fruclimadapt: An R package for climate adaptation assessment of temperate fruit species.

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ABSTRACT

Climate strongly determines the growing range of fruit plant species that can be grown successfully in an area, and also the cultivars that will perform best. Therefore, the assessment of the adequacy of a climate is critical for decision-making in the design of fruit orchards and vineyards, and also for the evaluation of the potential consequences of future climate on fruit production. Bioclimatic indices and plant phenology models are commonly used to assess the suitability of climate for growing quality fruit and to provide temporal and spatial information about regarding ongoing and future changes. In this paper, we present **`fruclimadapt`**, a flexible and versatile package in the R language that streamlines the assessment of climate adaptation and the identification of potential risks for grapevines and fruit trees. A core set of functions allows to assess climate adaptation of fruit tree species by calculating specific bioclimatic index values and to evaluate potential threats to yield and fruit quality. Three additional sets of functions have been included as companions to: i) downscale daily meteorological values to hourly data, ii) estimate winter chill and forcing heat accumulation and iii) estimate the occurrence of phenological phases. **`fruclimadapt`** is currently available from the CRAN website (https://cran.r-project.org/package=fruclimadapt).

Keywords: climate, R package, phenology, risk assessment

1. Introduction

The growing range of plant species and cultivar adaptation to a given area is strongly influenced by climate, and, in particular, by temperature and moisture regimes. Only a good match between climatic conditions of the growing site and the requirements of the species or cultivar considered will guarantee their successful growth and production, as decreases in yield or product quality associated to lack of adaptation may make the activity unprofitable. In this context, determining how species and cultivar are adapted to certain climates is of primary interest in research and decision-making, to explore potential for cultivation in new areas and to allow for the development of adaptation strategies to climate change in current locations.

In the particular case of fruit tree orchards, growers are particularly vulnerable to suffer adaptation problems associated to climate change (Thomson et al., 2014). In this regard, rising temperatures are causing changes in phenology (Hall et al., 2016), affecting fruit set and yield through problems associated with insufficient winter chill accumulation (Darbyshire et al., 2016; Luedeling, 2012), flowering anomalies, disorders in cross-pollination or advanced harvest (Chuine, 2010; Warrington et al., 1999). Fruit quality is also greatly influenced, as forward shifts of developmental timing cause fruit to ripe at higher temperatures, which results in detrimental impacts on fruit firmness (Tromp, 1997; Warrington et al., 1999), fruit composition (Musacchi and Serra, 2018; Poni et al., 2018), taste and texture (Sugiura et al., 2013), or skin red color development (Lin-Wang et al., 2011). Additionally, climate change can lead fruit growers to face to increased risks from climate-related hazards, such as frosts or sunburn, as they depend not only on the change in the frequency and occurrence of detrimental days but also on the shifting phenology of fruit species (Pfleiderer et al., 2019).

Taking all the above into account, reliable site-specific quantitative assessments are necessary (Fila et al., 2014). This has led to a rising interest in developing crop-specific tools and models. For temperate fruit tree species, many phenological models have been proposed and contrasted for their predictive capacity (Chuine and Régnière, 2017; Darbyshire et al., 2017; Parker et al., 2011; Pope and Dejong, 2017). Bioclimatic indices used to assess cultivar adaptation to a region are highly developed for grapevines (Badr et al., 2018; Jones et al., 2009; Tonietto and Carbonneau, 2004), and the calculation of several of those indices has already been implemented in the R packages **`agroclim`** (Serrano-Notivoli et al., 2020), **`ClimInd`** (Reig-Gracia et al., 2019), **`ClimClass`** (Eccel et al., 2016) and **`GrapeWeatheR`** (Bulsink, 2019). However, the implementation of specific bioclimatic indices is less advanced in other relevant species like pome or stone fruit. Extensive research has identified key moments in plant growth stages and climate thresholds to evaluate potential threats to fruit yield and quality such as spring frosts (Miranda et al., 2005; Salazar-Gutiérrez et al., 2014; Sgubin et al., 2018), sunburn (Racsko and Schrader, 2012), anthocyanin accumulation and skin color (Bonada and Sadras, 2015; Curry, 1997; Lin-Wang et al., 2011; Musacchi and Serra, 2018), weather-induced russet (Barceló-Vidal et al., 2013) or wind scab (Cataldo et al., 2013; Newenhouse, 1991). Indices and evaluators for those threats can be found scattered in the technical and scientific literature but, to our knowledge, they have not yet been implemented in the R environment.

