**Title**

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**Abstract**

**Keywords:**

# Introduction

Winter chill availability is a major factor regulating dormancy and therefore affecting deciduous nut and fruit tree production in Mediterranean and Temperate climate regions. Dormancy, which was divided into endo- and eco-dormancy (Lang, 1987), is a stage defined as the absence of growth in any meristem within a bud or in other part of the plant (Cooke et al., 2012; Rohde and Bhalerao, 2007). According to Faust et al. (1997), the main driver of endo-dormancy is low temperatures, while eco-dormancy would be modulated by heat (Harrington et al., 2010; Luedeling, 2012). Thus, in order to overcome endo-dormancy and maintain their productive potential in the following season, forest and fruit trees require cold temperatures during winter (Lang, 1987; Lang et al., 1987). In this phase of the dormancy period, buds “accumulate” a tree-specific amount of chill after which they respond to heat until reaching bud burst (Alburquerque et al., 2008; Lang et al., 1987). This chill necessity is known as the concept of “chill requirement” (CR) (Faust et al., 1997; Luedeling, 2012).

Chill requirement has been estimated for several species and varieties in different climate conditions through the use of statistical approaches on large phenological datasets (Benmoussa et al., 2017; Guo et al., 2015; Luedeling et al., 2013; Pope et al., 2014) or with the use of chill-forcing experiments using shoots or young potted trees (Alburquerque et al., 2008; Campoy et al., 2013; Egea et al., 2003; Ruiz et al., 2007). However, these reported estimates often differ among climates for the same species and varieties. For example, estimations of CR done by Viti et al. (2010) for apricot cv. “Currot” and cv. “Orange Red” in Italy differs up to 20 % from those done earlier by Ruiz et al. (2007) in Spain. Similar differences can be found among CR estimations done for almonds cv. “Ferragnes” in Tunisia (Benmoussa et al., 2017), the Central Valley of Chile (Ramírez et al., 2010) and Spain (Egea et al., 2003). This low accuracy and low transferability among regions might be explained either by the fact that CR could be highly site-specific (Campoy et al., 2011) or by the way in which winter chill accumulation is currently quantified (Luedeling, 2012). Nonetheless, it seems highly probable that most part of these observed differences be explained by using merely empirical chill models which were developed without considering any physiological parameter (Luedeling, 2012), rather than different CRs within the same variety.

Chill models have been developed in the frame of the question how plants can “sense” cold temperatures to overcome unfavorable winter conditions. This question has not a trivial answer since buds do not express any visible change during endo-dormancy phase. Although some efforts have been made in order to correlate chill accumulation with morphological changes (Fadon et al., 2018) or to review the metabolomics and genetics involved in dormancy progression (Beauvieux et al., 2018; Rios et al., 2014), available chill models do not include this knowledge yet. Thus, the most used models in agriculture are the Chilling Hours model (CH) (Bennett, 1949; Weinberger, 1950), the Utah Model (UM) (Richardson et al., 1974) and the Dynamic Model (DM) (Erez et al., 1990; Fishman et al., 1987a; Fishman et al., 1987b). While a lot of evidence has postulated the DM as the most plausible chill model (Benmoussa et al., 2017; Luedeling et al., 2009c; Ruiz et al., 2007; Zhang and Taylor, 2011) there are a number of works using only the UM or even the CH model in chill quantification (Horikoshi et al., 2017; Kaufmann and Blanke, 2019; Park et al., 2018; Sawamura et al., 2017). Those models are the most sensitives, predicting chill loses between 29 and 39% for the CH model and between 21 and 35% for the UM during the period 1950 – 2050 in the Central Valley of California, whereas DM predicted loses between 14 and 21% for the same period (Luedeling et al., 2009c). Moreover, Luedeling et al. (2009b) showed that the ratio between metrics from CH and DM varied over the time in response to warmer temperatures at a same location. In this line, Luedeling and Brown (2011) reported that all ratios between winter chill metrics oscillate substantially around the world, showing that models are not proportional across regions. This is highly problematic when farmers import varieties for which CR has been estimated elsewhere, even by using the same chill model.

