VINEYARDS INTEGRATED
SMART CLIMATE APPLICATION

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Deliverable abstract

The present document describes the principles of bud break and berry models for the seasonal forecast of the key grapevine phenological stages. The document also includes the description of the LEAF model. The document presents the calibration and validation analysis performed to test the availability of the models to predict the different phenological events. Although in its first version the validation analysis shows a good performance of the models, some efforts are needed to improve seasonal predictions. The advances in model performance would be possible thanks to the experiments specifically designed in the pilot plots.

[3] Creation, modification, final version for evaluation, revised version following evaluation, final.

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0. Document objectives

The present document provides a description of the phenology and LEAF models. The first part of the document draws the basic principles of the models and the main equations. Then, the results of the calibration and validation analysis are showed. Finally, some comments and future works are highlighted. It is important to notice that what it is presented here is a first version of the models. Further improvements will be implemented throughout the project based on the results of the pilot plots.

1. Introduction

Grapevines are extremely sensitive to their surrounding environment, with seasonal variations in yield much higher than other common crops. This fact has been studies by several authors. E.g., Keller (2010)[4] states that *an upward shift in seasonal temperature will dramatically shift the growing season thereby changing the normal pattern of grape development toward an earlier onset of flowering, veraison, and harvest.* Likewise, Santisi wrote: *Since minor shifts in seasonal temperature "can make the difference between a poor, good, or excellent vintage … colder-than normal temperatures lead to incomplete ripening with high acid, low sugar, and unripe flavors (whereas) warmer-than-normal temperatures create overripe fruit with low acid, high sugar, high alcohol and cooked flavors"* [5]. The result of the studies mentioned above, shown that any change on weather conditions, particularly during ripening, will have a huge impact on the wine quality.

[4] Keller M.M. (2010). Managing grapevines to optimise fruit development in a challenging environment: a climate change primer for viticulturists. *Aust. J. Grape Wine Res*., 16, pp. 56–69
[5] Santisi J. (2011). Warming up the wine industry. *E: Environ. Mag*., 22 (6), pp. 15–17

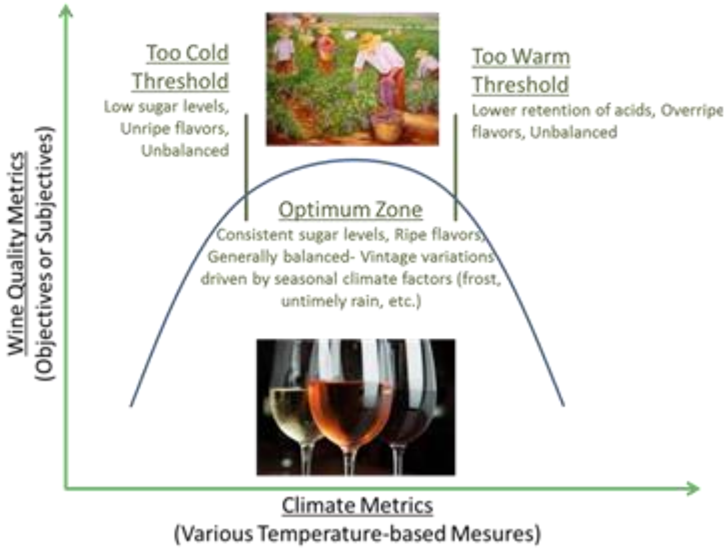

Figure 1. Relationships and thresholds between climate and wine production and quality metrics

The IPCC projections predicts that temperature will rise in wine regions. Such increase threatens traditional vine areas and risks wine-based economy regions. Under these conditions, any management strategy aimed at avoid the high temperatures during ripening will ameliorate the detrimental effects of climate change on wine quality in the traditional production regions.

Different management strategies have been proposed to shift harvest towards more favorable periods. One example is the crop forcing[6]. The crop forcing technique consist on removing all the leaves and bunches from the vine, "forcing" a restart of the phenological cycle and delaying the harvest as a consequence. Although promising to mitigate the negative effects of climate change, the success of such technique relies on finely adjusting the moment of application which in turn depends on future (months) weather conditions and on site specific factors, like soil, variety, trellis system and so on. This is where the combination of phenological models with weather projection can play a significant role; assisting growers to make decisions based on reliable information of their crops to properly apply the management strategy adapted to its region.

There will be three different phenological models that will predict different events according to the concerned organs of simulation: i) bud break model, ii) berry model and iii) leaf model. Model calibrations will be performed for Chardonnay and Tempranillo in Spain, for Touriga Nacional in Portugal and for Aglianico in Italy.

The bud break model will predict the date of bud break that is considered the time when plants start their vegetation season. The parameters of this model will be calibrated during the first year of the project using a historic data repository already available in the different academic institutions from past research projects.

[6] S. Gu, S. D. Jacobs, B. S. Mccarthy & H. L. Gohil (2015) Forcing vine regrowth and shifting fruit ripening in a warm region to enhance fruit quality in 'Cabernet Sauvignon' grapevine (*Vitis vinifera L.*), *The Journal of Horticultural Science and Biotechnology*, 87:4, 287-292, DOI: 10.1080/14620316.2012.11512866

The berry model will use a general flowering and veraison model to predict the following events: blooming, berry set, veraison and harvest. The parameters of this model will be calibrated during the first year of the project using a historic data repository already available in the different academic institutions from past research projects.

