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Modeling grapevine performance with 'VitiSim', a weather-based carbon balance model: Water status and climate change scenarios

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ABSTRACT

A carbon balance model (VitiSim) was used for assessing the effects of vine water status and different climate scenarios on the dry matter production and partitioning of 'Tempranillo' grapevines (*Vitis vinifera* L.) grown in two different Spanish regions. Inputs included weather daily variables, stem water potential measurements and vineyard system data. Partitioning is based on the supply and demand balance using relative sink strength coefficients when carbon supply is lower than organ demands. A new routine to consider the effect of vine water status on photosynthesis rate was implemented in the model. Experimental data from two Spanish locations, several seasons (2007–2011) and well-watered and water-stressed vines were used for validating the model. A sensitivity analysis showed that model outputs are greatly influenced by those inputs linked to light interception. Simulated dry matter productions were realistic even though in general the amounts were underestimated. VitiSim was able to reproduce the effect of water stress on dry matter production observed in the field. Then, the model was used to estimate vine dry mass in different locations within Spain and worldwide under the standard current meteorological condition and under two climate change scenarios. Results were in accordance with those commonly found in field studies. Hence, this model appears useful to estimate vine dry matter potential from few easily available inputs and to simulate the effects of deficit irrigation strategies on grape yield. Further routines must be implemented to enhance VitiSim predictive capabilities and reliability.

1. Introduction

A great number of interrelated factors (including photosynthesis, location of competing sinks, storage capacity and transport) control carbon partitioning in woody plants such as grapevines (*Vitis vinifera* L.). Environmental factors (e.g. water stress) and cultivation practices, including irrigation, might modify this carbon balance and affect fruit size, quality and yield (Deloire et al., 2004; Poni et al., 2018). 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 (Fraga et al., 2016; Maxwell et al., 2015). Furthermore, the response from several cultivars to these factors might be different; hence, the complexity of carbon partitioning in vines increases (Palliotti et al., 2014).

In order to cope with this complexity, models are useful tools to understand carbon balance in woody plants (Lescourret et al., 2011; Pallas et al., 2016) and might allow scientists to assess the effects of cultivation practices on this balance. In general, a comprehensive crop model should fulfill the following desirable and concurrent features: i) parsimony in data input; ii) high degree of user-friendliness in terms of usability and output visualization and interpretation; iii) reasonable accuracy of produced outputs and, iv) a broad output spectra covering plant growth, ripening and dry matter production and partitioning (Cola et al., 2014). Ideally, a model should be accessible, understandable and useable by those other than the model developers.

Many models have been developed for assessing plant growth and physiology, and they have been adapted to different crops (e.g. Grossman and DeJong, 1994; Lescourret et al., 2011). In the case of grapevines, there are models which accurately predict specific processes such as phenology (Fila et al., 2012), vegetative growth and yield (Bindi et al., 1997), leaf age, foliage density and canopy light interception and distribution (Louarn et al., 2008), sugar accumulation (Dai et al., 2009), carbon assimilation and allocation (Vivin et al., 2002). 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

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removal, hedging, cluster thinning, etc. These practices are effective agriculturally, but disrupt many of the natural growth habits and allometric relationships that underpin most plant models. Moreover, almost every vineyard has a unique combination of natural and managed factors. Thus modeling grapevines should not attempt excessively detailed simulations as results will have limited value to other conditions.

A model for predicting seasonal dry matter production in apple (Lakso et al., 2001) was used as a basis for assessing leaf area and daily carbon balance and dry matter accumulation in grapevines (Lakso and Poni, 2005; Poni et al., 2006). This approach proved to be simple, easy to use and provided quite fair estimations of leaf area, dry matter and carbon balance, proving its usefulness for simulating carbon exchange in vines (Poni et al., 2006; Lakso et al., 2008).

The aim of the current study was to improve an existing model of carbon balance in grapevine (Poni et al., 2006; Lakso et al., 2008) in order to take into account the effect of water stress and irrigation. Moreover, the model was tested with experimental data from vineyards (*Vitis vinifera* L. cv. 'Tempranillo') from two different Spanish regions. In addition, a sensitivity analysis was carried out for determining the inputs that exert the greatest influence on model outputs. Furthermore, the model was used to estimate dry mass accumulation of a standard vineyard located in different sites within Spain and worldwide as well as for simulating the effects of two different climate change scenarios on grapevine carbon balance.

2. Materials and methods

2.1. Plant material and experimental data

Field data came from experiments carried out in two Spanish locations (Supplementary Fig. 1), chosen on the basis of data availability: Badajoz (Extremadura, W Spain) and Requena (Valencia, E Spain). The vineyards studied were planted with 'Tempranillo'. Detailed descriptions of the study sites and irrigation treatments can be found in Picón-Toro et al. (2012) for Badajoz and Intrigliolo et al. (2012) for Requena. Therefore, only a brief description of each site is provided here.