Alternatives to those common chill models have been developed in the phenological study of deciduous forest and fruit trees. The North Carolina Model (NCM) (Shaltout and Unrath, 1983), the Positive Utah Model (PUM) (Linsley-Noakes et al., 1994) and the Low-Chill Model (LCM) (Gilreath and Buchanan, 1981) use the same structure as UM with modifications. In brief, the NCM uses a wider range of temperatures but including a higher chill negation (up to – 2) for temperatures above 23.3 °C. The PUM has no chill negation values, considering all temperatures between 1.4 and 12.4 °C effectives for chill accumulation, whereas the LCM only changes the temperature thresholds for each chill unit. The Modified Utah Model (MUM) (Linvill, 1990) considers all temperatures between 0 and 14 °C effectives (chilling unit ≤ 1) and temperatures above 14 °C as a negative contribution (chilling unit > ­–1, or –1 if T > 21 °C). Other agricultural and forest models which use daily extreme or hourly temperatures as input have been proposed in phenological studies predicting bud burst dates (Cesaraccio et al., 2004; Chmielewski et al., 2011; Hänninen, 1990; Harrington et al., 2010; Legave et al., 2013; Legave et al., 2008). These models use different functions to estimate chill and heat during the dormancy season and like the most used chill models, none of them include any physiological parameter in its development.

Representative Concentration Pathways (RCPs) represent the total radiative forcing (W m-2) expected by the end of the century due to atmospheric concentration of greenhouse gases (GHG). According to IPCC (2014), global surface temperature increases expected by the end of the 21st century range from 0.3 to 1.7 °C in the RCP2.6 scenario. Thus, winter chill is expected to decrease in the future in most of the regions of the world, being the most affected the Mediterranean climate areas (Baldocchi and Wong, 2008; Chmielewski et al., 2012; Darbyshire et al., 2016; Kerr et al., 2018; Luedeling et al., 2009a; Luedeling et al., 2011). Nevertheless, the chill model used to quantify this metric makes a substantial difference in the projection results. Future chill availability is an important input for farmers’ decision making and therefore the use of a common metric to estimate CR of fruit trees and to project winter chill is desirable. The main aim of this work is to compare common and alternative chill models for past and future climate scenarios in three different regions around the world. In each country (Chile, Tunisia and Germany) we selected three relevant sites for deciduous fruit tree production. At each site and using 13 chill models we analyzed winter chill for the past and projected future chill availability by the end of 21st century for two RCP scenarios (RCP4.5 and RCP8.5) using 15 global climate models.

# Materials and methods

## Site selection and weather data collection

At each country (Chile, Tunisia and Germany) we selected three relevant sites for deciduous fruit tree production. Those sites were Quillota, Curicó and Chillán in Chile; Ben Arous, Sfax and Mellita in Tunisia; and Bonn, Mannheim and Berlin in Germany. A weather station was selected as primary source of data at each site (Table 1). For sites in Chile we downloaded weather data from the website of the Center for Climate and Resilience Research ([CR]2) sponsored by the University of Chile ([www.cr2.cl](http://www.cr2.cl)) and summarized it with the function *“chile\_weather”* of the “eduaRdo” package (<https://github.com/EduardoFernandezC/eduaRdo.git>) for R (R Core Team, 2017). For sites in Tunisia and Germany we obtained the data through the function *“handle\_gsod”* of the “chillR” package (Luedeling, 2018a) for R (R Core Team, 2017). This function can download and summarize weather data from the Global Summary of the Day (GSOD) database from the National Climatic Data Centre (NCDC) of the National Oceanic and Atmospheric Administration (NOAA). In all sites, we selected daily minimum and maximum records between 1973 and 2017.

Table 1. Information of the weather stations used as primary source of data for three fruit tree production sites in Chile, Tunisia and Germany. DGA: Dirección General de Aguas (General Direction of Water Resources); DMC: Dirección Meteorológica de Chile (Meteorology Direction of Chile); NOAA (National Oceanic and Atmospheric Administration).

