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Evaluation of crop coefficients, water productivity, and water balance components for wine grapes irrigated at different deficit levels by a sub-surface drip

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ABSTRACT

Accurate estimation of evapotranspiration (*ET*) and its partitioning into transpiration and evaporation is fundamental for improving water management practices in water-limited environments and under deficit irrigation conditions. This investigation was conducted to estimate the water balance and *ET* components of subsurface drip (SDI) irrigated Chardonnay wine grapes for two seasons (2010–2011 and 2011–2012) using a numerical model (HYDRUS-2D). Treatments involved the application of different volumes [51% (I_1), 64% (I_2), 77% (I_3), and 92% (I_4) of normal application] of water for irrigation. A modified version of the FAO-56 dual crop coefficient approach was used to generate daily transpiration and evaporation as inputs to the HYDRUS-2D model. The calibrated and validated model produced estimates of actual evapotranspiration (ET_{Cact}), actual transpiration (T_{pact}), and actual evaporation (E_{sact}), and deep percolation under varied irrigation applications. The model-simulated values were then used to estimate actual crop coefficients (K_{cact} and K_{cbact}), and water productivity of wine grape under different deficit irrigation conditions.

Seasonal ET_{Cact} simulated by HYDRUS-2D for different treatments varied between 239 and 382 mm. However, seasonal evaporation accounted for 44–59% of seasonal ET_{Cact} losses in different treatments. The modelled daily transpiration rate in I_4 treatment (T_{p4act}) varied from 0.11–2.74 mm/day. Deep percolation accounted for 35–40% of the total water applied by rainfall and irrigation. The mean value of actual crop coefficient (K_{cact}) estimated by HYDRUS-2D simulated ET_{Cact} over the two seasons was 0.27, which matched with other investigations. Similarly, values of K_{cbact} for initial, mid and end stages were 0.13, 0.27 and 0.14, respectively. Monthly values of evaporation coefficient (K_e) ranged from 0.1 to 0.32, with a mean value of 0.18. Water productivity with respect to *ET* losses ($WPET_C$) ranged from 5.9 to 6.2 kg/m^3 of water use. However, water productivity for transpiration (WPT_C) almost doubled as compared to $WPET_C$ in all treatments. The impact of deficit irrigation on berry juice composition (Brix, pH and titratable acidity) was lower than the inter-seasonal variability. These results can help develop better irrigation management strategies for SDI irrigated wine grapes under water scarce conditions.

1. Introduction

Seasonal management of irrigation water is the most crucial decision that farmers have to contemplate for sustainable and profitable crop production, particularly in the arid and semiarid regions of the world where water availability for irrigation is not assured. The majority of high value horticultural orchards and vineyards in Australia are primarily dependent on irrigation. For example, 90% of Australian vineyards rely on some assured irrigation arrangement (Australian Bureau of Statistics, 2012). The allocation of water for irrigation in South Australia is highly influenced by the amount of seasonal rainfall on the eastern Australian high ranges and subsequent storage and flow in the Murray Darling river system. During drought years (2006–2009) the water allocation was severely reduced, to levels as low as 18% of normal allocations, which had serious repercussions on the sustainable

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production and resilience of vineyards and orchards. Similar conditions with limited availability of irrigation water occur in other arid and semi-arid regions of the world. As a consequence, judicious water use, long-term sustainability and increasing efficiency, i.e., improving the yield to water consumption ratio, become major priorities in viticulture.

Considerable research has been undertaken on various deficit irrigation techniques, such as regulated deficit irrigation (e.g., Costa et al., 2007; Romero et al., 2010, 2013; Santesteban et al., 2011; Edwards and Clingeleffer, 2013; Acevedo-Opazo et al., 2010; Faci et al., 2014), sustained deficit irrigation (e.g., Fereres and Soriano, 2007; Chalmers et al., 2010; Williams, 2010; Williams et al., 2010a,b), and partial root zone drying (e.g., Dry and Loveys, 1998; McCarthy et al., 2000; Intrigliolo and Castel, 2009; Sadras, 2009; Romero et al., 2015), in order to evaluate their impact on water use, yield, berry composition, and wine attributes. However, most of these studies were driven by the need to control vine vigour and maximize fruit quality rather than the need to improve the vineyard water use efficiency (Edwards and Clingeleffer, 2011) and water productivity. Moreover, research results on water use with respect to the application of deficit irrigation techniques under field conditions and the long-term impacts on production have been found to be contradictory (Chaves et al., 2010; Sadras, 2009), which suggests that site specific factors played a major role in evaluating the impact of deficit irrigation in these studies. In addition, most of these studies dealing with deficit irrigation are based on conventional drip or sprinkler irrigation. However, sub-surface drip irrigation (SDI) could have a different impact on water use, potential water losses, and overall vine performance compared to conventional drip and other irrigation methods. A few comparative studies (Fandiño et al., 2012; Cancela et al., 2015) showed slightly higher vine water uptake and crop coefficients under SDI than under conventional drip. Hence, there is need to evaluate the water balance components for wine grapes under SDI, and under varying volumes of irrigation application.

