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Physiological response of post-veraison deficit irrigation strategies and growth patterns of table grapes (cv. Crimson Seedless)

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ABSTRACT

To determine whether partial root-zone drying (PRD) offers physiological advantages compared with regulated deficit irrigation (RDI), a 3 year long-experiment was conducted on a commercial vineyard of ‘Crimson Seedless’ table grapes (*Vitis vinifera* L.). Four different drip irrigation treatments were imposed: (i) a Control treatment irrigated at 110% of seasonal crop evapotranspiration (ET_c), (ii), a regulated deficit irrigation (RDI) treatment irrigated similar to Control before veraison and at 50% of the Control treatment post-veraison, (iii) a partial root-zone drying (PRD) irrigated similar to RDI but alternating (every 10–14 days) the dry and wet side of the root-zone, and (iv) a null irrigation treatment (NI) which only received the natural precipitation and occasional supplementary irrigation when midday stem water potential (Ψ_s) dropped below −1.2 MPa. Post-veraison, PRD vines accumulated greater localized soil and plant water deficit at midday than RDI vines, but maintained similar pre-dawn water potential (Ψ_{pd}) values. Stomatal conductance (g_s) of PRD vines remained high, likely because there was sufficient root water uptake from irrigated soil. Xylem ABA concentration ($[ABA]_{xylem}$) did not change yet intrinsic WUE (WUEi) decreased compared to RDI vines, probably because PRD induced greater root density and root development at depth, allowing greater water uptake from roots in the wet part of the soil profile. Vegetative growth was only decreased by severe deficit irrigation (NI) although total leaf area index (LAI) was also affected by PRD in the 1st and 3rd year.. PRD can be considered a useful strategy in semiarid areas with limited water resources because sustained water use maintained assimilation rates despite greater stress than conventional RDI strategy, which may be related to root and morphological adjustment.

1. Introduction

Irrigated agriculture is known as the primary user of diverted water globally, reaching a proportion that exceeds 70–80% of the total in arid and semiarid zones. Since water withdrawals are forecast to sharply increase in the future, it is obvious that irrigated agriculture will become a primary consumer of water especially in emergency drought situations (Williams et al., 2010a,b). Moreover, other factors such as the booming global population and the progress of climate change will require increased food production under water deficit situations. Therefore, the challenge for the coming years will be to increase or at least maintain fruit production and quality with less irrigation water, which could be achieved by implementing different irrigation strategies that enhance irrigation water efficiency.

Table grapes need more water than grapevines because they require a greater leaf area to supply photoassimilates to developing berries, allowing large berries for fresh consumption (Williams and Ayars, 2005; Silva-Contreras et al., 2012). Thus, the determination of crop water requirements is essential to apply deficit irrigation (DI). In fact, the demand for seedless varieties (e.g. ‘Crimson Seedless’) has increased considerably in recent years as a result of increased international demand and new plantings.

Applying deficit irrigation (DI) practices can limit irrigation requirements while maintaining the yield and quality standards required

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Abbreviations: DI, deficit irrigation; RDI, regulated deficit irrigation; PRD, partial root-zone drying, A, net CO_2 assimilation rate; g_s, stomatal conductance; E, transpiration rate; A/g_s, intrinsic water use efficiency; $[ABA]_{xylem}$, xylem abscisic acid concentration; S-ABA, exogenous abscisic acid; θ_v, soil volumetric water content; Ψ_{stem}, stem water potential at midday; Ψ_{pd}, predawn leaf water potential; Ψ_o, predawn leaf osmotic potential; Ψ_{os}, predawn leaf osmotic potential at full turgor; Ψ_t, predawn leaf turgor potential; LAI, leaf area index; PE, productivity efficiency; TCSA, trunk cross-section area; ΔTCSA, annual increment trunk-section area

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by the fruit market (Ruiz-Sánchez et al., 2010; Pérez-Pastor et al., 2016). Two main techniques are regulated deficit irrigation (RDI) and partial root-zone drying (PRD). Both supply less irrigation during periods of the growing season when the crop is less sensitive to fruit growth (Chalmers et al., 1981; Dry et al., 1996). In this sense, table grapes are generally considered sensitive to water stress from fruit setting to veraison, since this determines the final yield and fruit quality. Thus, RDI and PRD should be applied post-veraison to minimise adverse effects on productivity (Conesa et al., 2016a).

Soil water deficit imposed by DI techniques alters vine physiology and plant hydraulic and chemical signalling systems, thereby affording commercial benefits such as increased water use efficiency (WUE) and decreased vegetative vigour (Romero et al., 2014). Stomatal conductance (g_s) can be decreased by the synthesis of chemical signals (predominantly abscisic acid - ABA) in the roots in response to drying soil, and their subsequent transport to the leaves via the transpiration stream to effect stomatal closure (Dodd et al., 2015; Puértolas et al., 2015). During PRD, typically one part of the root-zone is irrigated at a time, with the wet and dry parts of the root zone periodically alternated to transiently enhance ABA signalling (Dodd et al., 2006) and/or prevent excessive soil drying diminishing the transport of chemical signals to the shoot (Romero et al., 2012). ABA-induced stomatal closure limits transpiration and xylem cavitation (Beis and Patakas, 2010), even though prolonged stomatal closure also limits photosynthetic activity by decreasing Rubisco carboxylation activity (Chaves et al., 2010; Salazar-Parra et al., 2015). Conversely, prolonged soil drying cycles during PRD may limit ABA transport from roots in drying soil (Pérez-Pérez and Dodd, 2015), thereby minimising stomatal limitation of photosynthesis (Downton et al., 1988), which may enhance yield of PRD plants compared to conventional RDI plants (Antolín et al., 2006; Dodd, 2009). Thus, it is not clear whether ABA-induced stomatal closure (and effects on photosynthetic carbon gain) is enhanced or attenuated by PRD relative to RDI.