Although climate adaptation assessments can sometimes be performed calculating some indices and thresholds with simple computational tools, in the case of complex indices, or when evaluations are made on a regional or even higher scale, it is necessary to rely on more powerful tools to obtain the results in a reasonable time. The objective of this work is to introduce **`fruclimadapt`**, a flexible and versatile package in the R language that simplifies the assessment of climate adaptation and identification of potential risks for temperate fruit species by integrating all the necessary tools. The major differential aspects of **`fruclimadapt`** in comparison to the existing tools are i) it includes specific bioclimatic indices for species not yet covered in the R environment, and ii) the functions that calculate those indices are adaptive and dynamic. That is, the user can define the sensitivity thresholds to adapt them to different species and varieties, and the evaluation periods are defined according to the phenological evolution (recorded or estimated) of each year tested, instead of using fixed calendar periods or average phenological dates.

2. `fruclimadapt` package features

The package **`fruclimadapt`** currently consists of 25 functions visible for the end-user organized in four sets of functions (Figure 1). A core set of functions allows to assess climate adaptation of fruit tree species by calculating specific bioclimatic index values and to evaluate potential threats to yield and fruit quality. Three additional sets of functions have been included as companions for conveniency and to ease the calculation input of data required by the core functions, avoiding the necessity of using other packages and re-formatting data to adapt them to **`fruclimadapt`** format. Briefly, the companion sets allow to: i) downscale daily meteorological values to hourly data, ii) estimate winter chill and forcing heat accumulation and iii) estimate the occurrence of phenological phases. Comprehensive details and code examples of the package functionality are available in the online documentation (https://github.com/Carm1r/fruclimadapt) and inside the built-in R help system, whereas the following sections summarize the theoretical background behind the models and expressions built in the functions. To illustrate the features of the package, four example data sets (`Bigtop_reqs`, `Dates_BT`, `Tcrits_peach` and `Tudela_DW`) are distributed with **`fruclimadapt`**.

