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Automatic irrigation system based on dual crop coefficient, soil and plant water status for *Vitis vinifera* (cv Godello and cv Mencía)

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ABSTRACT

This research aims at testing an automatic control irrigation system, using a wireless sensor network, in traditional Galician vineyards of *Vitis vinifera* (L.) cv. 'Godello' and cv. 'Mencía' to determine the threshold values of soil water potential at which plant stress begins, calibrating crop coefficients, building soil–water characteristics curves and measuring plant water status. In the cv. 'Godello' trial, rain-fed and two irrigations systems (surface and subsurface drip irrigation) were conducted over two growing seasons (2012–2013); during the same seasons cv 'Mencía' was also studied, but only under rain-fed conditions. The SIMDualKc model, which estimates soil water balance by means of the dual K_c approach, was used to estimate crop evapotranspiration (ET_c) by calibrating the full basal crop coefficient for the vine and cover crop ($K_{cb\,full}$), which represents the transpiration component of ET_c, and a soil evaporation coefficient (K_e). The model was calibrated and validated by comparing model simulations with TDR observed soil water content data. Granular matrix sensor (GMS) was linked in a wireless sensor network; soil water potential measured with GMS, was used to correlate with TDR data. Leaf water potentials (LWP) – midday and stem – allowed us to obtain plant water status. A good fit was obtained between SIMDualKc model and TDR ($r^2 > 0.74$), TDR and LWP ($r^2 > 0.65$), TDR and GMS ($r^2 > 0.81$), showing that continuous measures with GMS permit establishing a threshold value related with leaf water potential (midday or stem). For both cultivars, the threshold was $\Psi_{soil} = -0.1$ MPa. The process applied in this study proved to be useful for managing water in real-time in a vineyard; triggering the irrigation system when the threshold value was reached.

1. Introduction

Water resource scarcity worldwide and competition among different water uses (FAO, 2013) makes necessary to find solutions that provide understanding the effects of water use reduction in crop irrigation (Hayashi et al., 2012), as well as to know the time and depth needed by plants (Pereira, 1999); thus making agricultural water use more efficient and competitive. The increasing technification in agriculture, by establishing monitoring networks in different crops (Zhang et al., 2013b), is presented as a tool for improving real-time irrigation efficiency (Smarsly, 2013). The availability of different variables in real-time, by the use of sensors, avoiding discontinuous measurements in the field (Acevedo-Opazo et al., 2010) is a key issue in precision irrigation management and, therefore, for irrigation scheduling, currently developed in many horticultural crops (López et al., 2011) and in main extensive crops (Ruíz-García et al., 2009).

In vineyards, irrigation effects need to be interpreted regarding soil water status, crop ecophysiological parameters and the studied cultivar (Cifre et al., 2005), as well as qualitative characteristics of the final product. Hence, automatic irrigation systems in vineyards need to integrate all these parameters and their relationships. Recently, many studies have shown the irrigation effects in vineyards for different cultivars and locations (Azevedo et al., 2008; Santesteban et al., 2011; Gouveia et al., 2012; Trigo-Córdoba et al., 2013). In general, the reference parameter used for irrigation management was the leaf water potential (Girona et al., 2006; van Leeuwen et al., 2009; Martínez et al., 2011, 2013), usually measured with an Scholander pressure chamber (Scholander et al., 1965), at midday (ψ_m) or stem (ψ_{stem}). Centeno et al. (2010) established relationships among these plant parameters and soil water potential (Ψ_{soil}), for Tempranillo cultivar, obtaining good adjustments as well as Williams and Araujo (2002) for Chardonnay and Cabernet Sauvignon, or Williams and Trout (2005) for Thompson seedless. In addition, soil texture (Tramontini et al., 2013) and soil hydraulic

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characteristics (Centeno et al., 2010) in the studied vineyards were required to manage irrigation correctly, in particular soil–water characteristic curves using soil water potential (Ψ_{soil}) and three soil water content (θ) attributes: saturation, field capacity (FC) and permanent wilting point (PWP) (Martínez et al., 2012).

Simultaneously, research on crop evapotranspiration (ET_c) and water use in vineyards has been performed using various methods and techniques including lysimeters (Azevedo et al., 2008), heat pulse and heat balance (Yunusa et al., 1997; Trambouze and Voltz, 2001; Intrigliolo et al., 2009; Zhang et al., 2010), Bowen ratio and surface renewal energy balance (Yunusa et al., 2004; Moratiel and Martínez-Cob, 2011; Zhang et al., 2011), eddy covariance and soil water balance (Singleton and Maudsley, 1996; Fooladmand and Sepaskhah, 2009; Ortega-Farias et al., 2010; Fandiño et al., 2012a). Current approaches are able to define a crop coefficient (K_c) when the observed ET_c is related to a reference crop evapotranspiration (ET_o) computed with local data. Hence, ET_c can be estimated for a vineyard by using the following equation: $ET_c = K_c \times ET_o$ (Allen et al., 1998).

The dual K_c approach with calibration of K_{cb} for local conditions, crop variety, trellis training system, cover crop and cultural practices was applied to cv Albariño (Fandiño et al., 2012a), using the SIMDualKc model (Rosa et al., 2012a). Poblete-Echeverría and Ortega-Farias (2013) had evaluated K_{cb} for cv. Merlot to know the actual evapotranspiration in two seasons. Fooladmand and Sepaskhah (2009) used the dual K_c approach to assess water use of vineyards in a water harvesting system. Differently, Yunusa et al. (2004) estimated the vineyard transpiration (T_v) and soil evaporation (E_s) components of ET_c from separate measurements but not by modeling.

