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Vineyard water relations in a karstic area: deep roots and irrigation management

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ABSTRACT

Ongoing variations in rainfall and temperature regimes affect the physiology and productivity of grapevines, calling for irrigation in drought-prone areas. During vintage 2015, we monitored plants water status and indirectly assessed rooting depth and exploited water sources (oxygen isotope analyses) in a mature *Vitis vinifera* cv. Malvasia Istriana vineyard on red soils ("terra rossa") developed on highly permeable carbonate rocks. We also investigated effects of topsoil irrigation or late summer rains on plant water status and yield. Under the harsh summer environmental conditions of 2015, the plant water status was overall favorable (moderate water deficit) and never reached critical levels, suggesting that irrigation was not mandatory. Leaf conductance to water vapor (g_L) measured in July decreased by about 70% compared to spring, while minimum leaf water potential (Ψ_{min}) dropped by only 16%, suggesting an isohydric behavior of the cultivar (strict stomatal control of transpiration). Both Ψ_{min} and g_L reached a minimum in July (peak of drought), and returned to pre-drought values in late summer. Rainfalls or supplemental irrigation (about 40 mm) promoted prompt recovery of plant water status. Irrigation treatments or occasional summer rainfalls can influence the water status of plants, although roots have access to deep water sources. In fact, the isotopic composition of xylem sap was similar to that of soil water sampled in a nearby deep cave, supporting the hypothesis that deep soil is the main water source for grapevines in karstic areas during summertime. Deficit irrigation, based on careful evaluation of physiological indicators of plant water status, might be an effective strategy for promoting sustainable viticulture, and a rationale use of water resources in karstic ecosystems.

1. Introduction

Grapevine (*Vitis vinifera* L.) is a crop widely cultivated in many countries (Lovisolo et al., 2010; Costa et al., 2016). Several vineyards regions are characterized by seasonal drought, imposing significant constraints on yield and quality. Rising global temperatures coupled to prolonged droughts (IPCC, 2014) have already negatively affected plants' growth and production in both natural and agricultural ecosystems (Marx et al., 2017; Nardini et al., 2014; Potopová et al., 2017; Tripathi et al., 2016). The projected increase in frequency/severity of anomalous drought events (IPCC, 2014) calls for adaptation of viticulture to climate change, by using drought-tolerant rootstocks/cultivars and suitable agronomic practices (Costa et al., 2016; Ferlito et al., 2014; Herrera et al., 2015; Koundouras et al., 2008; Lopes et al., 2011). Vineyards are traditionally rain-fed in the Mediterranean area, although irrigation practices are increasing to guarantee stable yield production, while in many other regions viticulture can thrive only when irrigation is available (Costa et al., 2016; Lovisolo et al., 2010).

Drought responses of grapevine have been investigated from a physiological and molecular point of view to select more resistant varieties/genotypes (Acevedo-Opazo et al., 2010; Bota et al., 2016; Chaves et al., 2010; Medrano et al., 2015; Tombesi et al., 2014). In general, grapevine responses to drought are influenced by the environment in which the plants grow (Hochberg et al., 2017), but are also partly cultivar-dependent, with some of them displaying relatively high resistance/resilience to environmental stress (Chaves et al., 2010;

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Medrano et al., 2015; Tombesi et al., 2014). In particular, cultivars differ in physiological traits which are at the base of their potential resistance to drought, i.e. osmoregulation, water use efficiency, vulnerability to xylem embolism, and stomatal response to water deficit (Bota et al., 2016; Chaves et al., 2010; Medrano et al., 2015; Tombesi et al., 2015). Hence, water use strategies of grapevine were suggested to range from perfect isohydry (strict stomatal control) to anisohydry (reduced stomatal control), although recent studies call for a revision of this terminology (Hochberg et al., 2017; Nardini et al., 2018; Schultz and Stoll, 2010; Tombesi et al., 2014).

Optimization of water use in arid-prone areas is the key to prevent wasting of water resources (Acevedo-Opazo et al., 2010; Chaves et al., 2010; Fernández and Cuevas, 2010; Tripathi et al., 2016). Deficit irrigation approaches significantly reduce the "water footprint" of agriculture, and in particular of vineyards (Chaves et al., 2010; Schultz and Stoll, 2010). Different physiological indicators can be used to assess plant water status and regulate water delivery, including soil water content/potential, plant stem diameter variation, sap flow, thermal and visible imaging (Brillante et al., 2016; Fernández and Cuevas, 2010; Lopes et al., 2011). However, the most reliable parameters to quantify plant water stress are pre-dawn, minimum, and stem water potential (Ψ_{pd}, Ψ_{min}, and Ψ_{stem}, respectively), as well as stomatal conductance to water vapor (Acevedo-Opazo et al., 2010; Fernández and Cuevas, 2010; Flexas et al., 2002; Medrano et al., 2015; van Leeuwen et al., 2009). Deficit irrigation based on water potential measurements has emerged as a strategy allowing grapevines to withstand water shortage with non-significant decreases of yield, and positive impacts on fruit and wine quality (Chaves et al., 2010; dos Santos et al., 2003; Girona et al., 2006; van Leeuwen et al., 2009). As an example, Acevedo-Opazo et al. (2010) reported that a regulated mild water stress ($\Psi_{min} = -1.3$ MPa) in Cabernet Sauvignon vines leads to 13% increase in skin to pulp ratio (compared to well-watered plants) and to significant increments in soluble solids and anthocyanins, without affecting pruning weight but assuring about 90% water saving. These results are in accordance with those reported by other authors, suggesting that moderate water deficit exerts direct and/or indirect effects on bunch development with consequent higher content of polyphenols (anthocyanins, flavonols, tannins), stilbenes, carotenoids, and terpenoids (Herrera et al., 2015; Medrano et al., 2015; Sivilotti et al., 2005; van Leeuwen et al., 2009).