The end of the vegetative season will be predicted using the LEAF model developed at the University of Naples

2. Model Description

2.1. Bud break model

The bud break model follows the approach proposed by Garcia de Cortazar-Atauri *et al.* (2009)[7]. According to its results, a simple model of growing degree days (GDD) starting the first of January has been implemented. The model uses a base temperature[8] T_b of 4º C. Such temperature has been calibrated based on phenology records available at IRTA for Chardonnay and Tempranillo varieties. This T_b will be used for the other grape varieties included in the project (Touriga National in Portugal and Aglianico in Italy). However, the value of T_b might change based on the results obtained from the pilot plots.

$$BB = \sum_{t_0}^{t_s} R_{bb}(T_{mean}) \geq GDD_{bb} \quad (1)$$

In equation 1, the bud break (BB) (see Figure 2. General scheme of the bud break and berry model.

is assumed to be reached at a certain time (t_s) when the accumulation rate of temperature (R_{bb}) equals a critical value of growing degree days (GDD_{bb}), being the R_{bb} defined as:

$$R_{bb}(T_{mean}) = \begin{Bmatrix} 0 & T_{mean} < T_b \\ T_{mean} - T_b & T_{mean} \geq T_b \end{Bmatrix} \quad (2)$$

Both the bud break and the berry model will run using monthly mean temperatures from the seasonal weather forecasts provided by BSC and from the weather stations placed in each pilot plot.

[7] Garcia de Cortazar-Atauri I, Brisson N, Gaudillere JP. 2009. Performance of several models for predicting budburst date of grapevine (*Vitis vinifera L.*). *Int J Biometeorol* 53(4): 317-326.
[8] Base temperature: is the lowest temperature where metabolic processes result in a net substance gain in aboveground biomass (Sitte et a 1999)

2.2. Berry model

The forecasts from bloom to harvest will be obtained using an adapted version of the spring warming model developed by Parker *et al.* (2011)[9]. The model allows the prediction of blooming, berry set, veraison and harvest using the GDD corresponding to each phase. The model has been modified including an upper threshold for temperature above which GDD accumulation is zero.

$$S_f(t_s) = \sum_{t_0}^{t_s} R_f(T_{mean}) \geq F^* \quad (3)$$

Equation 3 assumes that a phenological stage (S_f) is reached at a certain time (t_s) when the rate of forcing (R_f) equals a critical value of GDD (F*). The R_f calculation based on the mean air temperature (T_{mean}) is performed as follows:

$$R_f(T_{mean}) = \begin{Bmatrix} 0 & T_{mean} < T_b \\ T_{mean} - T_b & T_b \leq T_{mean} \leq T_{sup} \\ 0 & T_{mean} > T_{sup} \end{Bmatrix} \quad (4)$$

T_b and T_{sup} correspond to the base and upper-temperature thresholds for GDD calculation.

2.3. General scheme of the models

2.3.1. Bud break and Berry models

First, the bud break date is predicted using real and forecasted monthly mean temperatures. Once real bud break is achieved, the berry model starts using also real and forecasted monthly average temperatures. The purple dotted line states the running steps.

[9] Parker AK, De Cortazar-Atauri IG, Van Leeuwen C, Chuine I. 2011. General phenological model to characterise the timing of flowering and veraison of *Vitis vinifera L. Australian Journal of Grape and Wine Research* 17(2): 206-216.
SitteSitte P, Ziegler H, Ehrendorfer F, Bresinsky A, 1999. *Lehrbuch der Botanik*, 34. Aufl. Spektrum Akademischer Verlag, Heidelberg, 1007 pp. (in German)

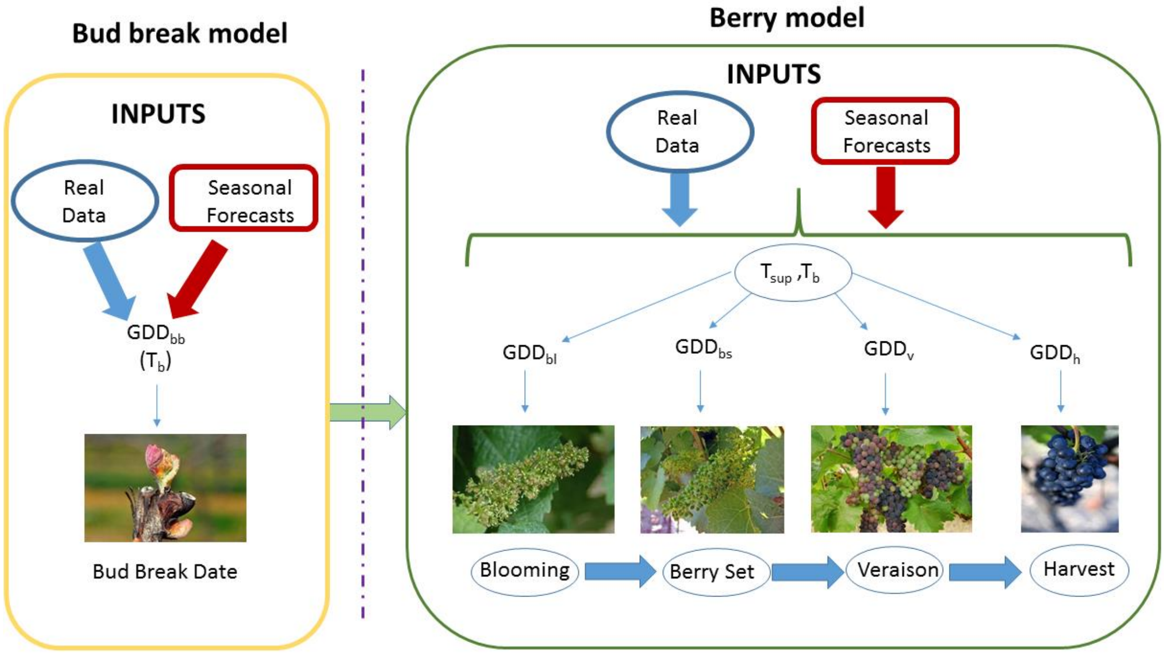

Figure 2. General scheme of the bud break and berry model.