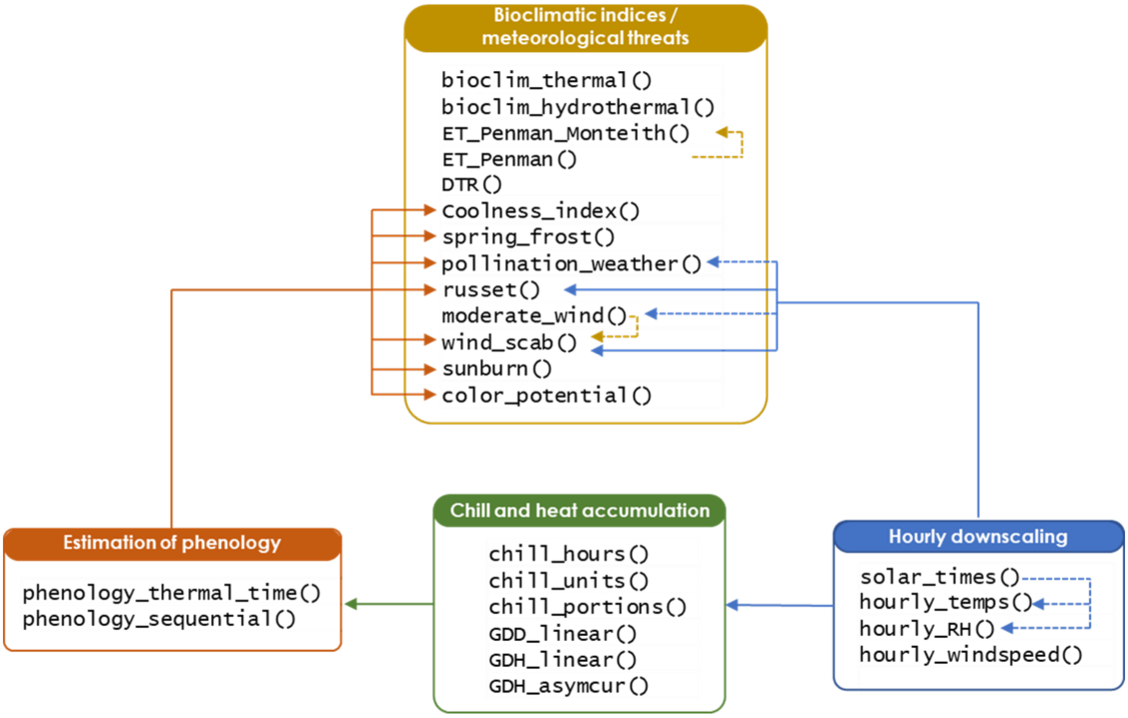

Figure 1. Schematic diagram of the features and functions of **`fruclimadapt`**. Solid arrows indicate that the output of one function is used as input in the other; dashed arrows indicate that the function is called internally by the destiny function.

1. <u>Estimation of bioclimatic indices and meteorological threats</u>: Bioclimatic indices are commonly used to characterize growing areas worldwide in a standardized way, and are also useful metrics to provide the information about climate change impacts and regional climate suitability (Jones et al., 2010). Moreover, horticultural crops are sensitive organisms and their production strongly depends on the climatic conditions of each year. This set of functions constitutes the core of **`fruclimadapt`** and allows the user to determine specific bioclimatic indices to evaluate potential threats to fruit yield and quality of temperate fruit species for time series of any length. Functions to determine the values of the most relevant bioclimatic indices used in viticulture (the horticultural crop most developed in this regard) have also been included in the set.

a. `spring_frost()` function evaluates the number of spring frosts and the expected frost damage during each season within a climate data series. Frost risks are usually estimated with a simplified approach in which a constant lethal temperature is considered for the entire vulnerable period. However, this function is an enhancement of the approach implemented in the Damage Estimator Excel application program (DEST.xls) by Snyder et al., (2005), not yet available in the R environment. This approach models much more realistically the expected effects of a frost, since it contemplates that the sensitivity to frost varies according to the phenology of the plant, and that there is also a range of temperatures between which the expected damages go from light to very severe. It compares daily minimum temperature with the critical frost temperature interpolated for that day, using a user-provided dataframe with the day of occurrence of the phenological stages (historical records or estimations produced by the companion functions `phenology_thermal_time()` or `phenology_sequential()`) for each season, and the critical frost temperatures for each phenological stage. The main advantage of `spring_frost()` over DEST.xls is that our function considers each year's phenology, rather than a common median date for all years evaluated as done in DEST.xls.

b. `DTR()` calculates the mean diurnal temperature range (DTR) for a custom period. The DTR influences fruit growth metabolism and resulting composition (Cohen et al., 2012), and changes in this parameter are used as indicators of climate change and as a diagnostic index for evaluating global climate models (Braganza et al., 2004; Lewis and Karoly, 2013). DTR is obtained by subtracting daily minimum temperature from daily maximum temperature and then averaged for the period defined by the user.

c. `color_potential()` evaluates the suitability of weather conditions for anthocyanin formation in apple skins. The function estimates the number of days that can be considered as highly favorable or unfavorable for anthocyanin accumulation in the skin of red apple cultivars during a number of days before harvest defined by the user (set by default in 30 days), using the temperature thresholds defined Lin-Wang et al. (2011). The function allows testing for several harvest dates in a single run.