The Badajoz vineyard was located in the research farm "Finca La Orden" (38° 51′ N, 6° 40′ W, elevation 198 m). Tempranillo vines were planted in 2001 and grafted onto Richter 110 at a spacing of 2.5 m by 1.2 m. Vines were trained to a vertical trellis on a bilateral cordon system oriented in the East-West direction. Vines were pruned to eight spurs and two buds per spur. The soil at this site had a silt-loam texture, with scarce calcium and low organic matter content, water holding capacity was 160 mm m^{-1}. Rooting depth was approximately 1.6 m. Climate is Mediterranean with mild Atlantic influence, dry hot summers and cold winters with irregular precipitations (470 mm annual average). In this case, the treatments considered were rain-fed and irrigation to replace 100% of crop evapotranspiration (Picón-Toro et al., 2012).

The vineyard located near Requena (39° 29′ N, 1° 13′ W, elevation 750 m) was planted in 1991 with Tempranillo vines on 161–149 rootstock at a spacing of 2.45 by 2.45 m. Vines were trained to a vertical trellis on a bilateral cordon system oriented in the North-South direction. The soil at this site had a clay loam to light clay texture, was highly calcareous and of low fertility, water holding capacity was 180 mm m^{-1}. Rooting depth was 2 m, approximately. Climate is continental with average annual rainfall of 430 mm of which about 65% falls during the dormant period. In this vineyard, rain-fed plants and those irrigated to the 75% of the estimated crop evapotranspiration were considered (Intrigliolo et al., 2012).

The period of study depended on the site: for Badajoz it was from 2007 to 2011 (5 years) and for Requena it was from 2008 to 2009 (2 years).

2.2. Field determinations for input data

Climate data (including maximum and minimum air temperature, rainfall, relative humidity, wind speed and solar radiation) were daily collected at weather stations located close to the experimental vineyards. These data allowed for computing vapor pressure deficit (VPD) and potential evapotranspiration (ET_0, Allen et al., 1998).

Over the growing season, midday stem water potential (Ψ_s) was measured in order to assess vine water status (Choné et al., 2001). Hence, Ψ_s readings were performed with a pressure chamber (Soil-Moisture Corp., Santa Barbara, USA) on three representative vines per replicate and one leaf per plant (9 readings per treatment). Measurements were carried out at midday (12:00–13:00 h) under sunny conditions on bagged leaves at 2-week intervals. Leaves were covered with a plastic bag and aluminum foil for at least 1 h prior to the measurements (Choné et al., 2001). At flowering, fruit set and veraison stages, the proportion of solar radiation intercepted by vine canopy was assessed in both sites using a ceptometer (LP-80, AccuPAR, Decagon Devices, Pullman, WA, USA). In order to obtain the curve of solar radiation proportion intercepted by the canopy over the growing season, the measured values were linearly interpolated between dates.

A dry mass evaluation of each plant organ (leaves, shoots and fruits) except roots (vines could not be sacrificed in the test vineyards) was carried out. Although the root systems of mature cropping vines may be large, the fraction of seasonal dry mass that is partitioned to them is often very small and the great majority remaining in the new seasonal growth (Bates et al., 2002). At harvest, all clusters from five plants per treatment were taken, weighed and dried in an oven at 65 °C till constant weight. Leaves from the same plants were removed and dried in the same conditions. At winter, vines were pruned and shoots were dried and weighed.

2.3. Model overview

'VitiSim' is a model for describing seasonal dry matter production of a grapevine that was originally developed for apple trees (Lakso and Johnson, 1990), modified over time (Lakso et al., 2001) and adapted to grape (Lakso and Poni, 2005; Lakso, 2006; Lakso et al., 2008). The model runs at a daily time-step in order to simplify the requirements for weather data and the complexities of diurnal radiation/canopy geometry. Also for simplicity the model uses the "big leaf" approach of combining individual organs, such as shoots or fruit, into a few super organs. It is assumed to be one leaf (canopy), one fruit (crop), one woody structure and one root made up of the population of individuals which may vary their numbers or activity. Previous details about canopy photosynthesis and tissues' respiration sub-models can be found in Lakso (2006), Lakso and Poni (2005) and Poni et al. (2006).

The model requires two types of inputs: vine descriptions and weather data. To describe the vine, latitude, day of budbreak, number of shoots, number of clusters per shoot, berries per cluster and row x vine spacings are needed. All these inputs come from data obtained in field experiments: the number of shoots was averaged from the sampled vines, as well as the number of clusters per shoot and that of berries per cluster (Table 1). Values of radiation interception, light-saturated photosynthesis rates, quantum yield, extinction coefficient, and temperature responses of organ respiration, leaf area development or photosynthesis, or cultivar specific growth data should be entered either from direct measurements or default values averaged from experimental and literature data. Due to the amount of common canopy manipulation and leaf removal, it is preferred to enter direct measurements of light interception than to model this process with assumptions that are often not met. Therefore, the values of the proportion of light intercepted by the canopy have been obtained from the field measurements made in the experimental vineyards, whereas the values for the remaining inputs (Table 1) have been taken from the literature. The weather daily records required are commonly available: