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In field quantification and discrimination of different vineyard water regimes by on-the-go NIR spectroscopy

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Precise and rapid methods to assess plant water status are needed in agriculture. The goal of this work was to evaluate the capability of a new plant-based method based on proximal near-infrared (NIR) spectroscopy acquired on-the-go from a moving vehicle to quantify and discriminate different water regimes in a commercial vineyard. Proximal on-the-go NIR spectroscopy (1100–2100 nm) was acquired at solar noon on five days from veraison (onset of ripening) to harvest 2015 in a commercial Tempranillo vineyard. Spectral measurements were taken at ~0.30 m from the canopy, on both canopy sides, from a vehicle moving at 5 km h^{-1}. Measurements of midday stem water potential (Ψ_s) and leaf stomatal conductance (g_s) were simultaneously acquired to be used as reference indicators of plant water status. Partial least squares (PLS) was used to build calibration, cross validation and predictive models for Ψ_s and g_s. The determination coefficients of prediction (R^2_p) were above 0.86 for Ψ_s and above 0.66 for g_s, while the root mean square errors of prediction (RMSEP) were less than 0.18 MPa and 93.7 mmol [H_2O] m^{-2} s^{-1}, respectively. PLS-Discriminant Analysis (PLS-DA) was applied to classify the data into three different water regimes, according to Ψ_s or g_s. The average correctly classified percentage was greater than 72% for Ψ_s and g_s. This discriminant capability, together with the large number of measurements that the on-the-go NIR spectroscopy can provide, enables the quantification and mapping of the variability of a vineyard water status and may help to define precise irrigation strategies in viticulture.

1. Introduction

Most wine regions worldwide are located in seasonally dry zones with high evaporative demand and low water resources (Chaves et al., 2010). Water scarcity may result in severe plant water deficit stress, which may negatively impact vegetative growth, yield and wine composition (Chaves et al., 2007; Ojeda, Andary, Kraeva, Carbonneau, & Deloire, 2002). In this framework precise irrigation emerges as the only solution to deal with limited water resources and to protect grapevines from water deficit stress. Precision irrigation can be defined as

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Nomenclature table

ATV	All-terrain vehicle
Ψ_s	Stem water potential (MPa)
g_s	stomatal conductance (mmol [H_2O] m^{-2} s^{-1})
InGaAs	Indium Gallium Arsenide
LVs	number of latent variables
NIR	near-infrared
NIRS	near-infrared spectroscopy
PCA	principal component analysis
PLS	partial least squares
PLS-DA	partial least squares – discrimination analysis
R^2	determination coefficient
R^2_c	determination coefficient of calibration
R^2_{cv}	determination coefficient of cross validation
R^2_p	determination coefficient of prediction
RMSEC	root mean square error of calibration
RMSECV	root mean square error of cross-validation
RMSEP	root mean square error of cross-prediction
RWC	relative water content (%)
SNV	standard normal variate

the irrigation regime that fits, in timing, duration and amount, the actual crop needs, at the smallest manageable scale, to achieve the desired crop performance (Cohen, Alchanatis, Meron, Saranga, & Tsipris, 2005).

Irrigation strategies may be steered by parameters describing the atmospheric demand (Allen, Pereira, Raes, & Smith, 1999) or the soil moisture (Smith & Mullins, 2000), or more adequately and precisely by plant-based indicators (Jones, 2004). Of the latter, some are direct measurements of the plant water status, such as the measurement of the relative water content (RWC) (Barrs & Weatherley, 1962), the plant water potential (Ψ) (Choné, Van Leeuwen, Dubourdieu, & Gaudillère, 2001) and the hydraulic conductivity (Lovisolo & Tramontini, 2010). Others are derived from the plant physiological responses, such as sap-flow meters (Escalona & Ribas-Carbó, 2010), thermal sensors (Jones et al., 2002) and devices measuring leaf thickness and fluctuations of stem or trunk diameter (Fernández, 2014). However, most of these indicators are either destructive, time and labour demanding, expensive, or can be appraised in only a limited number of plants.

Direct monitoring of Ψ has been proposed as the most effective way of assessing irrigation requirements (Choné et al., 2001; Ojeda, 2007). Recent studies have shown that Ψ exhibits a significant magnitude of variation in a single block (Acevedo-Opazo, Tisseyre, Ojeda, Ortega-Farias, & Guillaume, 2008; Tisseyre, Ojeda, Carillo, Deis, & Heywang, 2005) and at vineyard scale (Taylor, Acevedo-Opazo, Ojeda, & Tisseyre, 2010), and this becomes larger when water restriction increases, and more negative values of Ψ occur (Ojeda et al., 2005; Taylor et al., 2010). Therefore, assessing and mapping the spatial variability of vine water status within vineyards constitutes a major challenge (Bellvert et al., 2016). To achieve it, an effective sampling system, capable of providing a large amount of accurate observations is required to drive accurate irrigation decision-making. In this context, remote thermography from aerial platforms has been tested (Baluja et al., 2012) and provided a good estimation of Ψ and stomatal conductance (g_s). However, legal issues associated with drones are still a limiting factor for the practical implementation of this approach. Therefore, it is essential to investigate new, non-invasive alternative methods that are sensitive to the plant water fluctuations, and capable of providing reliable and fast response in an automated way, in order to yield a large number of data to appraise water status in commercial vineyards.

Near-infrared spectroscopy (NIRS) is a non-invasive analytical method, highly-suited to several agricultural applications due to its rapid data acquisition and the ability of determining more than one parameter (Cen & He, 2007; Huang, Yu, Xu, & Ying, 2008; McClure, 2003; Steidle Neto, Lopes, Pinto, & Zolnier, 2017). The NIR region is the part of the electromagnetic spectrum between 750 and 2500 nm and the spectra are defined by absorption bands associated with overtones and combinations of fundamental vibrations arising from functional groups of molecules (C–H, N–H, O–H and S–H) contained in the analysed sample (Williams, 2001). Water is the essential component of leaves, and their NIR reflectance spectra are highly influenced by the water spectrum, which shows overtone bands of the OH bonds at 760, 970 and 1450 nm and a combination band at 1940 nm (Nicolai et al., 2007). In the last years, a few studies (De Bei et al., 2011; Gutiérrez, Tardaguila, Fernández-Novales, Diago, et al., 2016; Santos & Kaye, 2009; Tardaguila, Fernández-Novales, Gutiérrez, & Diago, 2017; Vila, Hugalde, & Di Filippo, 2011) have demonstrated that NIR technology could be used to monitor the grapevine water status at leaf level. These authors have shown the performance of different portable manual NIR devices in contact with grapevine leaves to determine the plant water status, either leaf (Ψ_l) or stem water potential (Ψ_s) under field conditions. De Bei et al. (2011) reported a correlation coefficient of calibration (r_{cv}) of 0.84 for a model built from spectra acquired in the 1100–1830 nm wavelength range on the abaxial side of Chardonnay leaves to predict stem water potential. In the same study, similar values, of r_{cv} were obtained using another VIS–NIR device operating in the range of 300–1100 nm on the adaxial side of Cabernet Sauvignon and Shiraz. In a more recent work, Tardaguila et al. (2017) used a handheld NIR (1600–2400 nm) spectrophotometer to develop reliable prediction models for stem water potential with r_{cv} that ranged from 0.77 to 0.93 on the adaxial and abaxial side of the leaf in two different vineyards. One step towards the automation of this technique was recently reported by Diago et al. (2017), who obtained very good estimation of grapevine g_s from NIR spectra acquired, in a stop and go mode, with a contactless spectrometer mounted on an all-terrain vehicle (ATV). While the merit of this work is well recognised, a final step towards the true implementation of NIR spectroscopy for in-field water status assessment would be its on-the go acquisition in a fully automated way in commercial vineyards.

The goal of this study was to quantify and discriminate different grapevine water regimes in a commercial vineyard using proximal NIR spectroscopy acquired on-the-go from a moving vehicle.

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