2.4. LEAF model

The LEAF model has been developed to reproduce the vegetative growth cycle of grapevines (from bud break to leaf fall) as well as the growth of berries and their ripening (accumulation of soluble solids). The model is composed by six ordinary differential equations representing leaf fresh weight (*Lfw*), shoot fresh weight (*Sfw*), non-structural carbohydrates in the leaves (*S*), berry dry and fresh weight (*Bdw* and *Bfw*) and soluble solids in the berries (*SS*) (Figure 3).

The main driver of the model dynamics is the process of photosynthesis (PS), which is influenced by environmental factors such as light, temperature and water availability[10,11] . The photosynthetic rate (P_N) per unit of leaf area is calculated with the following equation:

$$P_N = \frac{\alpha I P_{max}}{(\alpha I + P_{max})} \min\big(f(SWC), g(T)\big) \quad (5)$$

where α is light use efficiency (mg µmol^{-1}), I is photon flux density (µmol m^{-2} s^{-1}), P_{max} is the theoretical maximum PS rate, while *f(SWC)* and *g(T)* are response functions to soil water content (SWC) and air temperature (T) (Figure 4). Starting from this equation, the daily amount of carbohydrates produced by PS is estimated and then allocated to the different growth processes according to the strength of

[10] Mullins MG, Bouquet A, Williams LE. 1992. *Biology of the Grapevine:* Cambridge University Press.
[11] Lambers H, Chapin FS, Pons TL. 2008. *Plant Physiological Ecology*: Springer New York.

the sinks. The process of leaf fall is assumed to result from the accumulation of soluble sugars in the leaves which occurs after the cessation of the growth of all the plant sinks.

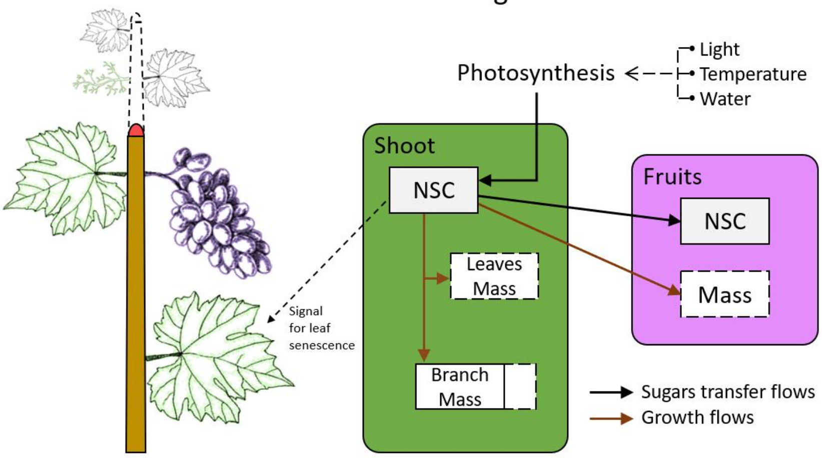

Figure 3. Schematic diagram of the LEAF model. NSC: non-structural carbohydrates. Dashed boxes represent newly formed mass during the growing season.

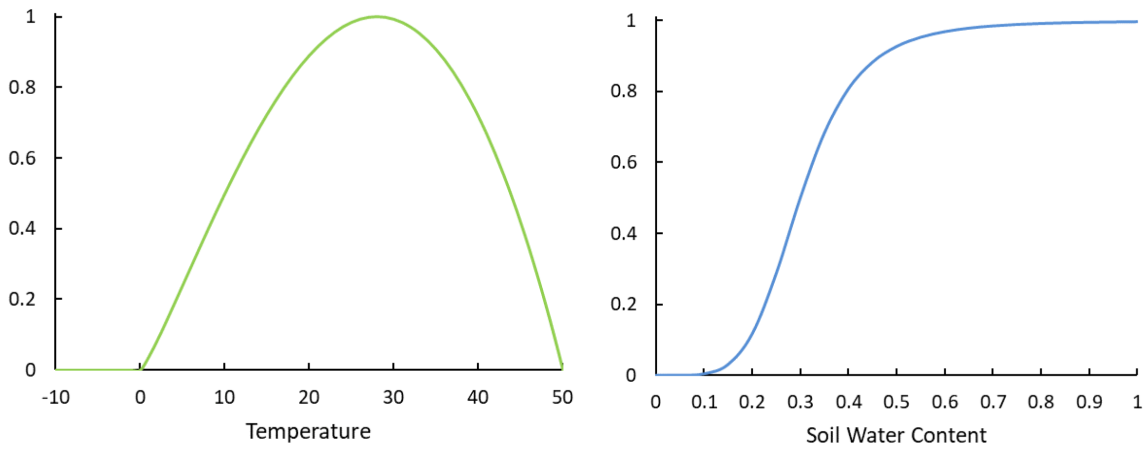

Figure 4. Functional responses of photosynthesis to temperature and water availability.

