A digital twin application for vineyards sustainable management

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Abstract. Environmental protection and production sustainability are the key actions required to the farming activities, especially to those with higher add value as wine production. Vineyard are one of the most demanding activities in terms of water consumption and environmental impacts, which can be mitigated only with a systematic approach based on smart agriculture to support and optimize vineyard management. This paper proposes a vineyard digital twin (VDT) based on a mathematical model able to predict the vegetative and productive growth of a vineyard (leaf area, shoot length, crop and yield mass), qualitative product parameters (sugar and acid) and the water footprint associated with production. The model implements a soil-atmosphere source-sink model, where water balance across vine is coupled with potential carbon demand functions to estimate water and temperature stresses and, through a mechanistic model for sugar accumulation and acid concentration, will evaluate the expected grape quality. The distinctive trait of this model is the integration and feedback among prediction of grapevine quality and vegetative growth, using a common boundary data set and integrating the agronomical operations on vineyard seasonal development. The VDT prototype will help producers to systematize, formalize, and accumulate knowledge to improve and optimize management processes to achieve sustainable production, increasing products healthy and reducing environmental footprint.

1 Introduction

Quality and production of vineyards (Vitis vinifera L.) are influenced by a great number of interrelated factors. Environmental factors (e.g. water stress) and cultivation practices, including irrigation, might modify this carbon balance and affect fruit size, quality and yield [1]-[3]. In addition, climate change will alter meteorological conditions in the near future, and this might affect grape yields and grape composition for high-quality wine production [4]. In general, a comprehensive crop model should fulfill the following desirable and concurrent features: i) limited requirements as input data; ii) high degree of user-friendliness in terms of usability and output visualization and interpretation; iii) reasonable accuracy of produced outputs and, iv) large spectrum of results including quality indicators of final product.

Ideally, a model should be accessible, understandable, and useable by those other than the model developers. Number of models have been developed for assessing plant growth and physiology, and they have been adapted to different crops [5]. In the case of grapevines, there are models which accurately predict specific processes such as phenology [6], vegetative growth and yield [7], sugar accumulation [8], carbon assimilation and allocation [9]. Nevertheless, these models do not comprehend all the desirable features listed above.

Grapevine in commercial production can be a difficult subject for modeling due to the extreme manipulations by growers such as variable pruning, training, shoot selection, canopy shoot positioning, leaf removal, hedging, cluster thinning, etc. In addition, those models often neglect fundamental phenomena like subsoil water balance, root-soil interaction, soil-plant atmosphere exchange and finally feedback on production quantity (fresh mass) and quality (sugar and berry pH).

Thus, modeling grapevines should not attempt excessively detailed simulations as results will have limited value to other conditions [10-12].

The present work deal with the development of a mathematical model able to predict, using time dependent meteorological data, soil and vine characteristics, the growing of a vine and grapevine in terms of leaf area, shoot length, fruit and vegetative mass and finally sugar and acid content of the berry.

The aim of this research is to provide a reliable tool to investigate impact of climate changes into grapevine and wine production and quality. The model was tested with

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experimental data from two different Italian regions (Tuscany and Umbria) and different cultivars and used to estimate dry mass accumulation of those vineyard during two consecutive years (2017 and 2018) to identify the impact of different climate scenarios on grapevine development. Results of the first model simulations are presented. Data requirements, and limits and improvements of the model are discussed**.**

2 Material and methods

In the following sections are reported the description of the experimental sites, an example of data set recorded and the snapshoot of measured meteorological data.

2.1 Site description

Data records for calibration purposes have been taken in three different locations in 2017 and 2018, following a similar work performed in [13]. The considered locations and vineyard characteristics are reported below

