studies, which have been conducted in Turkey (Küden et al., 1995), Iran (Afshari et al., 2009; Esmaeilizadeh et al., 2006; Rahemi and Pakkish, 2009) and Australia (Zhang and Taylor, 2011), chilling requirements of various pistachio cultivars ranged between 500 and 1400 Chilling Hours or between 500 and 1123 Chill Units (of the Utah Model). These estimates are clearly not applicable in Tunisia, where pistachios are successfully grown, but available chill does not even come close to these alleged requirements (Elloumi et al., 2013). The most promising model for more widely applicable estimates is the Dynamic Model (Erez and Fishman, 1998; Fishman et al., 1987a, 1987b), according to which 'Sirora' pistachios in Australia require around 60 Chill Portions (Zhang and Taylor, 2011). This is also far more than what is available in Tunisia, where, however, this cultivar is not grown. The only available information obtained under Tunisian conditions was produced for the widespread 'Mateur' cultivar, for which chilling requirements were estimated by Salhi et al. (2014) (600 Chill Units) and Elloumi et al. (2013) (206 Chilling Hours, 539 Chill Units or 36 Chill Portions). Information on heat requirements is similarly inconsistent, with studies from Turkey, Iran and Australia indicating a need for 8852–17,297 Growing Degree Hours (Küden et al., 1995; Rahemi and Pakkish, 2009; Zhang and Taylor, 2011) as opposed to 12,000 determined by Salhi et al. (2014) for Tunisia.

Recent warm winters in Tunisia raise concerns about tree responses to future temperature increases. There is thus an urgent need for locally appropriate information on tree responses to temperature, which can help anticipate problems and develop adaptation strategies.

To this end, we investigated the relationship between temperature and bloom dates for 7 pistachio cultivars of local and foreign origin, using an 18-year record from the Sfax region of Tunisia. We used Partial Least Squares (PLS) regression (Luedeling and Gassner, 2012) to correlate pistachio bloom dates with daily chill and heat accumulation and to delineate temperature response phases. This method has been used in several recent studies (Benmoussa et al., 2017; Guo et al., 2015a; Luedeling et al., 2013b) to determine the chilling and forcing periods of several fruit and nut species, including successful applications under warm conditions. We explored tree responses to temperature variation during these periods and evaluated correlations between agroclimatic metrics, phenology and productivity.

## 2. Materials and methods

### 2.1. Study site and cultivars

This study was carried out in the Olive Institute's experimental station in Taous (located at 34°56′08″N; 10°36′54″E), in the Sfax region of central Tunisia. The 3-ha experimental orchard is characterized by deep sandy soil, on which trees are grown under rain-fed conditions, using standard horticultural management practices typical of the region. The Sfax region is characterized by a semi-arid Mediterranean climate, with annual precipitation of 204 mm and reference evapotranspiration ($ET_0$) of 1340 mm.

Forty-year-old trees of 4 local and 3 foreign pistachio cultivars grafted on *Pistacia vera* were used for this study. The local cultivars were 'Mateur' (from northern Tunisia), 'El-Guetar' (central Tunisia), 'Nouri' (Sfax, Tunisia) and 'Meknassy' (central Tunisia). The foreign cultivars were 'Kerman' (from Rafsanjan, Iran and widely grown in California, USA), 'Ohadi' (Iran) and 'Red Aleppo' (Syria).

### 2.2. Phenology, yield and weather data

Pistachio tree phenology was observed from 1997 to 2016, with first bloom dates recorded when 5% of flower buds had reached the 'Brown Flowers Cluster' stage – one of several pistachio flower opening stages described by Zhang (2006). For the 'Mateur' cultivar, mean yields (in kg per tree) were recorded from 1983 to 2015.

Daily minimum and maximum temperatures from 1973 to 2016 were obtained from the Sfax El-Maou station and daily extreme temperatures in the orchard determined according to transfer functions developed by Benmoussa et al. (2017). Hourly temperatures, which were required for calculating chill and heat accumulation with common chill and heat models, were calculated from minimum and maximum temperatures using the chillR package (Luedeling, 2016) and based on procedures described by Almorox et al. (2005); Linvill (1990) and Spencer (1971).

### 2.3. Chilling and forcing phases, and chilling and heat requirements

Based on hourly temperatures, we calculated daily chill and heat accumulation between 1997 and 2016. Even though multiple chilling models are commonly used (e.g. the Chilling Hours or Utah Models), we