2.5. Working procedure of the models

2.5.1. Bud break and Berry model

Models will work in a sequential way. First, the bud break model will provide forecasts until real bud break is reached. From then on, the berry model will be running until harvest. Hence, the results of the berry model will not be displayed on the platform until real bud break is achieved.

The phenological predictions updates will be synchronized with the new releases of the seasonal weather forecasts. Those updates will have a monthly periodicity. In agreement with what it was discussed in previous meetings, the seasonal weather forecasts will start in March 2018.

In this first version of the berry model, the crop forcing date will not be predicted. Instead, the end user can provide an estimated crop forcing date and the berry model will recalculate the forecasts of the different phenological stages. Once we advance into our knowledge on the physiological responses of the plant when the crop forcing technique is applied, then we will discuss the implementation of the prediction of a crop forcing date. Since crop forcing is a novel management technique, more research is needed to understand the behaviour of the grape vine when is “forced”. Hence, the capacity of predicting a crop forcing date can only be evaluated at the end of the project, when all the results of the pilot plots are available.

2.5.2. LEAF model

The model works on a daily time scale and each simulation starts from the observed date of bud break. From that moment, the vegetative growth is simulated while the berry growth starts from the date of berry set either observed (for the calibration with past data) or predicted by the Berry model (for forecast scenarios). Similarly, fruits ripening begins at the date of veraison onset (either observed or predicted). The model will be developed to use medium term weather forecasts to predict ten days in advance the behaviour of the vineyard. This should be particularly useful for the end user to have information about the ripening phase and to plan the best moment for the harvest with the desired sugar concentration of the berries. Moreover, during the next years the model will be tested for its capability to predict the vineyard behaviour to crop forcing treatments, eventually including this feature in the platform.

3. Model calibration and validation

3.1. Bud Break and Berry model Calibration

The bud break and the berry model have been calibrated for the varieties included in the project using past phenological records. However, for the sake of clarity, only the calibration and validation procedures for Chardonnay variety in Raïmat are presented here. Nevertheless, the validation results are extensible to other locations and varieties included in the project.

Calibration of Tb and Tsup for GDD calculations have been performed using phenological records for Chardonnay from a database available at IRTA. The global optimization tool included in Matlab (MathWorks, Natick, MA USA) software was used for the calibration procedure. During the optimization, both temperatures were varied in order to minimize the standard deviation of the

GDD12. Calibrated Tb and Tsup values were 4 and 27 0C respectively. The results of GDD for each phenological stage are presented in
Table 1.

Table 1. Result of the calibration for the different phenological stages predicted in VISCA

PHENO STAGE	GDD Chardonnay
BUD BREAK	263
BLOOM	537
BERRY SET	784
VERAISON	1388
HARVEST (CAVA)	1922

For the bud break calibration only T_b was adjusted because the model does not includes the parameter of T_{sup}

3.2. Bud break and Berry model Validation

The validation procedure was divided into two steps. First, model predictability was tested using real monthly means for temperatures of years 2014, 2015 and 2016. Then, the prediction capacity of the phenological models in combination with the seasonal forecasts was examined. To do so, seasonal forecasts of the above years were generated. This allowed us to compare phenology records with the ones provided by the model. The limited amount of years used for the validation is a consequence of the lack of sufficient weather and phenology records to properly validate the model. However, during the course of this project, enough data will be generated to perform a more robust analysis.

3.2.1. Model predictability using real data

The bud break and berry model validation were performed using monthly means for three years (2014, 2015 and 2016). Phenological outputs of the model were compared with the records. Model efficiency was tested using the root mean squared error[13]. Figure 5 presents the results of the validation process from bud break to harvest.

[12] Oliveira M. 1998. Calculation of Budbreak and Flowering Base Temperatures for *Vitis vinifera cv*. Touriga Francesa in the Douro Region of Portugal. *American Journal of Enology and Viticulture* 49(1): 74-78.
[13] Brun F, Wallach D, Makowski D, Jones JW. 2006. Working with Dynamic Crop Models: Evaluation, Analysis, Parameterization, and Applications: Elsevier Science.

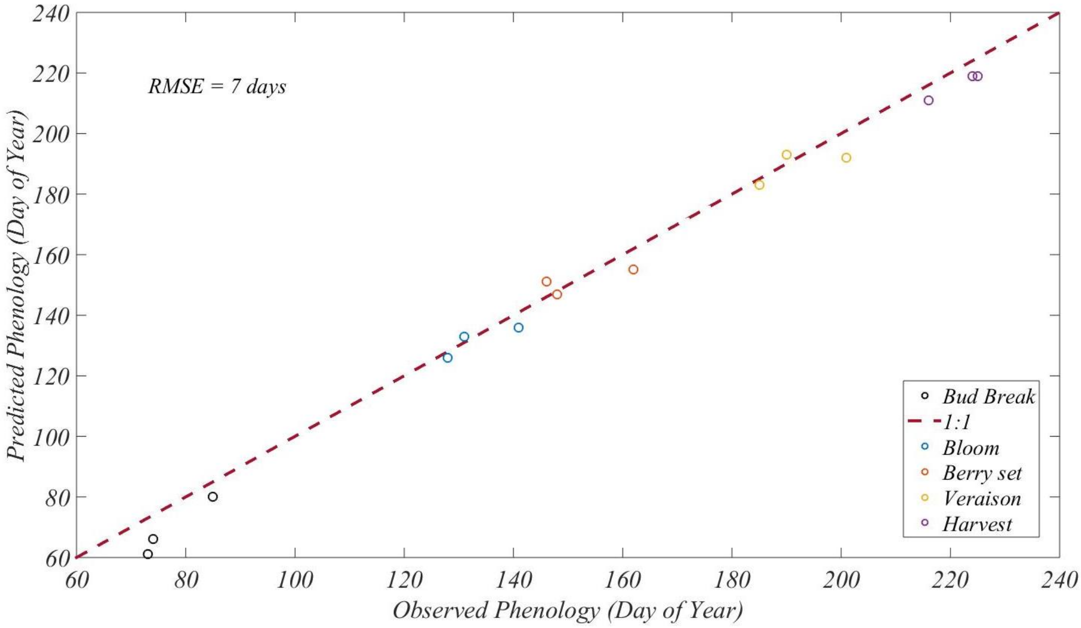

Figure 5. Observed and predicted phenology dates for years 2014, 2015 and 2016 from bud break to harvest. Each color corresponds to a phenology stage and each point of the same colour to a validation year. The dashed line represents 1:1 line (perfect agreement)

As we can see, the model is able to predict each phenological stage with an average error of 7 days. The extent of this error is acceptable, giving that, on average, phenological observations have a frequency of one week. The displayed forecasts in the platform will be shown on a weekly basis to be consistent with the result of the analysis. Analysing each phenological stage separately, it looks like bud break and harvest are underestimated, i.e. the model predicts both stages in advance. In the case of bud break, it is possible that the absence of a chilling module can explain the observed bias. The chilling module will account for the chilling requirements of the vine to flower. However, further analysis is needed to validate this hypothesis. For the harvest stage, the deviations are rather expected. Harvest depends on winery criteria and not only on plant physiological condition. Thus, an accurate forecast will rely on having the same harvesting standards as the ones used for the calibration years. If those criteria changes, harvest GDD will need to be calibrated again.

3.2.2. Model predictability using seasonal forecasts

The same analysis carried out in section 3.2.1 was performed using the seasonal weather forecasts provided by BSC. The weather forecasts are composed of 25 members, each one containing monthly averages of temperature. The model is run for each of the members and a distribution of dates is obtained.

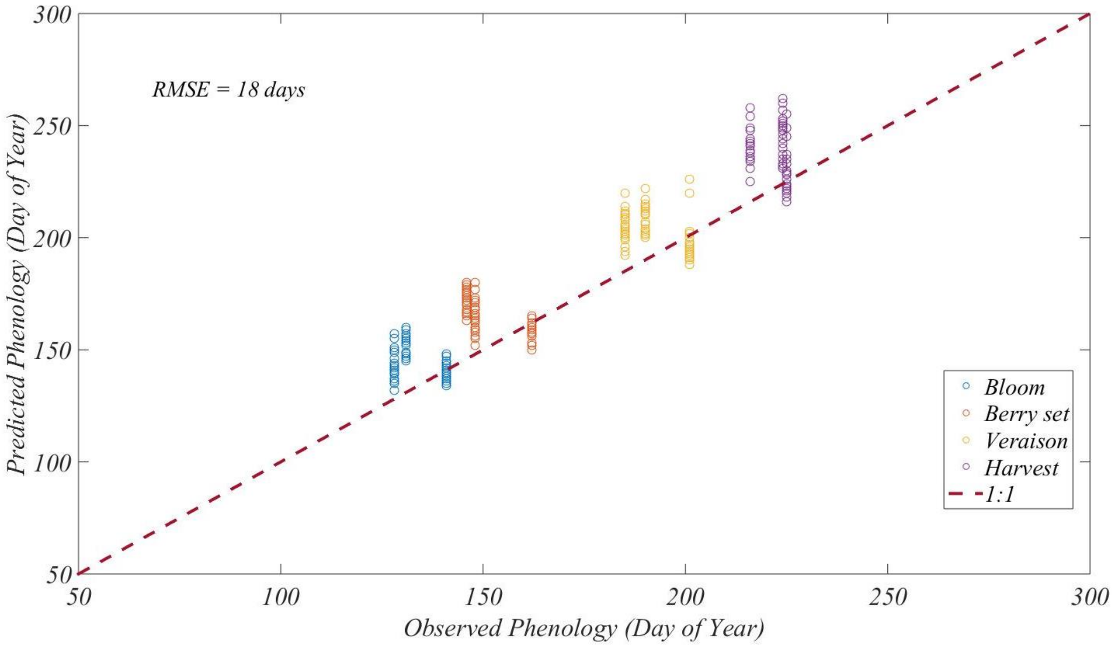

Figure 6. Observed and predicted phenology values from bloom to harvest. Each colour corresponds to a phenological stage and each point of the same colour represents one member of the seasonal weather forecast. The three groups of points comprise the three validation years used.

If the monthly forecasted temperature is plotted against the real values (Figure 7) this deviation could be explained. In fact, Figure 7 shows that for years 2014 and 2015, the forecasted mean temperature was cooler than the observed, probably causing the bias observed in Figure 6. However, with three years of phenological data to verify the seasonal forecast models, the conclusions drawn from Figure 6 should be taken with some caution. Nevertheless, considering that the collaboration with the end-users will progressively increase the amount of data available for the validation, it is expected that during the remaining two years of the project the analysis will become more robust. In two of the years (2014 and 2015) dates overestimate the phenological phases, so they tend to come later than the observed, increasing the prediction error.

Taking into account that the method applied by the BSC as a first version of the downscaling (calibration) uses reanalysis data to increase the resolution of the forecasts, this deviation in the temperature values is feasible. Still, three years are still too few to conclude anything robust from Figure 7, so it will be in future refinements of the datasets, bias-correction, and downscaling methodologies when we could finally issue a robust statement about the hinted deviation. For instance, this deviation may improve in future versions of the downscaling methodology and, if necessary, even with a mean bias correction applied to the output of the phenological model.

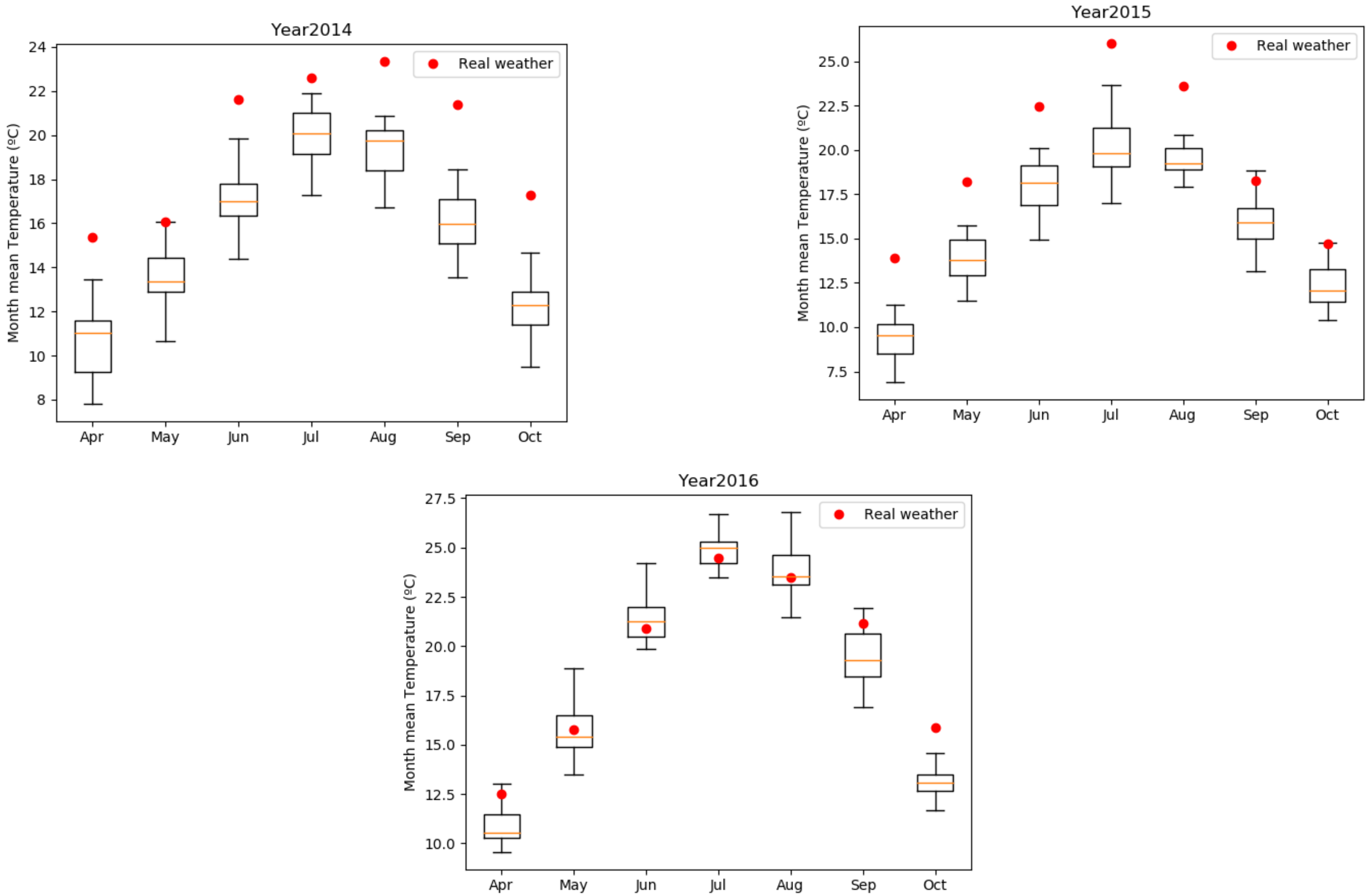

Figure 7. In each panel, real monthly average temperatures (red dots) and mean and standard error of the monthly weather forecasts (boxes) for years 2014, 2015 and 2016, respectively. The month period used for the analysis is displayed in the x-axis.