A wide range of methods and techniques have been used for estimating vineyard *ET* and water use, including lysimeter (Williams and Ayars, 2005; Netzer et al., 2009), sap flow (Lascano et al., 1992; Yunusa et al., 1997, 2000, 2004; Ferreira et al., 2012), Bowen ratio (Yunusa et al., 2004; Zhang et al., 2011), surface energy balance (Castellví and Snyder, 2010; Moratiel and Martínez-Cob, 2012), eddy covariance (Ortega-Farias et al., 2010; Rodríguez et al., 2010), soil water balance (Singleton and Maudsley, 1996; Fooladmand and Sepaskhah, 2009), and a combination of field measurements (Trambouze et al., 1998; Cancela et al., 2012; Styles et al., 2015). However, intensive field measurements of these agro-hydrological fluxes require large investment in sensors, labour, and time. On the other hand, precise estimation of the dynamics of evaporation and transpiration could help in judicious management of scarce water resources in drip-irrigated high-value cropping systems (Yunusa et al., 2004; Ortega-Farias et al., 2012). Besides evaporation and transpiration, reliable understanding of the drainage fraction is critical for better identification of productive and unproductive fractions of water for SDI, especially under sustained deficit conditions.

Numerical models are ideally suited to evaluate water balance in drip irrigation systems, and to study the importance of and interaction among various water fluxes under sparse vegetation and for different supplementary irrigation conditions. HYDRUS-2D/3D (Šimůnek et al., 2008, 2016) is a widely used numerical model simulating water flow in soils under cropped conditions. This model has been previously used to study *ET* components, for example, for almond (Phogat et al., 2012, 2013), maize (Ramos et al., 2012), citrus (Phogat et al., 2014), and other crops (Mei-Xian et al., 2013; González et al., 2015). Recently, Kool et al. (2014a) has successfully used this model for the estimation of evaporation losses from a commercial vineyard in combination with short term above canopy measurements of climatic parameters.

The objectives of this study thus were to (a) calibrate and validate HYDRUS-2D under deficit sub-surface drip irrigation of wine grape, (b) to estimate water balance and actual *ET* components of wine grape, and compare them under different SDI deficit irrigation treatments, (c) to estimate the actual crop coefficients of wine grapes, and (d) to assess yield, wine quality parameters and water productivity of Chardonnay wine grape under SDI under different deficit irrigation treatments, and compare these to other published research.

2. Materials and methods

2.1. Experimental details

A field experiment was conducted in the Markaranka vineyard (34.08°S and 139.87°E), located near Waikerie in South Australia. The Chardonnay wine grapes (clone Bernard 95) on Ramsey rootstock were planted in November 2004 at a vine spacing of 2.5 m and row spacing of 3.35 m, and were irrigated using subsurface drip (SDI). Monitoring of the experimental site was initiated in November 2010 and continued for two seasons. The soils at the site are predominately light textured, ranging from sand to loamy sand, with the sand content in the range of 84–91%, the clay content from 9 to 13%, and the silt content from 0 to 3%. The climate is characterized as dry, with warm to hot summers and mild winters. The total rainfall during the experimental period from 22 September 2010 to 30 June 2011 was 338 mm (Fig. 1), and from 7 September 2011 to 30 June 2012 was 236 mm. Unusually high precipitations of 95.2 and 68.2 mm occurred on 8 December 2010 and 14 January 2011, respectively, during the first season. Similar heavy summer rainfalls of 58.2 mm and 42 mm occurred on 17 December 2011 and 29 February 2012, respectively, during the second season. The grass reference *ET* (ET_0) was calculated using a modified Penman-Monteith equation, which incorporates a number of weather and energy balance parameters, as described in Allen et al. (1998). Estimated ET_0 during 2010–11 and 2011–12 seasons was 904 and 1055 mm, respectively (Fig. 1). The maximum daily ET_0 was estimated to be 8.4 mm on January 1, 2012. Mild frost conditions occurred during the winter months. Weather data were collected from an automated weather station located at Qualco, 4 km from the trial site.

The grapevine growth season at the field site started with budburst in late August–late September. Full leaf cover was attained before flowering, which started in late November and/or early December. The leaves remained active for 3 months till the end of March. The fruit yield and yield attributes (number of bunches per vine, average bunch weight) were recorded for all the treatments plots. Juice from a fresh fifty berry sample was extracted using a small hand-held press and centrifuged at 3000 rpm for 5 min. A bench-top refractometer was used to determine Total Soluble Solids (expressed as °Brix). A 10 mL sample of clear juice was used for the determination of pH and Titratable acid using an automated end-point titrator pH 8.2 with 1 M NaOH (Amerine, 1965).

2.2. Irrigation treatments and water content measurements

The irrigation system at the experimental site consisted of a pressure compensated drip system (Toro Drip-In® Rootguard®), with an emitters discharge rate of 1.6 L h^{-1} and a spacing of 40 cm. The SDI drip lines were installed at a depth of 25 cm, 25 cm away from the vine line. Water for irrigation was pumped directly from the Murray River. Irrigation treatments were designed to test the