d. `pollination_weather()` estimates the adequacy for insect pollination of fruit trees during the flowering period using daily weather data. Days are classified considering the classification proposed by Williams and Sims (1977), by accounting for the number of favorable hours for pollination within a day, which depends on temperature, windspeed and rainfall. Hourly temperature and wind speed values are internally generated by `hourly_Temps()` and `hourly_windspeed()` companion functions.

e. `russet()` function assesses the risk of russet in apple and pear fruits by estimating the number of hours with relative humidity above a threshold during a given period. For reference, in 'Golden' apple, the risk is defined by the number of hours with RH> 55% from 30 to 34 days after full bloom (Barceló-Vidal et al., 2013). The function requires hourly temperatures and humidity, that in absence of hourly records can be generated by `hourly_Temps()` and `hourly_RH()` companion functions from daily data.

f. `moderate_wind()` estimates the daily hours with wind speed equal or above the 'moderate breeze' wind in the Beaufort scale from a dataset with daily wind speeds. Hourly wind speeds from daily values are computed internally using `hourly_windspeed()` companion function.

g. `wind_scab()` estimates the risk of wind-induced abrasion injuries (wind scab) on fruit skin as hours above “moderate breeze” during the sensitive periods of the species, using daily data. Two sensitive periods can be evaluated: the early stages of fruit growth (Michailides and Morgan, 1993) and pre-harvest.

h. `sunburn()` function estimates the number of days in which apple fruit surface temperature (FST) exceeds the thresholds indicated by Racsko and Schrader (2012) for sunburn browning and sunburn necrosis. FST is estimated from daily maximum air temperature using the expression proposed by Schrader et al. (2003).

i. `coolness_index()` calculates a night coolness index based in the Cool Night index of Tonietto (1999), in which the user can define one or several custom periods (set by default in 30 days) for which the calculations will be made.

j. `bioclim_thermal()` calculates five bioclimatic viticultural indices focused on temperature, namely the Growing Season Average Temperature (GST), the Heliothermal Index (HI) of Huglin, the Winkler (WI) index, the Biologically Effective Degree Day (BEDD) index and the Cool Night (CI) index. GST index correlates broadly to the maturity potential for grape cultivars grown across many wine regions, and provides the basis for zoning viticultural areas in both hemispheres (Hall and Jones, 2009) . It is calculated by taking the average temperature of the growing season (April 1 to October 31 in the Northern Hemisphere, October 1 to April 30 in the Southern). WI index (Amerine and Winkler, 1944) classifies regions based on the accumulation of heat summation units by adding up hours above 10˚C during the growing season. The HI (Huglin, 1978) is a refinement of the WI, which incorporates the effect of maximum temperatures and the latitude of the location. The BEDD index (Gladstones, 1992) is another variant on calculating heat summation that incorporates upper and lower temperature thresholds, and a latitude correction similar to that in HI. Finally, the CI index (Tonietto, 1999) considers the average minimum temperature during grape maturation (the month of September in the Northern Hemisphere, or March in the Southern). The functions have been designed to operate in both the northern and southern hemispheres, which is indicated by the latitude of the site.

k. `bioclim_hydrothermal()` calculates two viticultural indices based on temperature and humidity: the hydrothermic index of Branas, Bernon and Levandoux (BBLI, Branas et al., 1946) and the Dryness index (Riou et al., 1994). The BBLI evaluates the influence of both temperature and precipitation on grape yield and wine quality during the growing season. The Dryness index (DI) indicates the potential water availability in the soil, related to the level of dryness in a region (Tonietto and Carbonneau, 2004), and the function uses potential evapotranspiration calculated with the Penman Monteith (Allen et al., 1998) method.

l. `ET_Penman_Monteith()` calculates the reference evapotranspiration for short and tall canopies using daily weather data. The method is based on the FAO56 guidelines (Allen et al., 1998) and on the standardized Penman Monteith equation from the Environmental Water Resources Institute of the American Society of Civil Engineers (Allen et al., 2005). Minimum data requirements are daily maximum and minimum temperatures, whereas relative humidity, solar radiation and wind speed are optional and, if missing, the function integrates the FAO56 estimations for them. An earlier version of the method, developed by Penman (1948), is also implemented as the function `ET_Penman()`.

2. Downscaling to hourly values: Many of the indices that allow the evaluation of plant responses to climate used in **`fruclimadapt`** require hourly data as input, because many processes have been found to respond to sub-daily variations. Quite frequently, when no high-resolution data is available, researchers have been able to develop procedures to generate idealized hourly values. This is possible because typical daily dynamics can be described with reasonable accuracy by mathematical equations. Such idealized values have been proven to be a useful substitute in the absence of hourly information (Bregaglio et al., 2010; Gelda et al., 2019; Luedeling, 2018; Waichler and Wigmosta, 2003). This set of functions generates hourly values from daily meteorological data that can be used as input in other functions in the package.

   a. `hourly_temps()` converts daily maximum and minimum temperatures into hourly temperatures using the sine-logarithmic approximation proposed by Linvill (1990). A sine curve is used for daytime temperatures, and a logarithmic decline curve for nighttime cooling. The method requires sunset and sunrise hours, as well as daylength, which are internally estimated using equations by Spencer (1971) and Almorox et al. (2005) with the function `solar_times()`, using code adapted from the function `daylength()` of the **`chillR`** package (Luedeling, 2020).

b. `hourly_RH()` estimates the hourly relative humidity (RH) from daily maximum and minimum values of temperature and humidity using the approximation proposed by Waichler and Wigmosta (2003), which has been shown to perform well in comparison with other downscaling approaches for RH when daily maximum and minimum values of RH are available (Bregaglio et al., 2010). In this approach, the daily evolution of RH follows an inverse pattern to that of temperature.

c. `hourly_windspeed()` estimates hourly wind speed from the daily average (required) and maximum (optional) using the cosine approximation proposed by Guo et al. (2016), in which the daily average is modified by a factor depending on the hour of the day. This approach has been found to perform well in simulations of climate change scenarios (Ayala et al., 2019; Gelda et al., 2019)

3. <u>Estimation of winter chill and forcing heat accumulation:</u> Perennial woody fruit species cultivated in temperate zones synchronize their annual growth patterns with seasonal environmental changes. During unfavorable winter conditions, temperate fruit species use bud dormancy as a defensive mechanism. During a first phase (endodormancy), buds are latent due to internal factors, and will not grow until certain biochemical changes occur, promoted by the accumulation of chilling, even if the environmental conditions are favorable. After chilling is completed, the plants are dormant only because of environmental factors (cold or cool weather, day length) are preventing growth (ecodormancy). At this point, buds can be induced to grow by exposure to a specific amount of heat. In **`fruclimadapt`**, this set of functions estimates chill accumulation during the endodormancy, and heat accumulation in the ecodormacy, that can additionally be used as inputs in other

package functions for phenological and climate adaptation analyses. Some of the functions included in this set have proven to be outdated, site-specific or too simplistic (Luedeling and Brown, 2011), but they have been included for pedagogical interest, as well as to calculate conversion factors to the most appropriate metrics.