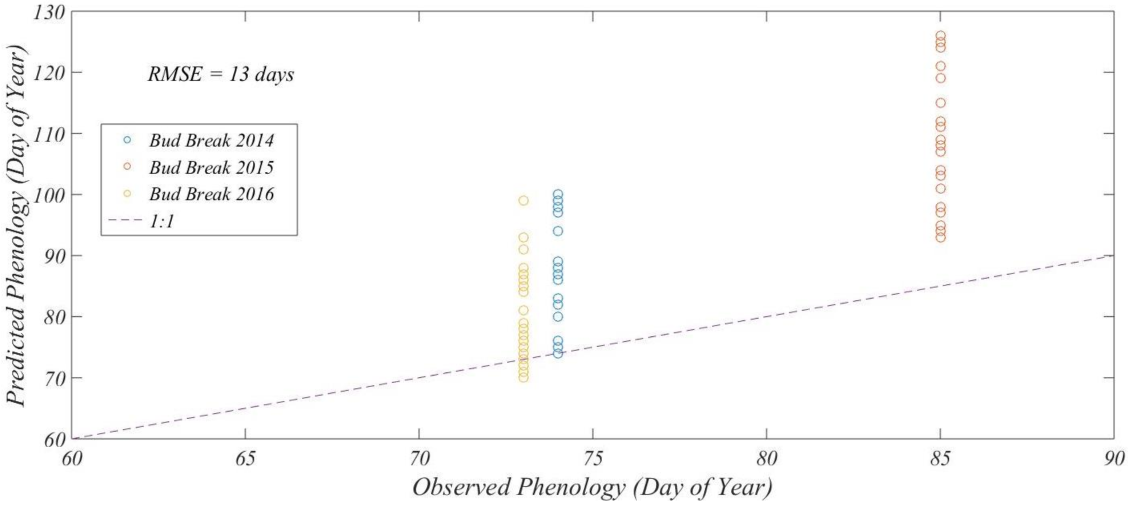

Figure 8. Observed and predicted bud break using seasonal forecast data from 2014, 2015 and 2016. The dashed line represents the 1:1 line.

Results of the Bud break predictions followed the same trends as the rest of the phenological stages predicted (Figure 8). The year 2016 seems to be more adjusted to the observed values than the other two years. Hence, the comments highlighted above for the Figure 6 applies also here.

3.3. LEAF model calibration and validation

The LEAF model has been calibrated for the Aglianico variety (Mastroberardino pilot plot) using data produced during the first year of the project (2017). The model calibration was performed by minimizing the sum of the squared errors (*SSE*) according to:

$$SSE = \sum_{i=1}^{n_1}(Lfw_i - Lfw_i^*)^2 + \sum_{i=1}^{n_2}(Sfw_i - Sfw_i^*)^2 + \sum_{i=1}^{n_3}(Bdw_i - Bdw_i^*)^2 + + \sum_{i=1}^{n_4}(Bfw_i - Bfw_i^*)^2 + \sum_{i=1}^{n_5}(SS_i - SS_i^*)^2 \quad (6)$$

where n_1, n_2, n_3, n_4 and n_5 are the number of samples per observed output, Lfw_i, Sfw_i, Bdw_i, Bfw_i and SS_i are the values of the i^{th} measured outputs and Lfw_i^*, Sfw_i^*, Bdw_i^*, Bfw_i^* and SS_i^* are the values of the i^{th} outputs predicted by the model. The minimization was performed by using the *fminsearch* MATLAB (MathWorks, Natick, MA USA) routine which implements a Nelder–Mead simplex algorithm[14]

Figure 9 shows an example of results produced by the model, reproducing the growth of Aglianico grapevines in the Mastroberardino pilot plot without defoliation treatment and without irrigation. The

[14] Lagarias JC, Reeds JA, Wright MH, Wright PE. 1998. Convergence Properties of the Nelder--Mead Simplex Method in Low Dimensions. *SIAM Journal on Optimization* 9(1): 112-147.

same results have been produced for all the nine experimental conditions (3 levels of irrigation x 3 levels of leaf removal).

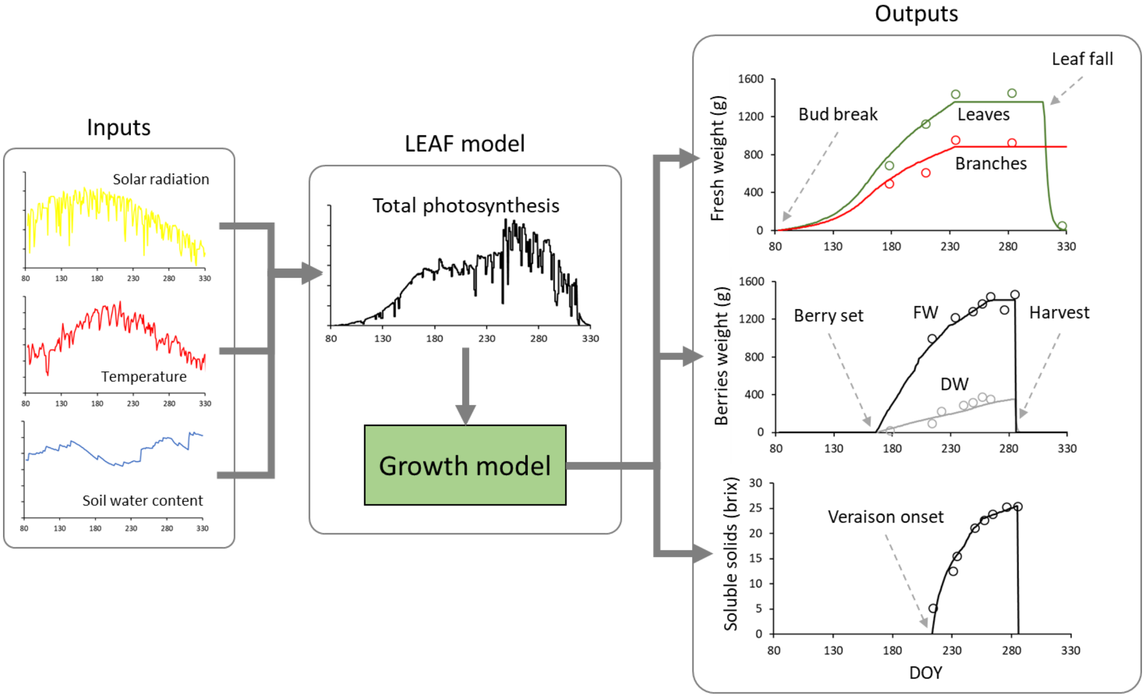

Figure 9. LEAF model simulation procedure and results.