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Country | Site | Station Name | Responsible organization | Latitude | Longitude | Elevation (above sea level) | Percentage of dataset complete1 |
| Chile | Quillota | Quillota | DGA | 32.89 °S | 71.20 °W | 130 m | 75.1 % |
| Curicó | General Freire | DMC | 34.96 °S | 71.21 °W | 225 m | 99.9 % |
| Chillán | Bernardo O’Higgins | DMC | 36.58 °S | 72.04 °W | 151 m | 99.6 % |
| Tunisia | Ben Arous | Carthage | NOAA | 36.85 °N | 10.22 °E | 7 m | 99.7 % |
| Sfax | Thyna | NOAA | 34.71 °N | 10.69 °E | 19 m | 99.7 % |
| Mellita | Zarzis | NOAA | 33.87 °N | 10.77 °E | 1 m | 99.3 % |
| Germany | Bonn | Köln/Bonn | NOAA | 50.86 °N | 7.14 °E | 80 m | 84.5 % |
| Mannheim | Mannheim City | NOAA | 49.47 °N | 8.51 °E | 97 m | 70.7 % |
| Berlin | Tegel | NOAA | 52.56 °N | 13.28 °E | 34 m | 71.2 % |

1Percentage of the dataset complete considering the period between 01/01/1973 and 31/12/2017 (32,872 observations of minimum and maximum temperatures).

Due to missing days in most of the weathers stations selected as primary source of data, we used records from the 24 closest weather stations as secondary source of information. For sites in Chile and Germany the closest weather stations were in average 69 and 50 km away from the primary weather station, respectively. Whereas in Tunisia, the average distance for the secondary source of data was 133 km away from the primary source of information. Using the function *patch\_daily\_temperatures* contained in the “chillR” package (Luedeling, 2018a) for R (R Core Team, 2017), we filled the gaps in the record for the primary weather station with data from the auxiliary stations. For each auxiliary station, this function determines temperature differences between sites and uses these to correct for between-station bias. Gaps in the primary station’s records are then filled with data from the auxiliary site. This process is applied sequentially for all auxiliary stations, until all gaps have been filled or no more stations are available. To avoid including non-representative data, the maximum acceptable bias of the auxiliary records for daily minimum and maximum temperatures compared to the primary station was set to 4 °C. Remaining gaps in all sites were then filled by procedures of linear interpolation proposed in Luedeling (2018b). This resulted in complete records of daily minimum and maximum temperatures for 45 years.

## Historic weather scenarios

We estimated chill metrics for each season of the historic record between 1973 and 2017. Nonetheless, this kind of analysis is often affected by inter-annual oscillations, and therefore the risk of a temperature-related phenomena, such as chill availability, is difficult to calculate. We fill this information gap applying the procedure reported by Fernandez et. al. (unpublished) whit some modifications. In brief, we trained the weather generator with data of ten years of the historic records. These years were 1974, 1978, 1983, 1988, 1993, 1998, 2003, 2008, 2013, and 2016. For each month of those years we used a running mean function to compute the typical values for mean daily minimum and maximum temperatures. We then used these scenarios to fed the weather generator to obtain 100 replicates of plausible weather data for each scenario year.

## Future weather scenarios

Future weather scenarios were obtained according to the procedure described by Fernandez et. al. (unpublished). We downloaded future projections for each site from the Climate Wizard database maintained by the International Center of Tropical Agriculture (CIAT). This was done via an application programming interface (<https://github.com/CIAT-DAPA/climate_wizard_api>), using functions contained in the “chillR” package (Luedeling, 2018a). Specifically, this database contains projections for two RCP scenarios (RCP4.5 and RCP8.5) obtained from fifteen Global Climate Models (GCMs) (Table 2). In both RCP scenarios, temperature projections were obtained for the period 2035 - 2065, and for the period 2070 - 2100. Those periods were represented by their central years 2050 and 2085, respectively. Data for 100 replicate years for each combination of site, RCP, year and climate model were then obtained by using these scenarios to fed the weather generator.