The present study adopted the dual crop coefficient approach to estimate ET_c in drip-irrigated vineyards of *Vitis vinifera* cv. 'Godello' (white variety) and rain-fed vineyards of cv. 'Mencía' (red variety) in Galicia, Northwest Spain. To adopt the dual K_c approach for these cultivars of grapevine is innovative and interesting since they are typical from Galician Designations of Origin (DO). In fact, Godello is the main variety in Valdeorras DO and Mencía is the main one in Ribeira Sacra DO. Moreover, they are widely cultivated in the rest of the Galician DO. In addition, there are no previous studies about crop water requirements accounting for soil and plant water status for these cultivars. Thus, the objectives of this study consist of: (a) computing ET_c of two grapevine cultivars using the dual K_c approach, thus with its separation into crop transpiration and soil evaporation; (b) testing the SIMDualKc model by calibrating and validating the $K_{cb\ full}$ values appropriate for these cultivars, using observed soil water data relative to various irrigation treatments and two years of observations (2012–2013); and (c) defining a threshold of water stress to trigger the irrigation, applying soil and plant water measurements, using an automatic irrigation system with real-time data, to keep an optimal range for grapevine activity.

2. Materials and methods

2.1. Site, crop and treatments

The experiment was conducted during 2012 and 2013 in two commercial vineyards planted with cv 'Godello' and 'Mencía'. 'Godello' plot is located in A Rúa (Galicia-NW Spain) within the DO Valdeorras (latitude 42°23′59″N, longitude 7°7′15″W and altitude 320 m above sea level, mean slope is 18%). Soil at the site is sandy clay-loam with 46.2% sand, 31% silt and 22.8% clay, pH (H_2O) 4.99 and 2.26% organic matter. Soil depth was, approximately, 1.2 m. No operations of soil tillage were undertaken during the studied seasons.

Table 1
Soil characteristics for the entire root depth (0.6 m) in DO Valdeorras and DO Ribeira Sacra (LAD-Ladredo, MEI-Meixemán).

	DO Valdeorras	DO Ribeira Sacra	
		LAD	MEI
FC ($m^3\ m^{-3}$)	0.25	0.23	0.20
PWP ($m^3\ m^{-3}$)	0.08	0.07	0.04
Saturation ($m^3\ m^{-3}$)	0.38	0.28	0.24
TAW (mm)	102	96	96

FC—field capacity, PWP—permanent wilting point, TAW—total available water.

In the case of cv. 'Mencía' two test plots: 'Meixemán' (MEI) and 'Ladredo' (LAD), were studied, both located in the 'Amandi' subarea (DO Ribeira Sacra), in Doade (Galicia, NW Spain), arranged in terraces and without irrigation (MEI: latitude 42°24′27″N, longitude 7°27′24″W and altitude 439 m above sea level; LAD: latitude 42°24′42″N, longitude 7°27′10″W and altitude 330 m above sea level). Soil in 'Mencía' plots has an average pH (H_2O) of 5.40; 10.6% and 6.2% organic matter, in MEI and LAD, respectively. MEI soil site is loamwith 41.5% sand and 40.8% silt, and in LAD plot is sandy-loam with 57.6% sand and 26.1% silt.

All data required to compute the soil water balance are presented in Table 1. Total available soil water (TAW) down to 0.6 m depth was calculated as the difference between the average FC and the PWP. The total evaporable water (TEW), the readily evaporable water (REW) and the depth of the evaporable layer (Z_e) were first estimated from standard data proposed by Allen et al. (1998, 2005) and then adjusted when calibrating/validating the model. The average crop height and the effective root depth averaged (0.6 m depth) were observed during all seasons (Table 2).

Meteorological data was collected from weather stations managed by MeteoGalicia, the Galician Meteorological Agency, 'Larouco' (cv 'Godello') and 'Ponte Boga' (cv. 'Mencía') located at less than 7 km and 4 km to the experimental sites, respectively. In 'Godello' plot, from March to October, the average temperature was 16.2 °C and 16.3 °C, for 2012 and 2013, respectively; total rainfall during this period was 347.9 mm and 518.2 mm for 2012 and 2013. In the case of 'Mencía' plots the average temperature was 16.1 °C and 16.2 °C, for 2012 and 2013, respectively; total rainfall from March to October was 449.7 mm and 623.9 mm for 2012 and 2013. Rainfall and reference evapotranspiration are shown in Fig. 1. The reference evapotranspiration (ET_o) was computed with the Penman–Monteith equation using the methodology proposed by Allen et al. (1998) for limited weather data, *i.e.*, estimating the actual vapor pressure from the daily minimum temperature and solar radiation from daily maximum and minimum temperature.

In the case of cv 'Godello', white grapevine cultivar native from Galicia, plants were about 15 years old at the beginning of this experiment; they were vertically shoot positioned and grafted on rootstock 110R. The spacing is 1.35 m × 1.95 m (3800 plants ha^{-1}). Two treatments were established following a completely randomized block design with four replications (7 plants each). The treatments were: rain-fed (R) and irrigation [surface (DI) and subsurface (SDI) drip irrigation systems]. The surface irrigation pipes were in the vineyard row at 40 cm above the soil, whereas the subsurface pipes were 40 cm deep into the soil, approximately. Both systems were equipped with 2 L h^{-1} emitters (Fandiño et al., 2013). In the case of cv 'Mencía', red grapevine cultivar native from Galicia, plants were about 70 years old at the beginning of this experiment; they were vertically shoot positioned. The vines were arranged in terraces, with a distance between plants of 1.4 m (4200 plants ha^{-1}). Grapevine phenology was surveyed over the studied growing seasons and was used to establish crop development stages (Table 2), these values were used in the soil water balance model.