Starting from climatic data (Figure 9, left panels), the model calculates the newly synthesized carbohydrates that are allocated for the growth of the different plant compartments (leaves, branches and berries). In each plot of the outputs (Figure 9, right panel), continuous lines represent simulations while open circles are experimental data. Grey dashed arrows indicate the main phenological events of the growing season. After the observed date of budbreak, the model starts simulating the dynamics of vegetative growth (leaves and branches fresh weight) which depend on the availability of photoassimilates. At the day of observed berry set the growth of berries starts to be simulated (both as dry and fresh weight), while after the date of veraison onset, soluble solids start to be accumulated in the berries. At the time of harvest the fruits are removed from the simulated plant. Since the vegetative growth has ended and the fruit sink has been manually removed, the photoassimilates start to accumulate providing the signal for leaves' senescence.

The dynamics of accumulation of soluble solids in the berries mainly depend on the photosynthetic activity of the plant which is influenced by light, temperature and water availability. At the time of berries ripening, water is the main limiting factor as can be seen by the positive effect of irrigation on the concentration of soluble solids in absence, or with low levels, of leaves removal (Figure 10). On the other hand, at higher levels of leaves removal, the main limiting factor becomes the availability of photoassimilates and the irrigation treatments start to have a negative effect since they promote the fresh weight increase of the berries without an adequate loading of sugars. This results in a decrease of the concentration of soluble solids (Figure 10).

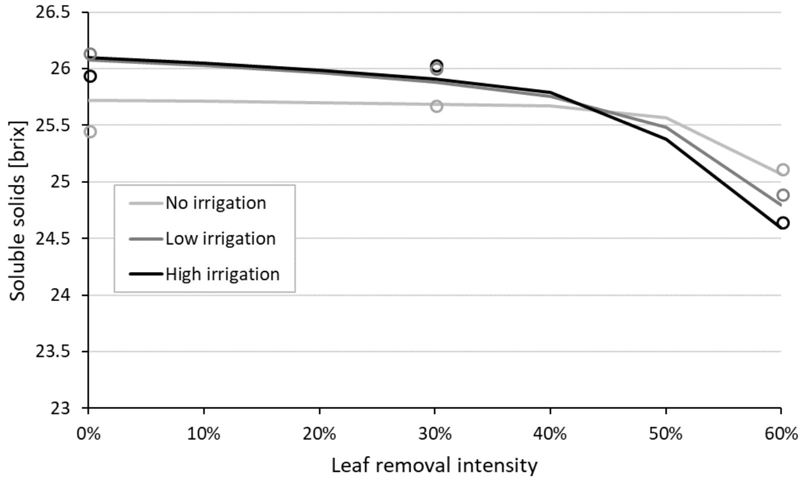

Figure 10. Results of simulated (continuous lines) soluble solids content compared with experimental data (open circles) at different levels of irrigation (from light to dark grey) and leaf removal intensity (x-axis).

Calibration for the other experimental sites of the project is ongoing. Due to the lack of previously available data, the model will be validated with the experimental results produced during the following years of the project.

4. Future work

During the life time of the project, models will be tested and improved - if necessary -, based on the results of the pilot plots. By the end of the project, some of the physiological results of the crop forcing experiment will be included in the tool. Another objective of the pilot plots is to increase the number of phenological records for the grape varieties included in the project to have enough data to perform a more robust validation analysis. This will have a positive impact on model performance.

LEAF model calibration is ongoing for the other experimental sites and varieties of the project. Once the calibration and validation procedures will be completed, the model predictive capability will be tested using the medium-term weather forecasts.

5. List of inputs and outputs

5.1. Bud break model

Table 2. Bud break model parameters and units

Inputs	units
Average monthly temperatures (T_{mean})	^0C
Growing degree days to reach bud break (GDD_{bb})	^0C day^{-1}
Base temperature for GDD calculations (T_b)	^0C
Initial day to start with the GDD calculation (if no crop forcing is applied, the default day is January 1^{st})	-

5.2. Berry Model

Table 3. Berry model parameters and units

Inputs	units
Average monthly temperatures (T_{mean})	^0C
Growing degree days to reach bud break (GDD_{bb})	^0C day^{-1}
Base temperature for GDD calculations (T_b)	^0C
Upper temperature for GDD calculations (T_{sup})	^0C
Initial day to start with the GDD calculation (if no crop forcing is applied, the default day is January 1^{st})	-

5.3. LEAF model

Table 4. List of inputs of the LEAF model and its simulated outputs.

Inputs	units	time step
PAR	µmol m^{-2} s^{-1}	day
Air temperature	°C	day
Soil water content	%	day
Leaf removal/Crop forcing date	DOY	-
Leaf removal/Crop forcing intensity	%	-
Date of bud break	DOY	
Date of berry set	DOY	
Date of veraison onset	DOY	
Outputs	**units**	**time step**
Shoot mass (fresh weight)	g	day
Leaf mass (fresh weight)	g	day
Leaf area	m^2	day
Berry mass (dry and fresh weight)	g	day
Berry soluble solids content	°Brix	day
Date of leaf senescence/fall	DOY	-