a. `chill_hours()` estimates chill accumulation using the Weinberger (1950) method, with one chill hour accumulated for hourly temperatures between 0˚C and 7.2˚C .
b. `chill_units()` estimates chill accumulation using the Utah model (Richardson et al., 1974). This model is based on chill units, and assigns different weight to different temperature bands; a full unit per hour is assigned only to temperatures between 2.5 °C and 9.1 °C. It performs better than chill hours for a wider range of climates, and it has been regarded for a long time as the ‘reference’ method.
c. `chill_portions()` calculates chill portions according to the Dynamic model developed by Fishman et al. (1987) for use in subtropical regions. The function uses the formulas extracted by Luedeling et al. (2009) from the Excel functions produced by Erez and Fishman (1997). This model considers a two-step process for chill accumulation, once a certain amount of an intermediate product is amassed because of moderate temperatures, it is banked as a chill portion that cannot be altered by subsequent conditions. This model is more complex, but also more accurate than the alternatives, so it has become the most advisable option to estimate chill at this time (Luedeling, 2012).
d. `GDD_linear()` calculates the daily heat unit accumulation (GDD) from daily temperature data with a linear method by subtracting the plant's lower base temperature, defined by the user, from the average daily air temperature (Arnold, 1960). An upper temperature threshold can also be defined, so that all temperatures above it will have equal value in GDD summation.
e. `GDH_linear()` calculates the daily heat unit accumulation (GDH) from hourly temperature data, using a standard linear model or the linear model proposed by

Anderson and Seeley (1992). The standard model just subtracts the base temperature from the hourly one, whereas the Anderson and Seeley (1992) variant adds two temperature caps, so that heat unit accumulation is constant above an optimum temperature and heat units are no longer counted for temperatures above a critical value.

   f. `GDH_asymcur()` calculates the daily heat unit accumulation (GDH) from hourly temperature data, using the ASYMCUR model proposed by Anderson et al. (1986). The model is defined by a base, optimum and critical temperature as in the Anderson and Seeley (1992) model, but it uses an asymmetric curvilinear relationship to model heat accumulation. The user can define the base, optimum and critical values of temperature.

4. <u>Estimation of phenology</u>: Phenological models are used as a tool to predict the phenology of fruit species and assume that temperature is the main factor regulating bud development. Several conceptual approaches have been developed, which vary on how they manage the interplaying between chilling temperatures that break dormancy and heat temperatures that force growth after dormancy release. Two of the most commonly used approaches have been implemented as functions in **`fruclimadapt:`**

   a. `phenology_thermal_time():` The function predicts phenological phases for a climate series using the thermal time approach, in which heat accumulated from a date set by the user explains the date of occurrence of the phenological stage, assuming that dormancy release occurs before that date. The function predicts phenology using a user-defined starting date and forcing heat data (GDD or GDH), and a dataframe for starting dates and heat requirements. Although the thermal models are highly unrealistic in a biological sense, and not recommended for most species, so far is still the best approach to estimate phenology in grapevine, as more realistic models have not demonstrated superior efficacy (Parker et al., 2011; Prats-llinàs et al., 2018), in contrast to other species like apple (Darbyshire et al., 2017), cherry (Darbyshire et al., 2020) or almond (Diez-Palet et al., 2019).

b. `phenology_sequential()`: The function predicts phenological phases for a climate series using the sequential approach, which considers that chilling and heat have independent and consecutive effects. Chill is accumulated up to the plant requirement, and then heat up to the forcing requirement follows, with no overlap between the two phases. This approach can be considered the reference method for many temperate fruit species, and is widely used by the industry and the scientific community (Darbyshire et al., 2020). In the function, chill can be supplied as chill hours, chill units, or chill portions, and forcing heat accumulation can be supplied either as GDD or GDH. Several stages can be calculated in a single run of the function supplying a dataframe with rows of chill and heat requirements.

3. Using fruclimadapt

The package **`fruclimadapt`** can be installed and run on any computer with the R environment version 3.5.0 or higher. The package was tested on a wide span of Windows instances, and on several Linux and MacOS distributions, and has positively undergone numerous tests before being published in the CRAN repository. The stable version of the package is available on CRAN (https://CRAN.R-project.org/package=fruclimadapt), while the latest version is hosted in GitHub (https://github.com/Carm1r/fruclimadapt). **`fruclimadapt`** exploits functionalities provided by several R packages, that are automatically installed alongside the package (Table 1). Source Code 1 provides example R code for installing **`fruclimadapt`** package from either the official CRAN repository or from GitHub source code repository using the **`devtools`** R package (Wickham et al., 2020).