Table 2. Information of the Global Climate models available at the Climate Wizard database to generate future temperature data.

|  |  |  |
| --- | --- | --- |
| Name | Abbreviation | Reference and/or link |
| Beijing Climate Center – Climate System Model 1.1 | bcc-csm1-1 | Wu (2012) <http://forecast.bcccsm.ncc-cma.net/web/channel-43.htm> |
| Geophysical Fluid Dynamics Laboratory – Earth System Models | GFDL-ESM2G | Delworth et al. (2006) <https://www.gfdl.noaa.gov/earth-system-model/> |
| GFDL-ESM2M |
| GFDL-CM3 | Donner et al. (2011) |
| Institute of Numerical Mathematics Climate Model version 4 | inmcm4 | Volodin et al. (2010) |
| Institute Pierre – Simon Laplace – Climate Model 5ª | IPSL-CM5A-LR | <https://cmc.ipsl.fr/ipsl-climate-models/ipsl-cm5/> |
| IPSL-CM5A-MR |
| Community Climate System Model 4 | CCSM4 | <http://www.cesm.ucar.edu/models/ccsm4.0/> |
| Community Earth System Model version 1 – BioGeoChemical model enabled | CESM1-BGC | Lindsay et al. (2014) |
| Beijing Normal University – Earth System Model | BNU-ESM | Ji et al. (2014) |
| Canadian Earth System Model 2 | CanESM2 | Chylek et al. (2011) |
| Model for Interdisciplinary Research On Climate – Earth System Model | MIROC-ESM | Watanabe et al. (2011) |
| Centre National de Recherches Météorologiques – Climate Model 5 | CNRM-CM5 | <http://www.umr-cnrm.fr/spip.php?article126&lang=en> |
| Australian Community Climate and Earth-System Simulator 1.0 | ACCESS1-0 | Bi et al. (2013) |
| Commonwealth Scientific and Industrial Research Organisation – Mark3.6.0 | CSIRO-Mk3-6-0 | Rotstayn et al. (2010) |

## Chill metrics estimations

We estimated seasonal winter chill availability for i) each year of the historic record, ii) each year of each past scenario, and iii) each future scenario year (2050 and 2085), both RCPs, and each of 15 GCMs. For locations in the southern hemisphere we defined a winter season as the period between 1st of May and 31st of August in each year, while for sites in the northern hemisphere, the period between 1st of November and 28th of February was used.

Winter chill was estimated according to 13 chill models which are described in Table 3 and Supplementary material. For using the Chilling Hours model, the Utah Model and the Dynamic Model we accessed to the respective functions contained in the “chillR” package (Luedeling, 2018a). While for using the rest of the models we programed these functions into the “eduaRdo” package (<https://github.com/EduardoFernandezC/eduaRdo.git>) for the R programing language (R Core Team, 2017). Results were then summarized by using the “ggplot2” package (Wickham, 2016) for R.

Table 3. Information about the models used to quantifying chill accumulation at each site.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Model name | Metric name | Field of development | Time step | Chill negation by heat | Author/Reference |
| Dynamic Model | Chill Portions | Agriculture | Hourly | Yes | Erez et al. (1990), Fishman et al. (1987a) and  Fishman et al. (1987b) |
| Chilling Hours Model | Chilling Hours | Agriculture | Hourly | No | Bennett (1949) and Weinberger (1950) |
| Utah Model | Chill Units | Agriculture | Hourly | Yes | Richardson et al. (1974) |
| Positive Utah Model | Chill Units | Agriculture | Hourly | No | (Linsley-Noakes et al., 1994) |
| North Carolina Model | Chill Units | Agriculture | Hourly | Yes | Shaltout and Unrath (1983) |
| Modified Utah Model | Chill Units | Agriculture | Hourly | Yes | Linvill (1990) |
| Low-Chill Model | Chill Units | Agriculture | Hourly | Yes | Gilreath and Buchanan (1981) |
| Chill Days Model | Chill Days | Agriculture and Forestry | Daily | No | Cesaraccio et al. (2004) |
| Chmielewski’ Model | Rate of Chill | Agriculture | Daily | No | Chmielewski et al. (2011) |
| Triangular Chill Function | Chill Function | Agriculture | Daily | No | Legave et al. (2008) and Legave et al. (2013) |
| Exponential Chill Function | Chill Function | Agriculture | Daily | No | Legave et al. (2008) and Legave et al. (2013) |
| Chilling Units Model | Chilling Units | Forestry | Hourly | No | Harrington et al. (2010) |
| Triangular Chill Function | Rate of Chilling | Forestry | Daily | No | Hänninen (1990) |

