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Evaluation of neural network modeling to predict non-water-stressed leaf temperature in wine grape for calculation of crop water stress index

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ABSTRACT

Precision irrigation management of wine grape requires a reliable method to easily quantify and monitor vine water status to allow effective manipulation of plant water stress in response to water demand, cultivar management and producer objective. Mild to moderate water stress is desirable in wine grape in determined phenological periods for controlling vine vigor and optimizing fruit yield and quality according to producer preferences and objectives. The traditional leaf temperature based crop water stress index (CWSI) for monitoring plant water status has not been widely used for irrigated crops in general partly because of the need to know well-watered and non-transpiring leaf temperatures under identical environmental conditions. In this study, leaf temperature of vines irrigated at rates of 35, 70 or 100% of estimated evapotranspiration demand (ET_c) under warm, semiarid field conditions in southwestern Idaho USA was monitored from berry development through fruit harvest in 2013 and 2014. Neural network (NN) models were developed based on meteorological measurements to predict well-watered leaf temperature of wine grape cultivars 'Syrah' and 'Malbec' (*Vitis vinifera* L.). Input variables for the cultivar specific NN models with lowest mean squared error were 15-min average values for air temperature, relative humidity, solar radiation and wind speed collected within ±90 min of solar noon (13:00 and 15:00 MDT). Correlation coefficients between NN predicted and measured well-watered leaf temperature were 0.93 and 0.89 for 'Syrah' and 'Malbec', respectively. Mean squared error and mean average error for the NN models were 1.07 and 0.82 °C for 'Syrah' and 1.30, and 0.98 °C for 'Malbec', respectively. The NN models predicted well-watered leaf temperature with significantly less variability than traditional multiple linear regression using the same input variables. Non-transpiring leaf temperature was estimated as air temperature plus 15 °C based on maximum temperatures measured for vines irrigated at 35% (ET_c). Daily mean CWSI calculated using NN estimated well-watered leaf temperatures between 13:00 and 15:00 MDT and air temperature plus 15 °C for non-transpiring leaf temperature consistently differentiated between deficit irrigation amounts, irrigation events, and rainfall. The methodology used to calculate a daily CWSI for wine grape in this study provided a daily indicator of vine water status that could be automated for use as a decision-support tool in a precision irrigation system.

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1. Introduction

In many arid wine grape production areas irrigation is widely used to manage vine vigor and yield to induce desirable changes in berry composition for wine production (Chaves et al., 2010; Lovisolo et al., 2010). In red-skinned wine grape cultivars, a mild to moderate water stress in determined phenological periods has been found to increase water productivity and to improve fruit quality (Romero et al., 2010; Shellie, 2014). The optimum severity and phenological timing of imposed water deficit is influenced by cultivar, climatic and edaphic growing conditions, and wine grape cultural practices. Application of precision irrigation techniques requires accurate, reliable methods for determining vine water demand and for monitoring vine water status coupled with an irrigation system capable of applying water on-demand, in precise amounts (Jones, 2004). The lack of a rapid, reliable method for monitoring vine water status with high spatial and temporal resolution has hindered the adoption of precision irrigation practices in wine grape production.

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Many of the methods currently available for determining water demand and monitoring vine water status are either too laborious for automation or have poor spatial and temporal resolution. The Penman–Monteith equation is commonly used to estimate evapotranspiration demand (ET_c) and calculate an irrigation amount (Allen et al., 1998); however, periodic measurements of plant or soil water status are required to verify that the supplied amount actually induced the desired severity of water stress. Soil volumetric water content is not a suitable indicator of vine water status because it has low spatial resolution and is influenced by spatially heterogeneous soil attributes, such as texture and depth. Williams and Trout (2005) found that measurement of soil water content to a depth of 3m at nine locations within one-quarter of an individual vine root zone was necessary to accurately determine the amount of water within the soil profile available to drip-irrigated vines. Also, a given soil volumetric water content may induce differing severities of water stress in different grapevine cultivars due to intrinsic differences among cultivars in their hydraulic behavior ranging from isohydric to anisohydric (Schultz, 2003; Shellie and Bowen 2014; Williams et al., 2012; Bellvert et al., 2015a). Thus, bulk changes in soil water content or soil water potential may not correspond with changes in vine water status (Jones, 2004; Williams and Trout, 2005; Ortega-Farias et al., 2012). Measurements of leaf or stem water potential offer the advantage of integrating soil, plant and environmental factors; however, their poor temporal and spatial resolution and high labor requirement limit their potential for automation into a precision irrigation system. Plant water potential has poor temporal resolution due to its high sensitivity to environmental conditions (Rodrigues et al., 2012; Williams and Baeza, 2007; Jones, 2004). There also is no general agreement as to which measurement of plant water potential (pre-dawn leaf or midday stem or leaf) most reliably indicates vine water status (Williams and Araujo, 2002; Williams and Trout, 2005; Ortega-Farias et al., 2012). Williams and Trout (2005) found that pre-dawn leaf water potential was unsatisfactory for accurately determining vine water status while midday leaf and stem water potential were linearly correlated and equally suitable for determining vine water status. Midday leaf water potential is the most common method used in California to indicate vine water status (Williams et al., 2012) perhaps because it is less time consuming than either pre-dawn leaf water potential or midday stem water potential allowing more acreage to be covered during midday climatic conditions (Williams and Araujo, 2002). Midday stem and leaf water potential of grape vines are highly correlated with vapor pressure deficit (VPD) under semi-arid conditions but the correlations differ for leaf water potentials less than or greater than 1.2 MPa (Williams and Baeza, 2007; Williams et al., 2012) In general, a midday value of leaf water potential less negative than −1.0 MPa under high evaporative demand has generally been accepted as indicative of well-watered vines (Shellie, 2006; Williams and Trout, 2005; Williams et al., 2012; Shellie and Bowen, 2014; Bellvert et al., 2014).