Source Code 1. Example code for installing and using the `fruclimadapt` R package.

```
# Install fruclimadapt package from GitHub source using devtools
devtools::install_github(‘htpps://github.com/Carm1r/fruclimadapt’)
# Install fruclimadapt package from CRAN
```

```
install.packages(fruclimadapt)
# Load the fruclimadapt package
library(fruclimadapt)
```

Table 1. List of `fruclimadapt` package dependencies

R package	Reference	Usage
data.table	Dowle and Srinivasan (2020)	Management of large tabular data
lubridate	Grolemund and Wickham (2011)	Management of date-time data
tidyverse	Wickham et al. (2019)	Manipulation, transformation and reshape of dataframes; pipe operator
zoo	Zeileis and Grothendieck (2005)	Creation of indexed ordered observations in irregular time series (spring frosts)

Most functions in **`fruclimadapt`** include the argument `climdata`, which is a dataframe containing the required daily/hourly climate data, in which dates must be present as three separate columns (Year, Month, Day). In some cases, the day of the year (DOY) must also be present. For files using dates in ISO 8601 (yyyy-mmm-dd) format or others, date component columns can be easily generated using the functions `year()`, `month()`, `day()` and `yday()` of the **`lubridate`** package (Grolemund and Wickham, 2011). Hours must be encoded from 1 to 24.

`fruclimadapt` has been designed to be easily adaptable to the specific needs of the user. Thus, the day of the year to begin accumulating chill in `chill_hours()`, `chill_units()` and `chill_portions()` can be defined by the user, as well as the base, optimal and critical temperatures in heat accumulation functions, or the periods evaluated in the bioclimatic indices. This adaptability allows the user, for example, to set the function `GDD_linear()` to various base temperatures used in other models, such as 0°C to be compatible with the grapevine flowering veraison (GFV) phenological model (Parker et al., 2013), or 4.5°C or 10°C for applications with “classic” phenological models used, respectively, in many fruit tree species and viticulture. The same occurs for the functions estimating phenology, which support any combination of chill and heat models generated by the functions in **`fruclimadapt`** or other R packages like **`chillR`** (Luedeling, 2020) or **`ChillModels`** (Pertille et al., 2019). Moreover, the package has been designed to ease the evaluation of long climate series, so that there is no limit (other than computing restraints) in the number or years that can be evaluated in a single run of a function.

We illustrate a typical **`fruclimadapt`** workflow in Source Code 2. The workflow results in the estimation of the spring frost risks for each of the 10 growing seasons on the dataset `Tudela_DW`, included in the package, which contains daily climate data (temperatures, humidity, rainfall, wind speed and solar radiation) for a location in southern Navarre (Spain). It generates hourly temperatures and calculate chill units with the Utah model and forcing heat with the Asymcur model, merging the outcomes in a dataframe compatible with `phenology_sequential()`. This is used to estimate the date of occurrence of six phenological stages for a peach variety using the requirements obtained by Mounzer et al. (2008). Dataframes with the critical frost temperatures for each of those stages (Miranda et al., 2005) and minimum daily temperatures with the format required by `spring_frost()` are defined, and the number of and accumulated damage from the spring frosts for each growing season is estimated and written to a CSV file. The entire process shown in Source Code 2, performed on a standard PC laptop (CPU: Intel® Core™ i7-7700HQ 2.8GHz, RAM: 16 GB DDR4 SDRAM, Windows 10 version 20H2 64 bits) requires 1.33 seconds to be concluded. To provide a benchmark of **`fruclimadapt`** performance a typical use case was tested on the same PC laptop. The case use consisted of a frost risk assessment for grapevine at a regional scale with a series of 60 years and 23 x 20 points on a grid of 5x5 km spatial resolution, estimating 10 phenological stages and the risk associated to each point and year. The process involved calculating GDD and estimating phenology using `phenology_thermal_time()`, and the output consists of a CSV file with 27,600 observations. On the laptop used to perform the test, the whole operations required 41 min 26 s to be concluded, of which 37 min 46 s (91%) were to compute GDD and phenology.