# Results

## Subtitle 1

# Discussion

# Conclusions

# Conflict of interest

# Author contributions

# Acknowledgments

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# Supplementary material

## Additional information about the chill models used in this study

## Dynamic Model

The Dynamic Model (Erez et al., 1990; Fishman et al., 1987a; Fishman et al., 1987b) has emerged as the most plausible model from several comparisons due to its increased physiological approach compared with earlier models. It was developed to be used in warm winter climates such as Israel and South Africa. This model postulates that chill is accumulated in a two-step process in which cold temperatures lead to the formation of an intermediate product. Once a certain amount of this product has been accumulated, it can be transformed into a Chill Portion (CP), by a process that require relatively warm temperatures. The equations to compute Chill Portions, from an hourly dataset of temperatures, are more complex than other models. In here we present a summary of functions reported in Luedeling et al. (2009c).

Where:

slp = 1.6

tetmlt = 277

a0 = 139,500

a1 = 2.567 × 1018

e0 = 12,888.8

e1 = 4153.5

Tk = temperature in Kelvin

t = time during the season in hours

t0 = starting point for chill accumulation

## Chilling Hours Model

Chilling Hours model, reported by Bennett (1949) and Weinberger (1950), was developed to study the dormancy period of peaches in Fort Valley, Georgia, USA. This model considers that all temperatures between 0 and 7.2 °C are effective to overcome dormancy. Specifically, and using hourly records, this model computes the total amount of hours in which temperature fall between the range of interest. The metric used by this model is Chilling Hours (CH)

## Utah Model

The Utah Model (Richardson et al., 1974) uses a similar concept of chill accumulation as Chilling Hours model, but the value of each Chill Unit (CU) has different weights according to different temperature ranges. Another important trait of this model is the addition of negative contributions to chill accumulation for warm temperatures. This model was developed to study the dormancy period on “Redhaven” and “Elberta” peach trees. The function requires, as input, hourly temperature records.

## Positive Utah Model

The Positive Utah Model (Linsley-Noakes et al., 1994) was developed to obtain a user friendly way to estimate winter chill improving the accuracy of the Utah Model when used in warm winter zones of the South African fruit growing areas. This model takes into account concepts of the Dynamic Model avoiding the necessity of complex programming skills to estimate Chill Portions at that time. Unlike Utah Model, this variation cancelled the carry-over effect of negating high temperatures from one day to the next considering only Positive Chill Units (PCU). This model uses hourly temperature data as input.

## North Carolina Model

The North Carolina Model (Shaltout and Unrath, 1983) uses the same structure and concepts as the Utah Model, but it considers a higher chill negation for temperatures above 22.1 °C. This trait has reduced the application in warm winters areas. This model, which uses hourly temperature records as input, was developed to study dormancy on apple trees in North Carolina, USA.

## Modified Utah Model

The Modified Utah Model was developed by Linvill (1990) working on peach trees in Pontiac, South Carolina. Unlike the original approach, this model uses a continuous function instead solid steps boundaries. Chill Units (CU) are estimated from hourly temperature following a sinusoidal shape between two cut points (0 and 21 °C). This implies that positive values (≤1) are obtained for temperatures between 0 and 14 °C, reaching a maximum accumulation at 7 °C. Negative contributions (> -1) are assigned for temperatures in the range 14 – 21°C.