1) Montecarlo di Lucca (43°51′N, 10°40′ E): vineyard established since 1970 at Montecarlo di Lucca, and featuring a Guyot training systems in a North–South row orientation. Data were taken for the following cultivars: Sangiovese, Cabernet, Chardonnay, Trebbiano, Vermentino. No information about clone type and stock where available. Average plant density was 4000 plants/hectare (1.2 m x 1.8 m spacing), and the trellis frame featuring a main support wire holding the cane (cordon) at 0.9 m above the ground surmounted by a fixed wires placed respectively at 1.2 m and 1.8 m from the ground.
2) Terricciola (43°31′32″N 10°40′51″E): vineyard established since 1960 and partially renewed in 2012 and featuring a cordon training systems in a East-West row orientation. Data were taken for the following cultivars: Sangiovese and Foglia Tonda (an ancient Tuscany cultivar). No information about clone type and stock where available. Average plant density was 5000 plants/hectare (1.1 m x 1.7 m spacing), and the trellis frame featuring a main support wire holding the cane (cordon) at 0.8 m above the ground surmounted by a fixed wires placed respectively at 1.2 m and 1.8 m from the ground.
3) Tuoro sul Trasimeno, (43°12′N 12°5′E): vineyard 25 year old and featuring a guyot training systems in a East-West row orientation. Data were taken for the following cultivars: Cabernet Sauvignon and Merlot. Average plant density was 5000 plants/hectare (1.1 m x 1.7 m spacing), and the trellis frame featuring a main support wire holding the cane (cordon) at 0.7 m above the ground.

Data were taken on selected test rows (30% of the total) in three different points (both row ends and center), randomly choosing a different vine every measurement to increase statistical reliability of data. Four spurs per wine were counted in average after pruning, with 2 buds for each for cordon training system, while for guyot training an average number of 8 buds was identified. The location on the test sites is reported in (Fig. 1).

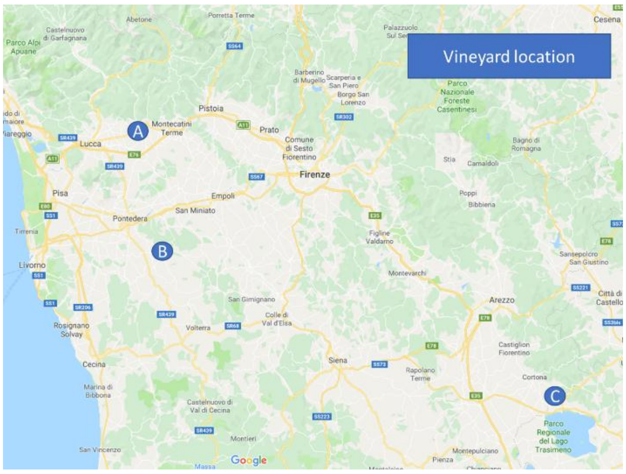

Figure 1. Vineyard locations.

2.2 Data collection

With reference to phenological monitoring, vegetative and reproductive stages were classified according to the GDD scale [14]. The following parameters were monitored, and data collected among veraison and ripening phase:

- Air temperature and relative humidity
- Leaf and berry surface temperature
- Surface Soil Humidity
- Berry sugar content
- Berry pH
- Berry diameter
- Vine leaf area
- Vine production
- Fresh mass.

Measurements of reported variables were performed directly on the field by means of the following instrumentation:

- Optical refractometer for sugar measurements
- Portable pH meter for pH calculation and soil humidity
- Leaf count and canopy picture interpretation for leaf area measurement.

Dry and fresh mass was evaluated as follow: three leaves were taken each plant and the weight was measured prior and after drying at 180°C for 20 m in a a commercial hoover, Berry fresh and dry mass was calculated in the same way, taking randomly for each cluster of the plant two berries. Prior drying, weight and diameter was measured.

In addition, temperature and rainfall data were also taken from meteorological stations nearby vineyard and properly averaged. Some example of the data collected and used for model tuning and assessment are reported from Figs. 2 to 7.

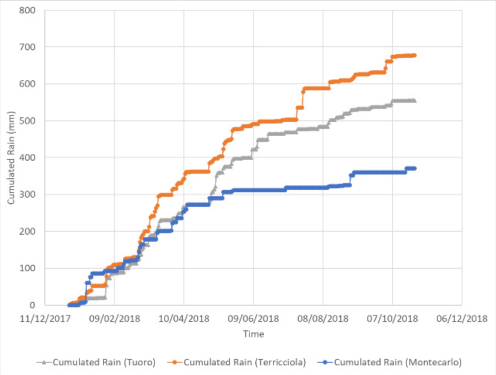

Figure 2. Cumulated rain (All sites, 2017).

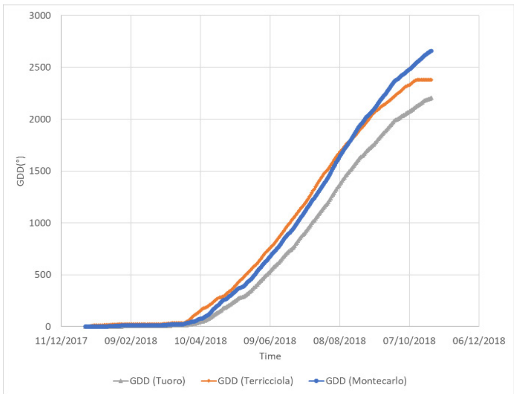

Figure 3. Cumulated GDD (All sites, 2017).

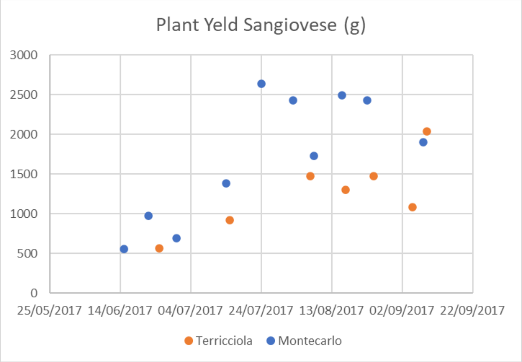

Figure 4. Leaf area (Sangiovese, 2017).

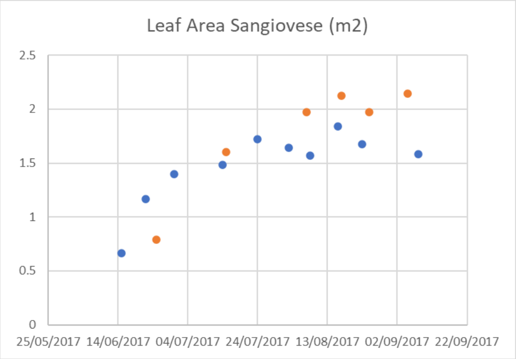

Figure 5. Plant Yeld (Sangiovese, 2017).

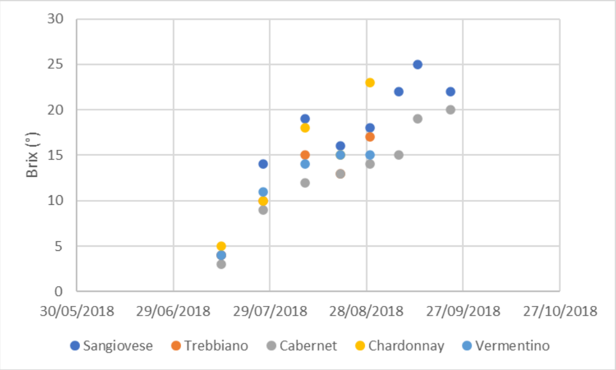

Figure 6. Berry Brix trend (Montecarlo, 2017).

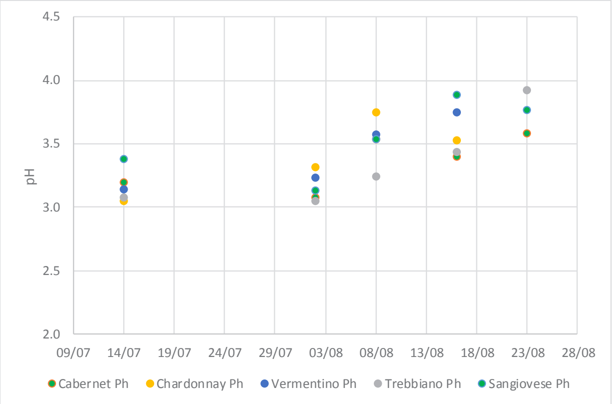

Figure 7. Berry pH trend (Montecarlo, 2017).

2.3 Model overview

The prediction model has been derived by sink-source approach presented by [1, 7] and [9] modified to take into account water and nutritional stresses and using a full set of daily based meteorological data to evaluate the vine development during a given time frame. In addition, sugar and acid accumulation within the berry is evaluated during the time. The model simulates grapevine growth and development as summarized in Fig. 8, where variables are represented as boxes and mathematical models as diamonds, respectively. The meteorological input data of the model are represented by daily maximum and minimum temperatures and daily total precipitation. A simplified soil water balance model is providing time step-based soil water content, as well as the nutritional model provide N_2 content in the root zone (not part of the present activity). Phenological state are modelled following the work reported in [13]. A simplified photosynthetic model based on calculated leaf surface temperature coupled with a logistic-based growing function is used to evaluate carbon supply. The leaf temperature and the calculated water stress (balance among water available and required) are the coefficients which are the growing limiting factor of the vineyard and the berry. Finally, a berry sugar accumulation model (based on dry mass and fresh fruit mass increment) is applied to evaluate the berry sugar trend accumulation increase, including already possible stresses due to lack of water supply.