Typically, water stress limits leaf area expansion prior to any decrease in photosynthetic assimilation (Beis and Patakas, 2015) and canopy development and vegetative growth are more sensitive to water deficit than fruit growth. Insufficient canopy development may also limit berry development in low vigour varieties (Ruiz-Sánchez et al., 2010). Moreover, decreased vegetative growth under RDI or PRD might be also due to limited cell expansion mediated by lower cellular turgor (Chaves et al., 2010). When PRD and RDI vines received the same irrigation volumes, only subtle differences in leaf water relations, WUE, crop yield and fruit quality were detected (dos Santos et al., 2005; de Souza et al., 2005; Romero et al., 2012). However, in some cases, PRD vines appeared to maintain higher water status with a lower (Chaves et al., 2010; Rodrigues et al., 2008), higher (Antolín et al., 2006), or similar (Antolín et al., 2008) leaf area than RDI vines. Therefore, it is not clear whether leaf water relations are regulating canopy development (Lovisolo et al., 2010) or *vice versa*.

Earlier studies that compared PRD and RDI under the same irrigation volumes revealed differential physiological and biochemical responses in wine grapes (Romero et al., 2012, 2014; Beis and Patakas, 2015), but there is little information on table grapes. While there is no reason to suppose table grapes and wine grapes should differ in their physiological responses to PRD and RDI, irrigation is typically withheld from table grapes post-veraison (Conesa et al., 2016a; Pinillos et al., 2016) and from wine grapes throughout berry development (Chaves et al., 2010; Costello and Patterson, 2012). Interestingly, stomatal closure of winegrapes was less sensitive to ABA post-veraison (dos Santos et al., 2005), suggesting that the timing of deficit irrigation may modify stomatal responses (Torres-Ruiz et al., 2016). Furthermore, grower implementation of PRD in favour of conventional RDI requires positive agronomic effects, especially due to higher costs of infrastructure installation and complex irrigation management (Marsal et al., 2008; García García et al., 2012; Romero et al., 2016; Permanhani et al., 2016). Nevertheless, PRD enhanced berry coloration and health-promoting bioactive compounds (e.g. anthocyanins, resveratrol and antioxidant capacity) compared to RDI in the table grape Crimson Seedless (Conesa et al., 2016a). To determine whether these biochemical differences were coincident with altered vine physiology, the physiological responses and vegetative growth of RDI and PRD vines (that received the same irrigation volumes) were compared in the same experiment previously described (Conesa et al., 2015, 2016a, b).

2. Material and methods

2.1. Experimental conditions, plant material and irrigation treatments

The experimental design, soil characteristics, climate parameters, fertilization and standard cultural practices have been described in detail (Conesa et al., 2015; 2016a, b). Briefly, this research was carried out in a 1-ha vineyard at Cieza, Murcia (SE Spain, 38°15′N; 1°33′W) during three consecutive years (2011–2013). The table grapes were 11-year-old Crimson Seedless (*Vitis vinifera* L.), grafted onto 1103 Paulsen rootstock. The training system was a bilateral cordon trellised to a three-wire vertical system. The vine rows ran N–NW to S–SE and the planting density was 4 m both between rows and between vines (625 vines ha^{-1}). The experiment involved four different irrigation treatments which were irrigated daily in the early evening from April to October. A Control treatment irrigated to satisfy maximum crop water requirements (ET_c-110%) through the whole growing season; (ii) a RDI treatment was irrigated as the Control except post-veraison, when the vines were irrigated at 50% of Control levels (iii) a PRD treatment that received the same irrigation amount as RDI, but applied to only part of the rootzone, with the dry and wet sides of the root-zone alternated every 10–14 days, when the dry side of the rootzone reached 75% of field capacity ($\sim$34% θ_v); and (iv) a null irrigation (NI) treatment, which only received rainfall and supplementary irrigation when the daily stem water potential (Ψ_s) exceeded the established threshold value of -1.2 MPa (Conesa et al., 2012). In Control, RDI and NI treatments, the irrigation system comprised one drip-line in each vine row, with four self-compensating drippers (4 L h^{-1}) 0.50 m apart, whereas the PRD treatment utilised two drip-lines with two drippers (4 L h^{-1}) per vine to each side of the root system. Crop evapotranspiration ($ETc = ET_0$ x kc) was estimated using crop coefficients (kc) based on Williams and Ayars (2005) varying from 0.2 to 0.8 according to the phenological stage, whereas reference crop evapotranspiration (ET_0) was calculated with the Penman Montheith-FAO method (Allen et al., 1998), with daily climatic data recorded by an automatic weather station of the Servicio de Información Agraria de Murcia, located 8.5 km from the experimental plot (CIA-42, www.siam.es).

2.2. Soil water status

Soil volumetric water content (θ_v) was measured to a maximum depth of 1 m every 0.1 m with a frequency domain reflectometry (FDR) probe (Diviner 2000®, Sentek Pty. Ltd., South Australia). Measurements were expressed in the profile 0–50 cm, coinciding with the effective root depth (data not shown). Three access tubes (1 per each replicate, n = 3) located 25 cm from the drippers, were installed within the wetting area on randomly selected vines. In PRD treatment, FDR probes were installed on both sides of the vine row (2 per each replicate, n = 6). Measurements were taken every 7–10 days between 10:00 h-12:00 h during the experimental period.