## Low-Chill Model

The Low-Chill Model (Gilreath and Buchanan, 1981) was developed to predict bud burst on “Sungold” 1-year-old rooted cuttings nectarine plants. This model uses the same structure and concept of chill negation for warm temperatures as the original Utah Model. The most significant modifications are the shift of the optimal temperatures for chill accumulation to between 7.9 and 13.9 °C and the shift for the threshold of chill negation to 19.4 °C. Chill Units (CU) are computed from hourly temperature records.

## Chill Days Model

The Chill Days Model (Cesaraccio et al., 2004) was developed to estimate chill requirements and predict bud burst in temperate forest and fruit tree species in Italy. This sequential model uses the accumulation of Chill Days (CD) to break rest and the accumulation of Anti-Chill Days (CA) to overcome quiescence (defined as a separated stage during dormancy). Chill and Anti-Chill days depends on the use of a temperature threshold and a chill requirement. Both are specific for each species and cultivar. This model uses daily minimum and maximum temperature data as input. Originally, this model computes chill accumulation as a negative value. Instead that, in this research we used the absolute value in order to clarify and compare results between models.

Where:

Tc = temperature threshold

Tn = minimum daily temperature

Tx = maximum daily temperature

TM = mean daily temperature

In this research we used the mean threshold for all species and varieties reported in the original paper. Those species and varieties were pears (cv. Butirra, cv.Coscia, cv. Precoce, cv. S. Maria), kiwifruit (cv.Hayward) and cherry (cv. Burlat, cv. Moreau, cv. D. Osini, cv. Comune, cv. Forli, cv. Ferrovia, cv. Marracocca). The respective thresholds were 7.0, 6.8, 6.9 and 7.0 °C for pears, 7.9 °C for kiwifruit and 7.5, 7.0, 7.0, 7.3, 7.1, 7.1 and 7.2 °C for cherries.

## Chmielewski’s Model

This model is part of a bigger set of models used to predict the beginning of apple blossom in Germany (Chmielewski et al., 2011). Specifically, this chill function is used in a sequential model which considers both the state of chilling and the state of forcing. The rate of chilling (Rc) is computed according to the equations proposed by Hänninen (1990) with modifications. In this model, the thresholds were modified to 0.0 °C for Tmin and 10.0 °C for Tmax. As inputs, the model requires the use of daily mean temperature (T) and the base temperature for chilling (TB = 4.2 °C; as was reported by the authors in the original document).

## Triangular and Exponential Chill Functions

These functions, proposed in Legave et al. (2008) and Legave et al. (2013), are part of a wide range of functions used to compute chill and to predict flowering time of apple trees in Europe. In the phenological model, all functions are coupled with a heat sub-model in a sequential structure. In here we selected those chill sub-models identified by the authors as the best option for predicting F1 phenological stage dates in apple trees. Such chill sub-models were the Triangular Chilling (TC) and the Exponential Chilling (EC). According to the authors the parameters of the Exponential Chilling model were settled to TC (specific temperature) = 15 °C while for the Triangular Chilling model the parameters TC (optimal temperature) and IC (temperature interval of efficiency around TC) were settled to 1 and 24 °C, respectively. In this version of the models, EC uses maximum daily records as input whereas TC uses mean daily records as source of data.

## Chilling Units Model

Some efforts on modeling dormancy release in Douglas-fir plants have been made by Harrington et al. (2010). In their works the authors used chilling and forcing functions to predict bud burst dates of forest plants. Chilling Units (CU) are computed by the following function:

Where T is the hourly temperature and *e* is the base of the natural logarithm.

## Triangular Chill Function

Another important effort for modeling bud burst dates of forest trees was reported in Hänninen (1990). In here we present the function to compute the rate of chill (RC) developed for Finnish forest tree species. This function uses daily mean records and therefore express the chill accumulation in a day scale.