Figure 8. Model structure.

2.4 Soil water content and balance

The soil model implemented in VINESYM includes both a module for water content calculation (θ_{act}, mm within the soil layer explored by roots). The main balance equation is te following:

$$\Delta\theta_{act}/dt = RR - PR - RD - Ru + Irr \qquad (1)$$

$$RD = (\psi_{root}, \psi_{soil})/r_{root} \qquad (2)$$

where $\Delta\theta_{act} = (\theta_{act,d} - \theta_{act,d-1})$ is soil water content gradient at day d and d−1, RR is daily rainfall, Ru is daily surface runoff, RD is the root uptake rate [16], PR is daily percolation on deep soil [17], Irr is the daily irrigation (if present). RR is obtained with direct measurements while Ru is estimate assuming water runoff proportional to the soil slope. The RD term, where ψ_{soil} and ψ_{root} are soil and root water potential and r_{root} is the flow resistance among soil and roots, is equal to the plant sap flow and represent the interface from oil balance model and plant balance model described in the next paragraph.

2.5 Plant-atmosphere model and stem, leaf potential and sap flow evaluation

To evaluate possible plant water stress a balance among transpiration, sap flow and root uptake potential is required to provide reliable evaluation of available water for dry mass prediction through photosynthesis. The time dependent balance of plant and leaf potential (among actual and previous day of calculation), required to evaluate sap flow along the vine system is described using a model below [18-22] and [23]:

$$C_{plant}V_{plant}\Delta\psi_{plant}/dt = k_{plant}(\psi_{soil} - \psi_{plant})\, A_{plant} - SapFlow \qquad (3)$$

$$C_{leaf}V_{leaf}\Delta\psi_{leaf}/dt = ETRP(T_{leaf}, \psi_{leaf}) - SapFlow \qquad (4)$$

$$SapFlow = A_{petiole}(\psi_{plant} - \psi_{leaf})/r_{petiole} \qquad (5)$$

Where C_{leaf} and C_{plant} are the water capacitance of leaf and plant (1/m), ψ_{plant} and ψ_{leaf} the daily variation of stem and leaf potential (m), k_{plant} (m/s) and $r_{petiole}$ (s) the plant conductance and petiole resistence, A_{plant} and $A_{petiole}$ the xylem area of stem and leaf petiole (m^2), V_{plant} and V_{leaf} the plant and leaf volume and the ETRP and SapFlow the actual evapotranspiration (previous calculated day) and the plant sap flow (m^3/s).The time derivative are simplified as incremental ratio among quantities at actual day (d) and previous one of calculation (d-1) Solving the three equations above in iterative way (since ETRP depends on leaf potential), the actual water potential for stem, leaf and sap flow is calculated. Combining the Eqs. (3-5) with eqs. (1-2) the overall water potential distribution from soil to leaf is determined, as well as the soil eater content and the actual evapotranspiration.

1.6 Plant water stress

The water stress is evaluated based on the following relationship:

$$Water\_stress = min(1, SapFlow_d / ETRP_{d-1}) \qquad (6)$$

The relationship indicated that stress exist when the required evapotranspiration (calculated at previous time stem) is larger than the actual sap flow. The calculated water stress is then used in the evaluation of dry mass (see below), reducing the leaf area increment, and then reducing the evapotranspiration.

The calculated water stress will be than used in the next calculation step to estimate the new water potential and water requirements of the plant, thus linking the available and required water amount of plant during vegetative development.