Source code 2. Example workflow for estimating the risk of spring frosts using the `Tudela_DW` dataset of daily temperatures bundled with `fruclimadapt`.

```
# Load in the global environment the dataset Tudela_DW included in the
package
data(Tudela_DW)
# Extract data with a format compatible with hourly_temps from the
# example climate dataset with daily values bundled in the package
Tudela_DW <- Tudela_DW %>% select(Year, Month, Day, Tmax, Tmin)
# Generate hourly temperatures
Tudela_HT <- hourly_temps(Tudela_DW, 42.81687)
# Calculate chill as chill units from day of the year 305
Chill <- chill_units(Tudela_HT, 305)
# Calculate forcing heat as growing degree hours (GDH) with asymcur
# model, using default temperature thresholds
GDH <- GDH_asymcur(Tudela_HT)
# Combine Chill and GDH values in a dataframe with a format compatible
# with the function phenology_sequential
Data_fen <- merge(Chill,GDH) %>%
  select(Date, Year, Month, Day, DOY, Chill, GDH) %>%
  arrange(Date) %>%
  rename(GD=GDH)
# Create a dataframe with chilling and heat requirements for the
# phenological growth stages in 'Flordastar' peach (Mounzer et al.,
# 2008) with the format required by the function phenology_sequential()
Creq <- c(225, 225, 225, 225, 225, 225)
Freq <- c(3476, 4498, 5026, 6244, 6838, 9473)
Peach_reqs <- as.data.frame(cbind(Creq,Freq))
# Predict the dates for the phenological stages and create a dataframe
# compatible with the function spring_frost()
Dates_peach <- phenology_sequential(Data_fen,Peach_reqs, 305) %>%
  select(Freq_Year,Freq_DOY) %>%
```

```
  rename(Year=Freq_Year,Pheno_date=Freq_DOY)
# Create a dataframe with the critical frost temperatures with
# the format required by spring_frost()
LT_10 <- c(-6.6, -8.0, -4.7, -2.6, -2.6, -2.3)
LT_90 <- c(-15.4, -13.8, -9.9, -6.6, -4.0, -3.6)
Tcrit_peach <- as.data.frame(cbind(LT_10, LT_90))
# Create a dataframe with daily minimum temperatures with the format
# required by spring_frost()
Tmin_Tudela <- Tudela_DW %>%
  mutate(Date=make_date(Year,Month,Day), DOY=yday(Date)) %>%
  select(Year, DOY, Tmin)
# Estimate the number and accumulated damage of the spring frosts
# and extract the dataframe with the total damage for each year
Frost_peach <- spring_frost(Tmin_Tudela, Dates_peach , Tcrit_peach, 181)
Frost_results <- as.data.frame(Frost_peach [['Damage_frosts']])
# write the results in a csv file
write.table(Frost_results ,"Results_Tudela_peach.csv", sep="," ,
            dec=".",row.names = FALSE)
```

4. Summary and future improvements

In summary, the **fruclimadapt** package makes easy to assess climate adaptation and potential threats for yield and quality in fruit species for both climate change research and decision-making, in order to allow the development of adaptation strategies for already established orchards and to explore potential for cultivation of new areas. Additionally, **fruclimadapt** also can play a relevant role for educational purposes since it allows the calculation and comparison of different indices modelling a biological process. Users will find in **fruclimadapt** a complete framework to implement the most commonly used models and indices in their analyses. The package provides a foundation for further development of functionality, and in the near future new functions will be implemented such as including more specific bioclimatic indices, innovative phenological models that are gaining traction [like the chill overlap proposed by Darbyshire et al. (2017)] to encourage their widespread use by the technical and scientific community and new forms of presenting the results.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Carlos Miranda: Conceptualization, Methodology, Software, Writing – original draft; **Gonzaga Santesteban**: Methodology, Writing – reviewing and editing; **Jorge Urrestarazu**: Writing – reviewing and editing.

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