The effectiveness of irrigation strategies in improving plant water status and productivity depends on a combination of plant-, climate- and soil-related factors. In particular, root hydraulic properties and distribution in the soil are fundamental traits influencing both plant water relations, and plant responses to rain events or irrigation treatments. Soil structure, stoniness, and the depth of the water table significantly influence root growth, while the genotype has relatively little influence (Deloire et al., 2004). However, different rootstocks can partially influence water supply to the plants, making mandatory the correct selection of rootstocks adapted to local climate and soil type (Deloire et al., 2004; Koundouras et al., 2008; Nardini et al., 2006). Grapevine root systems have been studied in a range of climates (Mediterranean, humid continental, subtropic) and soil textures (loam, clay, sand), revealing that approximately 80% of roots lies within the upper 1 m (Celette et al., 2005; Smart et al., 2006). The few studies addressing maximum rooting depth suggested that *V. vinifera* roots can reach depths of more than 6 m. However, even deeper rooting patterns cannot be excluded in water limited environments (Smart et al., 2006). Significant gaps remain in our understanding of rooting depth and water relations of grapevines growing on shallow soils overlying fractured bedrock, mainly due to experimental difficulties limiting the use of the "profile wall method" based on excavation (Smart et al., 2006). However, limestone environments subjected to marked moisture stress are relatively frequent across European wine-producing regions (FAO, 1981). In karstic ecosystems, plants can develop deep roots growing through rock cracks and fissures often filled with clay pockets, that might represent important water sources (Estrada-Medina et al., 2013a,b; McElrone et al., 2004; Nardini et al., 2016; Querejeta et al., 2006; Schwinning, 2010). It is not clear whether grapevine can also adopt a similar strategy, and how this eventually relates to the effectiveness of irrigation strategies in such substrates. Hence, considering the ongoing climate changes and the economic importance of viticulture in limestone-dominated regions, information on vines rooting depth is fundamental for future irrigation scheduling, and water management.

This study was carried out in the Classical Karst (NE Italy), an area which experienced an anomalous summer drought in 2012 (+2.3 °C and −50% rains compared to the historical mean) leading to important losses of wine production, and posing a new threat to local agriculture. The loss of yield and plant mortality were mainly a consequence of scarcely developed irrigation systems and practices, not based on actual plants water needs. We monitored grapevine water status over a growing season, indirectly assessed rooting depth and estimated which water sources are exploited by plants in a mature karstic vineyard. We hypothesized that a deep rooting system enables plants to thrive under summer harsh environmental conditions. Furthermore, we investigated effects of irrigation of top soil on plant water status and yield.

2. Materials and methods

2.1. Study site and plant material

The research was carried out in a commercial vineyard in NE Italy (6 km from the town of Trieste, 45° 44′ 10" N, 13° 45′ 2" E; 290 m a.s.l) during the 2015 growing season. The area is located in the Classical Karst, a plateau extending between Italy and Slovenia dominated by carbonate rocks (mainly Cretaceous limestone and dolostome; Jurkovšek et al., 2016), covered by few centimeters of red karst loam ("terra rossa", red soil, carbonate and flysch product; Lenaz et al., 1996; Mrak and Repe, 2004). The climate is semi-Mediterranean, with strong continental influences, warm and dry summers, and mild winters. The average annual temperature is 13 °C, and yearly rainfall is 1385 mm, with less than 200 mm falling in July-August (www.osmer.fvg.it, 1992–2017). The effects of relatively high precipitation on natural vegetation and crops are however contrasted by high permeability of the substrate (Mrak and Repe, 2004).

The studied cultivar was *V. vinifera* cv. Malvasia Istriana, a local white wine variety largely cultivated in Croatia, Slovenia and Italy. In the Classical Karst, "Malvasia Istriana" is of high economic importance as one of the leading wine varieties (AIS, 2010; Bianchi et al., 2008). A mature 25-years-old vineyard of about 0.1 ha with grapevines grafted on SO4 rootstock was selected. The planting density was 5000 plants per hectare, with vines spaced 1 m and 2 m within and between rows, respectively. The row orientation was NW-SE. Annual pruning was performed in late winter by leaving three canes per plant, while during spring the shoots were trained to trellis (wires). According to traditional practices, some summer leaf removal was performed as part of canopy management. The substrate consisted of about 40 cm deep red soil laying on fractured carbonate bedrock. The bedrock consists in dolostones and limestones, and is widely and deeply karstified (Zini et al., 2015). The underground karst features mainly consists in karstified vertical fractures which can be empty or filled with soil. According to local cultural practices, the soil was tilled to a depth of 20 cm two times during the growing season. Throughout the study period, air temperature (T_{air}) and relative humidity (RH) were recorded on hourly basis, using two data loggers (EasyLog-USB-2, Lascar Electronics Inc., Salisbury, UK) installed at 1.5 m height, facing north, and partially shielded with aluminum foil to prevent over-heating. Average midday daily T_{air} and RH (11:00–14:00, solar time) were used to calculate maximum vapor pressure deficit, as VPD = $E_0 \times (1–RH)$, where E_0 is the saturated vapor pressure at any definite T_{air}. The daily reference evapotranspiration (ET_0) was calculated with the Penman-Monteith equation (Snyder and Eching, 2007). Rainfall data were obtained from the