2.7 Radiation and leaf temperature model

The leaf superficial temperature has been retained necessary both to characterize the phenological stages of the vine and to be used in the evaluation of the limiting factors for carbon supply mechanism. In addition, leaf temperature impact in the evapotranspiration phenomena, through stomatal opening degree, and finally in the evaluation of leaf damage due to solar radiation. The leaf superficial temperature model has been based on the work of [23-25]. The model considers boundary layer heat exchange and stomatal opening mechanisms, and has been implemented as follow:

$$IR = \varepsilon \bullet \sigma \bullet (T_{leaf})^4 + hc \bullet (T_{leaf} - Ta) + \lambda\, (el - ea)/\, r_{tot} \qquad (7)$$

In the above relationship **IR** is the incoming radiation, **Ta** is air temperature, **Tleaf** is the leaf temperature, **el** and **ea** are water and air saturation pressure, **σ** is the Stephan Boltzman constant, **ε** is the emissivity**, hc** is the heat transfer coefficient and **rtot** is the stomatal resistance. The resulting equation on leaf temperature is solved in a explicit form, using the stomatal resistance of the previous step. Then the new leaf temperature is calculated, which will be used in the next time step to adjust radiation efficiency of the leaf and resulting biomass production, as well as the leaf evapotranspiration.

2.8 Carbon supply

The carbon pool available for distribution is the daily assimilated carbon (PHO). To describe the rate of dry mass creation, several models have been evaluated [26-27].As the model focuses on the allocation and utilization of assimilates, PHO (g/d) is estimated as the daily product of incoming photosynthetic radiation above the canopy (R_{tot}), a light interception function based on an exponential Beer-Lambert attenuation law, the radiation use efficiency (RUE) and a function which reflect the impact of daily temperature on carbon assimilation, based on [27] i.e. the amount of carbon accumulated per unit irradiance intercepted:

$$PHO=R_{tot*}RUE*F(T)*F(LAI)*pld*\ WS \qquad (8)$$

$$F(LAI)=\ 1-e^{(-Kext*LAI)} \qquad (9)$$

where **pld** is the plant density(m^2/plant), **Kext** and **LAI** are the light extinction coefficient [7, 9], and the leaf area index (i.e. total canopy leaf area per unit ground area), respectively. **RUE** is variable in time and primarily depends on radiation intensity, temperature and nutrient availability, **WS** is the previously defined water stress and **F(T)** function has been defined starting from [27] where the original values expressed in terms of DOY (day of years) are reported in equivalent GDD

Based on calculated dry mass, the actual fresh mass for stem, leaf and berries are evaluated as follow:

$$FM_k = PHO*(1-WC)*(1-PC) \qquad (10)$$

where **WC** is the ration among dry and fresh mass for the k element (*K*=stem, leaf,berry) and **PC** is the partition coefficient, ratio among dry mass assimilated by the k element and the total dry mass, calculated as per [28].

2.9 Sugar accumulation model

The sugar accumulation is predicted using the model from ([8]), based on the following time-dependent balance equation:

$$\frac{dM_{HS}}{dt} = C_{fl}\frac{dDW}{dt} - K(t)M_{HS}, \qquad (11)$$

where M_{HS} is the sugar mass, DW is the berry dry mass, C_{fl} is the carbon transfer rate coefficient, K(t) the sugar metabolic consumption and dt the time step of equation. The sugar content is then evaluated solving the above equation using an explicit method.

2.10 Acid concentration

The accumulation of acids within the berry has been simulated using a correlation tuned on field data. Which depend on GDD$_0$, the growing degree days' scale using 0° as base temperature and a, b and c where tuned over recorded field data. Based on this correlation and the work of [29], a correlation has been used to calculate TA, the total fixed acidity concentration (g/l))

$$pH= a*GDD_0^2+b*GDD_0+c \qquad (12)$$

$$TA\ =\ -10.754*pH\ +\ 51.033 \qquad (13)$$

3 Results and Discussion

The VDT has been tested against a field data collected for three years monitoring campaign performed in three different vineyards located in The Tuscany region (Montecarlo di Lucca, Terricciola and Tuoro, Italy). The results of the application of the model here described have been retained so far acceptable to predict the following vineyard parameters:

- Leaf area and temperature
- Vegetative and fruit mass
- Sugar berry content.

The results obtained by the model using the monitored vineyard show an accuracy ranging among 20% and 35% in evaluating the above-mentioned parameters (Figs. 10-12). In some cases, the dispersion of results is significative, due to the fact that the model uses as input average values and does not consider local or plant specific data which were not monitored. Moreover, the tuning of the model was limited since some relevant parameters as soil water content were not available at the time of monitoring campaign. Due to the above limitations, the assessment of the model will be completed after a second field campaign in 2022.