Thermal remote sensing has recently been used to estimate evapotranspiration and drought stress in many crops, including grapevine (Maes and Steppe, 2012). Water stress promotes stomatal closure, reducing transpiration and evaporative cooling while increasing leaf temperature. Infrared radiometers have been used under field conditions to measure the increase in wine grape leaf surface temperature under differing severities of deficit irrigation (Cohen et al., 2005; Glenn et al., 2010; Shellie and King 2013; Bellvert et al., 2014, 2015a). Changes in leaf temperature have been correlated with rates of stomatal conductance and leaf or stem water potential in grapevine and responsiveness has been shown to vary by cultivar (Cohen et al., 2005; Glenn et al., 2010; Pou et al., 2014; Bellvert et al., 2015a,b). The difference in leaf temperature between stressed and non-water stressed plants relative to ambient air temperature has been used to develop a normalized crop water stress index (CWSI) (Idso et al., 1981; Jackson et al., 1981) for quantifying plant water status. The CWSI is defined as:

$$\mathrm{CWSI} = \frac{\left(T_{\mathrm{canopy}} - T_{\mathrm{nws}}\right)}{\left(T_{\mathrm{dry}} - T_{\mathrm{nws}}\right)} \tag{1}$$

where T_{canopy} is the temperature of fully sunlit canopy leaves (°C), T_{nws} is the temperature of fully sunlit canopy leaves (°C) when the crop is non-water-stressed (well-watered) and T_{dry} is the temperature of fully sunlit canopy leaves (°C) when the crop is severely water stressed due to low soil water availability. Temperatures T_{nws} and T_{dry} are the lower and upper baselines used to normalize CWSI for the effects of environmental conditions (air temperature, relative humidity, radiation, wind speed, etc.) on T_{canopy}. Ideally, CWSI ranges from 0 to 1 where 0 represents a well-watered condition and 1 represents a non-transpiring, water-stressed condition. Practical application of the CWSI has been limited by the difficulty of estimating without actually measuring T_{nws} and T_{dry} (Maes and Steppe, 2012). Experimental determination of a crop specific constant for T_{nws} and T_{dry} relative to ambient air temperature has not been fruitful due to the poorly understood and complex influences of environmental conditions on the soil–plant–air continuum (Idso et al., 1981; Jones, 1999, 2004; Payero and Irmak, 2006). In the original development and application of the CWSI, T_{nws} and T_{dry} were experimentally determined with T_{nws} correlated with VPD to account for climatic effects on T_{canopy} measurements. Canopy temperature measurements and application of the CWSI were restricted to times near solar noon on cloudless days to account for the effect of solar radiation on stomatal conductance. Artificial wet and dry reference surfaces have been used successfully to estimate T_{nws} and T_{dry} under the same environmental conditions as T_{canopy}. (Jones, 1999; O'shaughnessy et al., 2011; Jones et al., 2002; Leinonen and Jones, 2004; Cohen et al., 2005; Grant et al., 2007; Möller et al., 2007; Alchanatis et al., 2010; Pou et al., 2014); however, the required maintenance of the artificial references limits potential use for automation in a precision irrigation system.

Physical and empirical models have been developed to estimate T_{nws} and T_{dry} with varying degrees of success. A leaf energy balance (Jones, 1992) approach was used by Jones (1999) to develop the following equations for calculating T_{wet} and T_{dry}:

$$T_{\mathrm{wet}} = T_{\mathrm{air}} - \frac{r_{\mathrm{HR}} r_{\mathrm{aW}} \gamma R_{\mathrm{ni}}}{\rho c_p \left[\gamma r_{\mathrm{aW}} + s r_{\mathrm{HR}}\right]} - \frac{r_{\mathrm{HR}} \delta_e}{\gamma r_{\mathrm{aW}} + s r_{\mathrm{HR}}} \tag{2}$$

$$T_{\mathrm{dry}} = T_{\mathrm{air}} + \frac{r_{\mathrm{HR}} R_{\mathrm{ni}}}{\rho c_p} \tag{3}$$

where T_{wet} is the temperature (°C) of an artificially wet leaf, T_{air} is air temperature (°C), r_{aW} is boundary layer resistance to water vapor ($\mathrm{s\,m^{-1}}$), R_{ni} is the net isothermal radiation ($\mathrm{W\,m^{-2}}$), δ_e is water air vapor pressure deficit (Pa), r_{HR} is the parallel resistance to heat and radiative transfer ($\mathrm{s\,m^{-1}}$), γ is the psychrometric constant ($\mathrm{Pa\,°C^{-1}}$), ρ is the density of air ($\mathrm{kg\,m^{-3}}$), c_p is the specific heat capacity of air ($\mathrm{J\,kg^{-1}\,°C^{-1}}$) and s is the slope of the curve relating saturation vapor pressure to temperature ($\mathrm{Pa\,°C^{-1}}$). Sensible heat loss for a dry surface with the same radiative and aerodynamic properties of a leaf was assumed to be equal to net absorbed radiation (Eq (3)). Heat transfer resistance in leaves (r_{HR}) was estimated to be a function of characteristic dimension (d) and wind speed (μ) (Jones, 1992) and, assuming isothermal radiation, can be estimated as (Jones, 1999):

$$r_{\mathrm{HR}} = 100\sqrt{\left(\frac{d}{\mu}\right)} \tag{4}$$

where d and μ are measured in m and $\mathrm{m\,s^{-1}}$, respectively. Fuentes et al. (2012) found excellent agreement between artificial reference leaf surface temperatures and T_{wet} and T_{dry} calculated using Eqs. (2)–(4) and in-canopy micrometeorological measure-

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