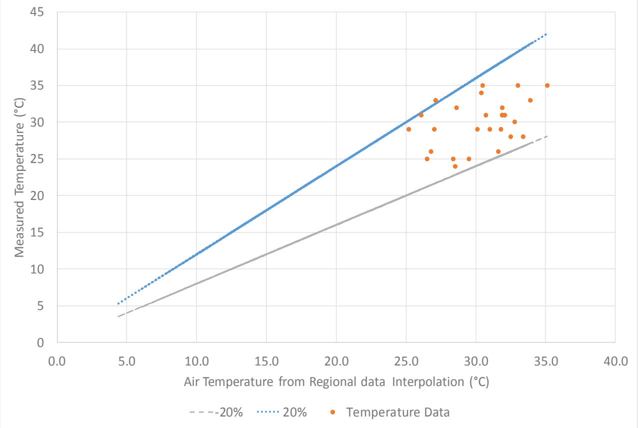

Figure 9. Leaf Temperature (Sangiovese, Montecarlo, 2017).

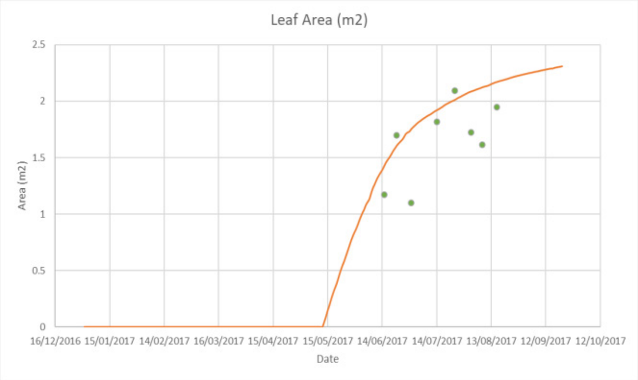

Figure 10. Leaf Area prediction (Cabernet, Montecarlo, 2017).

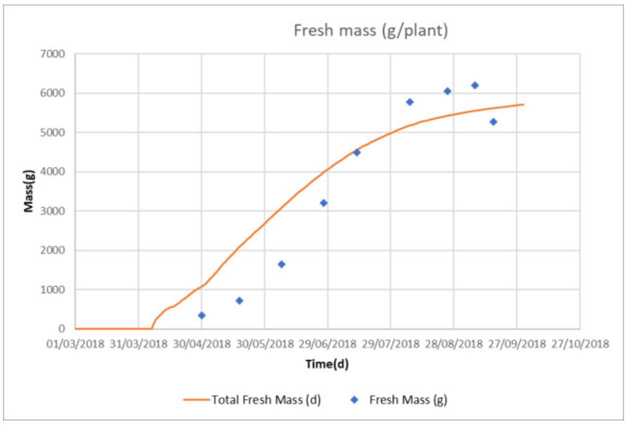

Figure 11. Fresh mass prediction (Sangiovese, Terricciola, 2018).

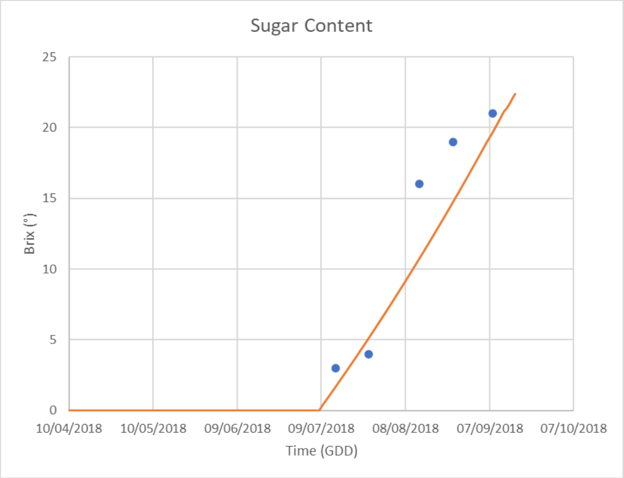

Figure 12. Sugar content prediction (Cabernet, Tuoro, 2017).

4 Conclusions

The model developed allow to simulate the main parameters related to vine and grapevine growing with sufficient accuracy to be used to identify the impact of meteorological changes in the grapevine and finally wine quality. The feedback of water and nutrient balance, as well as the impact of proper calculation of leaf temperature into the source-sink model for organic matter increment show an interesting accuracy in predictions, as shown by comparison with measured data of both vine leaf area and fruit mass. Since the model is however based on some cultivar-related parameters, a wider test on different sites and cultivar is required, to generalize some of the results so far achieved.

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